Tonalites from the Hospitais massif (Ossa-Morena Zone, SW Iberian Massif, Portugal) II: Geochemistry and petrogenesis

Tonalitas del Macizo de Hospitais (Zona de Ossa Morena, SO Macizo Ibérico, Portugal). II: Geoquímica y petrogénesis

P. Moita [(1)], J.F. Santos [(2)] y M.F. Pereira [(1)]

[(1)] Grupo de Tectónica- Centro de Geofísica de Évora, Dept. Geociências, Universidade de Évora, Apt 94, 7002 –554 Évora, Portugal
[(2)] Departamento Geociências, Universidade de Aveiro, 3810-193 Aveiro, Portugal

ABSTRACT

As described in the first part of this work (Moita et al., this volume), the Hospitais Massif belongs to a syn-orogenic Variscan magmatic association, intrusive in a gneissic-migmatitic complex of the Évora High-Grade Metamorphic Terrains. In this paper, geochemical data obtained on tonalites and dioritic enclaves, from the Hospitais Massif, and on gabbros, from smaller plutonic bodies in the neighbourhood of that massif, are used to constrain hypotheses on the petrogenetic processes responsible for the mentioned lithologies. Major and trace element geochemistry reveal calc-alkaline affinities and suggest that gabbros, diorites and tonalites belong to a magma suite derived dominantly by fractional crystallization. The presence of microgranular mafic enclaves, within the tonalites, could be interpreted as representing an additional process of mingling/mixing for the evolution of these rocks. According to their geochemical features, the enclaves may have resulted from an intermediate differentiation product internally mixed with the tonalite melt. A filter-pressing process can explain the amphibole-dominated cumulate REE pattern displayed by the enclaves.

Key words: *tonalite, mafic enclave, fractional crystallization, accumulation, Ossa-Morena Zone*

RESUMEN

Como se ha descrito en la primera parte del trabajo (Moita et al. en este volumen), el Macizo de Hospitais pertenece a una serie magmática sinorogénica Varisca intruida en un complejo de gneises y migmatitas perteneciente a los Terrenos de Alto-grado Metamórfico de Évora. Se han utilizado datos geoquímicos de las tonalitas, de los enclaves dioríticos y de pequeños cuerpos, espacialmente asociados, de gabro, para caracterizar los procesos petrogenéticos relacionados con esta serie magmática. La geoquímica de elementos mayores y traza muestra una afinidad calco-alcalina y sugiere que los gabros, dioritas y tonalitas pertenecen a una serie magmática originada mediante procesos de cristalización fraccionada. La presencia de enclaves microgranulares máficos en tonalitas, puede ser interpretada como el resultado de un proceso adicional de "mingling/mixing" en la evolución en estas rocas. De acuerdo con sus características geoquímicas los enclaves serián el resultado de un producto intermedio de diferenciación internamente mezclado con el magma tonalítico. Un proceso de "filter-pressing" puede explicar los patrones de tierras raras de cumulados anfibólicos característicos de los enclaves estudiados.

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Introduction

Tonalites are common members of low-K tholeiitic and calc-alkaline magmatic suites in convergent plate margin setting (Barnes *et al*., 1996) and their genesis have been ascribed to one of two possible processes: (1) either fractional crystallization from a sub-alkaline basaltic parental magma (e.g. Arth *et al*., 1978), or (2) partial melting of mafic metamorphic rocks with amphibolitic or eclogitic assemblages (*e.g*. Rapp *et al*., 1991 and Drummond and Defant, 1990, respectively).

Another controversial issue concerning this type of plutonic rocks is the origin of microgranular mafic enclaves. These type of inclusions have been interpreted elsewhere (e.g. Didier, 1973) as: (1) xenoliths of wall rocks, (2) globules of mafic magma in a process of mingling, (3) refractory pods of a source rock or (4) accumulations of early formed minerals.

In this work, geochemical and petrological data obtained in the Hospitais Massif (HM), and in some small basic intrusions, of probable similar age, in its vicinities, are used to define the main petrogenetic processes and characterize the geodynamic setting responsible for this magmatic

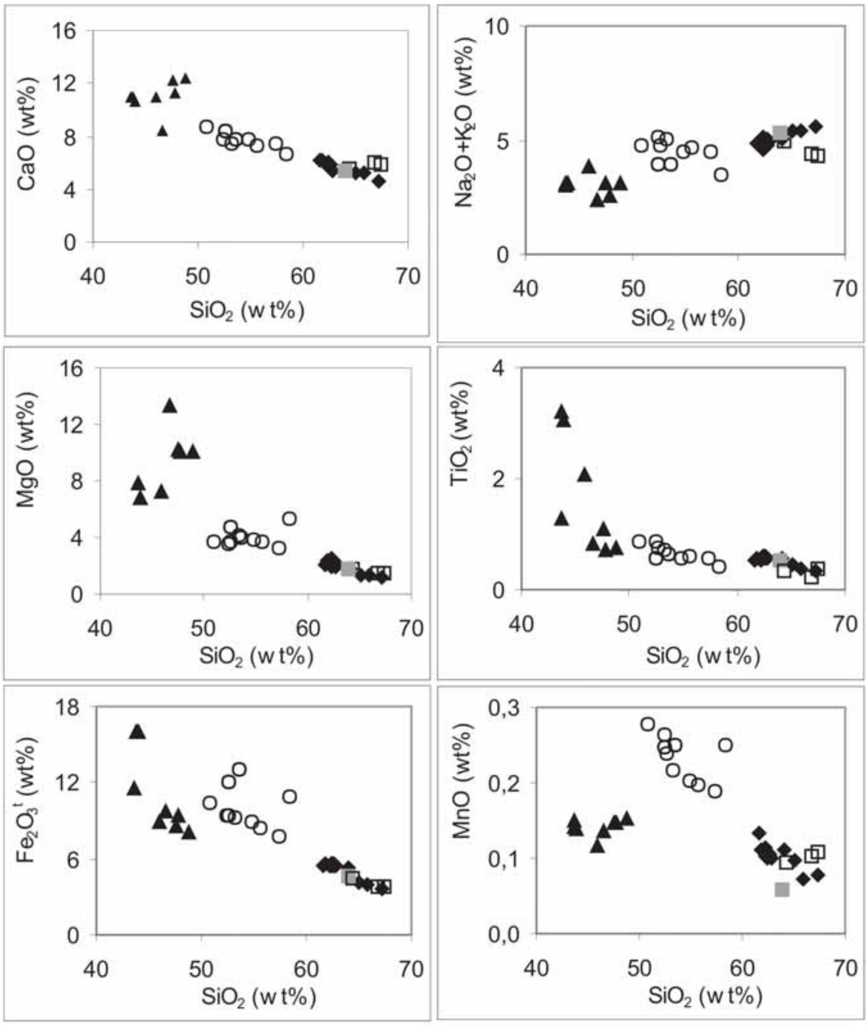

Fig. 1.- Some whole-rock major elements variation (Harker diagrams), using SiO_2 as differentiation index, for tonalites (◆), LTH (□), LTL (■), mafic enclaves (O) and gabbros (▲).

Fig. 1.- Diagramas de variación para elementos mayores (diagramas de Harker), con SiO_2 como índice de diferenciación para tonalitas (◆), LTH (□), LTL (■), enclaves máficos (O) y gabros (▲).

association. Geological setting, field data and petrographic features are discussed in Moita *et al.* (this volume).

Geochemistry

For this study, 36 samples were analysed: (1) a group comprising fourteen rock samples of the main tonalite, ten of the mafic enclaves, three of the leucocratic halos (LTH) and one of a leucocratic tonalite layer (LTL), from the Hospitais Massif; (2) a second group of eight samples of mafic rocks (gabbros) from the surroundings of the Hospitais Massif (for location, see figure 1 of Moita *et al*., this volume). In three places, sets of three samples were collected, representing (i) a mafic enclave, (ii) the halo around the enclave and (iii) the host "normal" tonalite.

Major elements

The gabbros, the dioritic enclaves within tonalites and the leucocratic rocks (main tonalite, LTH and LTL) constitute three distinct groups based on their silica contents: the first ranges from 43.67 to 48.86%; the second, from 50.87 to 58.31%; and the third from 61.65 to 67.41%. Using all the lithologies, Harker diagrams (Fig. 1) show: roughly linear trends for CaO and Na_2O+K_2O, with a positive slope for the oxides of the alkalies and negative slopes for lime; also a linear trend, defined by most samples, for MgO, although some basic rocks are outliers with excess magnesium, probably as a result of accumulation of Mg-rich silicates; a strongly curved trend for TiO_2, caused by a rapid decrease of titanium with differentiation but also by spreading of its concentrations in the basic compositions as a consequence of oxide mineral accumulation in some gabbros; scattered data, particularly in the more mafic compositions, for Al_2O_3 and P_2O_5; compositions of the dioritic enclaves enriched in $Fe_2O_3{}^t$ and MnO relative to hypothetical lines (with negative slopes) from the gabbros to the tonalites. The LTH and LTL samples usually plot on the trend of the main tonalite, although they reveal a slight enrichment in SiO_2 (2-5%) when compared to the enclosing rocks.

The major element variation diagrams, taken separately from the other geochemical evidence, do not allow precise conclusions. It is noteworthy that rectilinear correlations are only sporadic: therefore, the compositions of the materials present in zones where tonalite encloses mafic enclaves cannot be explained as simple mixing of two extreme compositions. The significant scatter observed in some diagrams does not discard the hypothesis of a cogenetic relationship amongst all the sampled lithologies, since it may be caused by mineral accumulation (and, in some gabbros, by alteration).

The major element data (specially the low slope of the correlation in the Na_2O+K_2O *vs.* SiO_2 diagram) confirms the expected subalkaline character of the studied rocks. The petrographic and geochemical evidence for early fractionation of oxide minerals reveals a calc-alkaline affinity, but the absence of a clear increase of K_2O with SiO_2 is more typical of tholeiitic suites; therefore, if the studied lithologies are cogenetic, they constitute an association transitional between tholeiitic and calc-alkaline series. Low values of A/CNK in the tonalitic lithologies (0.94-1.01) show that they are essentially metaluminous, which, taken together with their modal compositions, allows the classification of these rocks as I-type granitoids (Chappel and White, 1974).

Trace elements

The main tonalite samples are slightly LREE-enriched in primitive mantle normalization (Sun and McDonough, 1989), with La_N/Lu_N ratios of 2.50-9.10 (Fig. 2). Eu anomalies are small and may be either positive or negative (Eu/Eu*:0.88-1.31). The LTH accompany the main tonalite compositions (La_N/Lu_N: 2.51-4.24; Eu/Eu*: 1.03-1.06), whereas the LTL has the highest Eu positive anomaly and one of the most fractionated REE patterns amongst all samples of the

Hospitais Massif (La_N/Lu_N: 8.79; Eu/Eu* = 1.59).

REE patterns for the gabbros are very similar to those obtained in the main tonalite, with La_N/Lu_N = 1.99-7.31. Nevertheless, the ÓREE contents, although variable in the gabbros, are in average slightly higher in the basic rocks than in the tonalites. These values correlate well with the higher modal composition of apatite observed in the samples of the mafic intrusions.

The dioritic enclaves can be distinguished from the previous lithologies by having normalized patterns varying from nearly flat to concave downwards, always with pronounced negative Eu anomalies (Eu/Eu*: 0.40-0.69). There is a strong negative correlation between Eu/Eu* and ÓREE: the highest contents of REE correspond to the deepest Eu anomalies. Within this group of samples, the REE behaviour seems to depend not from a hypothetical abundance of apatite but from the modal proportions of hornblende. In fact, the patterns with the most concave shape, highest contents of lanthanides and strongest negative anomalies of Eu correspond to the samples richer in the calcic amphibole. The available data on hornblende/melt partition coefficients (Arth, 1976; Hanson, 1978) corroborate the hypothesis that the geochemical features of mafic enclaves represent the effects of mineral segregation (cumulates) rather than the composition of dioritic melts

On multi-element diagrams (Fig. 3), the main tonalite and the gabbroic rocks show, again, similar patterns: moderate LILE/HFSE enrichment (Th_N/Y_N: 2.71-11.43 for the main tonalite and Th_N/Y_N: 2.50-6.61 for the gabbros); pronounced negative anomalies for Ti and Nb (Th_N/Nb_N: 1.33-6.22 for the main tonalite and Th_N/Nb_N: 1.45-3.77 for the gabbros). Only one sample of gabbro exhibits a positive Ti anomaly, which can be explained by the high modal proportions of Fe-Ti oxides of early generation observed on that rock.

The spider diagrams for LTH and LTL show that the two samples with the highest contents of incompatible elements have essentially the same geochemical features of the main tonalite, whilst the two other samples (both from LTH) diverge from the dominant patterns, particularly in the left sector of the plot; this difference is probably an artifact caused by the small dimensions of the samples of LTH.

Mafic enclaves have peculiar trace element characteristics, with most samples displaying low Th_N/Nb_N ratios (usually, less than 0.5) and Zr negative anomalies. Considering the partition coefficients between amphibole and melt for Nb and Zr (Arth, 1976, Pearce and Norry, 1979) and their comparison with the coefficients for the elements that occupy the immediate positions in the spiderdiagrams, it can not be ruled out that the mafic enclaves are cumulates derived from melts with a geochemical signature similar to the described for tonalites and gabbros. In particular, the absence of Nb negative anomaly in mafic enclaves may fit into a process of segregation of amphibole from a magma with that type of anomaly.

Discussion

The main geochemical characteristics described in the previous section have shown that the studied rocks probably belong to a suite transitional between low-K tholeiitic and calc-alkaline series. A supra-subduction geodynamic setting is the most likely situation for that type of magmatism, and this hypothesis is supported by significant trace element fingerprints, namely Nb and Ti negative anomalies (Pearce and Parkinson, 1993), in the lithologies that are closer to represent magma compositions. Plotting of samples from the Hospitais massif in tectonic discrimination diagrams for granitoids (Rb *vs*. (Y+Nb); Ta *vs*. Yb) proposed by Pearce *et al.* (1984) confirm that their compositions are typical of igneous rocks from volcanic arc environment.

The similarities of REE and multi-element patterns for tonalites and gabbros, associated with some trends in Harker diagrams, suggest that those lithologies are cogenetic and that fractional crystallization could have played an important role in the generation of tonalitic magmas. The fractionation of clinopyroxene, amphibole, calcic plagioclase and Fe-Ti oxides can account for the decreases in CaO, MgO, $Fe_2O_3^t$ and TiO_2 - and the increase in Na_2O+K_2O - with the differentiation index. Additionally, crystallization of apatite from the basic melts, which is testified by its presence in gabbros, should have prevented increase of the REE contents in the differentiated magmas. Some diagrams show, for basic rocks, poor correlations and scattered data (*e.g.*: MgO, TiO_2, Al_2O_3, P_2O_5), possible due to

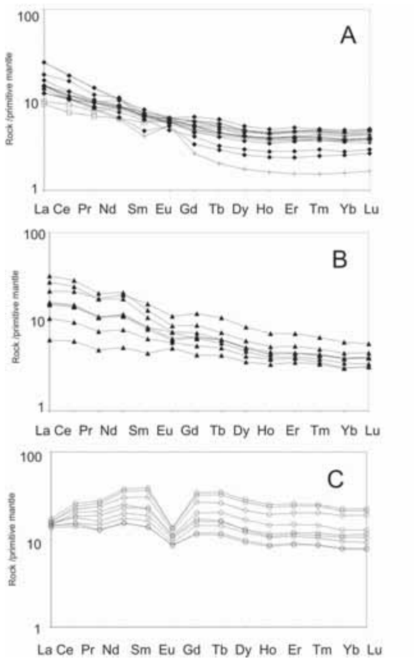

Fig. 2.- Rare earth elements patterns for: a) leucocratic rocks (tonalites (◆), LTL (+), LTH (□)); b) gabbros, c) mafic enclaves. Primitive mantle values from Sun y McDonough (1989).

Fig. 2.- Espectros de REE para: a) rocas leucocraticas (tonalitas (◆), LTL (+), LTH (□)); b) gabros, c) enclaves maficos. Valores del manto primitivo de Sun and McDonough (1989).

variable accumulation effects of ferromagnesian silicates (clinopyroxene and hornblende), plagioclase, Fe-Ti oxides and apatite.

Although the sample of LTL is richer in hygromagmatophile elements and poorer in compatible elements when compared to the tonalite in its contact, that lithology is almost geochemically indistinguishable from the whole set of samples of the main tonalite. The most significant difference is the occurrence in LTL of the most clearly defined positive Eu anomaly (Eu/Eu* = 1.59); additionally this rock displays a relatively high LREE/HREE ratio. Therefore, the leucotonalitic layer, rather than corresponding to a highly evolved magma, probably represents a stage of strong fractionation of plagioclase (Arth and Barker, 1976), leading to its accumulation in several parts of the magma chamber (see description of LTL and of magmatic banding in Moita *et al*., this volume).

The dioritic modal composition of the mafic enclaves and the evidence for complex zoning in plagioclase crystals in the samples of the Hospitais Massif is suggestive of mixing/mingling between

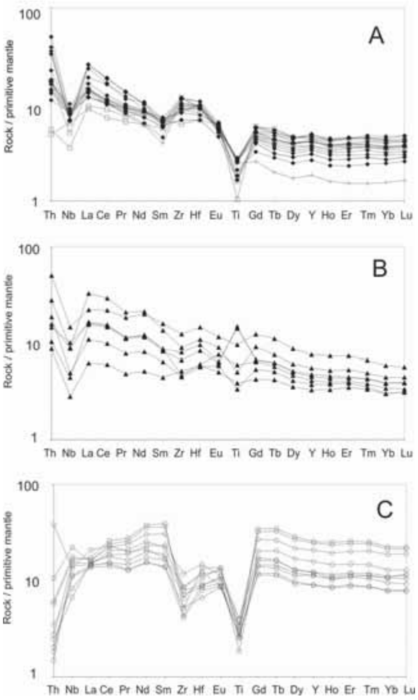

Fig. 3.- Multi-element diagrams for a) leucocratic rocks (tonalites (◆), LTL (+), LTH (□)), b) gabbros and c) mafic enclaves. Primitive mantle values from Sun y McDonough (1989).

Fig. 3.- Diagramas multi-elemental para: a) rocas leucocraticas (tonalitas (◆), LTL (+), LTH (□)); b) gabros, c) enclaves maficos. Valores del manto primitivo de Sun and McDonough (1989).

mafic and felsic melts in this pluton. Since tonalites from the HM and gabbros from nearby small intrusions seem to be cogenetic (as discussed above), if the main process of differentiation was magma mixing, the mafic enclaves should be colinear with the other lithologies in Harker diagrams and have intermediate trace elements patterns. However, the plots of major elements against silica show that the enclaves are richer than expected in Fe and Mn, whilst REE and multi-element diagrams reveal clearly amphibole dependent geochemical features. As such, mafic enclaves are probably cumulate material from the fractionation process that resulted in the generation of tonalitic magma. The similarities between amphiboles present in both lithologies (namely the widespread hornblende–cummingtonite association) also argue in favour of a common parent melt.

Considering field, petrographic and geochemical evidence, the enclaves may represent an intermediate fractionation product - probably mafic layers that were disrupted - in a magma chamber where convection-dominated segregation resulted in *internal mixing*, as proposed in the model of Hibbard (1995). This author also claims that simultaneous tectonic adjustments promote this type of processes.

It is also likely that during the mingling of the dark-coloured segregations within the main tonalite magma their limits constituted *basic fronts* (Raguin, 1976) where preferential nucleation and growth of amphibole went on. In the immediate vicinity of a *basic front*, the migration of ferromagnesian components towards the mafic segregation could produce an aureole, corresponding to a *siliceous front*, depleted in those components. The leucocratic halos (LTH) around the enclaves can be seen as testimonies of the siliceous fronts, complementary of the developing zones of the enclaves.

The absence of typical cumulate textures in the mafic enclaves is apparently contradictory with their geochemical features, but that may be the result, as proposed by Bacon (1986) and Barnes *et al.* (1992), of a mechanism of filter pressing that led to the removal of the intersticial melt from the enclaves, leaving behind a cumulus residue.

Conclusions

Geochemical and petrographic data suggest that gabbros, tonalites and dioritic enclaves (within tonalites), in the Montemor-o-Novo area (Évora High-Grade Metamorphic Terrains), represent a cogenetic magma suite that was mainly derived by fractional crystallization. This igneous association is intermediate between low-K tholeiitic and calcoalkaline series, and their non-cumulate lithologies have major and trace element fingerprints typical of magmas generated in supra-subduction setting. Some terms of the association show evidence of accumulation processes, namely leucotonalitic layers where plagioclase became concentrated, or mafic enclaves that testimony for amphibole segregation.

Mafic enclaves in the Hospitais Massif are interpreted as an intermediate fractionation product, between the gabbros and the main tonalite, internally mixed with the tonalitic melt. Their geochemical cumulate characteristics (particularly obvious in the trace element patterns) may be inherited from the original segregation of mafic material (layers that suffered disruption?) but probably became prominent due to filter pressing, during mingling within the main tonalite.

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