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Geochemistry of lower Paleozoic anorogenic basic rocks from the Evora Massif (Western Ossa-Morena Zone, Portugal)

Geoquímica de las rocas básicas anorogénicas del Paleozoico inferior del Macizo de Évora (domínios occidentales de la zona de Ossa-Morena, Portugal)

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ABSTRACT

Undated basic rocks included in the Ossa-Morena westernmost domains (Alentejo region, Portugal) have been studied in an attempt to fill the lack of geochemical data for the Evora Massif. The selected outcrops, interpreted to belong to the lower Paleozoic stratigraphic record, are mainly represented by amphibolites associated with metamorphosed detritic, carbonate and volcanic-sedimentary series. According to their petrography and variations of major, trace and REE elements, these basic rocks seem to derive from protoliths with tholeiitic basalt compositions probably related to an anorogenic geotectonic scenario controlled by transtension and the development of clastic and carbonate basin sedimentary sequences. Fractional crystallization of olivine, clinopyroxene and plagioclase may have played an important role in the generation of different melt composition, however, it is also necessary to invoke source heterogeneity and/or different degrees of partial melting of a mantle source with garnet lherzolite composition to explain the observed range of incompatible trace element ratios. The most likely sources of the basaltic melts may have varied from depleted mantle (similar to N-MORB sources) to mantle rocks affected by within-plate enrichment.

Key words: *geochemistry, anorogenic basic rocks, lower Paleozoic series, Évora massif, Ossa-Morena zone*

RESUMEN

Rocas básicas de edad desconocida incluidas en los dominios occidentales de la Zona de Ossa-Morena (Alentejo, Portugal) fueron estudiadas con el objetivo de completar a falta de datos geoquímicos del Macizo de Évora. Los afloramientos seleccionados incluyen esencialmente anfibolitas asociadas a series detríticas, carbonatadas y volcanosedimentarias metamorfizadas que son interpretadas como pertenecientes al Paleozoico inferior.

Los datos petrográficos y las variaciones observadas en los elementos mayores, traza y REE de las rocas básicas indican que provienen de protolitos con composición de basaltos toleíticos probablemente asociados a un ambiente geotectónico anórogenico con transtension y desarrollo de cuencas sedimentarias con secuencias clásticas y carbonatadas. La cristalización fraccionada de olivino, clinopiroxeno y plagioclasa habrían sido fundamentales en la formación de distintas composiciones mantélicas. También es necesario admitir heterogeneidades en la fuente y distintos grados de fusión parcial da la fuente mantélica de composición lherzolítica con granate para explicar las variaciones observadas en el comportamiento de los elementos traza incompatibles. Las fuentes más probables para los magmas basálticos habrían derivado de manto empobrecido (N-MORB) a rocas mantélicas afectadas por enriquecimientos intra-placa.

Palabras clave: *geoquímica, rocas básicas anorogenicas, series del Paleozoico inferior, macizo de Evora, zona de Ossa-Morena*

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Geological setting

In the Iberian Massif the geochemical characteristics of basic rocks have been used in the reconstruction of distinct geotectonic scenarios, concerning the places in the lithosphere where these igneous materials were probably formed (e.g. oceanic island or continental to oceanic rifting environments). The fact that it is possible to recognise a continuous and complex history in the Ossa-Morena Zone (OMZ) where can be found well-preserved occurrences of basic rocks related to distinct Neoproterozoic to Paleozoic tectonic events (Eguiluz *et al.*, 2000; Simancas *et al.*, 2001; Sánchez-Garcia *et al.*, 2003; Gómez-Pugnaire *et al.*, 2003) makes this zone an ideal target to apply geochemical analysis. As a result of deformation controlled by transcurrent movements the present-day geometry of the OMZ is characterised by the existence of different kilometric-scale sigmoidal-shape domains that have been tentatively defined based on their stratigraphy, deformation, igneous content and metamorphism (e.g. Apalategui *et al.*, 1990; Oliveira *et al.*, 1991). In this context, the Evora Massif (EM- Carvalhosa, 1983; Quesada and Munhá, 1990) represents the westernmost domain of the OMZ, in Portugal, composed by Neoproterozoic to Upper Paleozoic rocks showing great variations in style and intensity of deformation and metamorphism (e.g. Pereira *et al.*, 2003).

Based on field observations (Pereira *et al.*, 2003) and in the stratigraphic columns presented in 1:50,000 scale geological maps from Montemor-o-Novo (e.g. Carvalhosa and Zbyszweski, 1994) and Arraiolos (e.g.

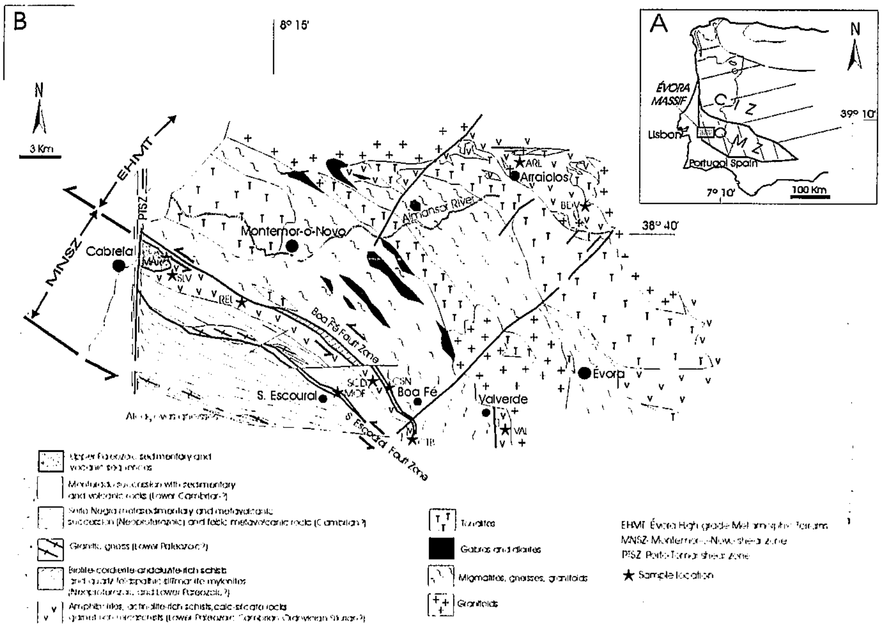

Fig. 1.- A- inset: Location of the Évora Massif within the OMZ as part of the SW Iberian Massif). B- Schematic geological map of the Évora Massif showing the location of the Lower Paleozoic basic rocks analysed samples. Modified after Pereira et al., 2003.

Fig. 1.- A- Mapa con localización del Macizo de Évora en la zona de Ossa-Morena (SO Macizo Ibérico). B- Esbozo geológico del Macizo de Évora con la localización de las muestras analizadas de rocas básicas del Paleozóico Inferior. Modificado de Pereira et al., 2003.

Carvalhosa, 1999) it is possible to interpret the stratigraphic record exposed in the EM as including, from bottom to top: (1) Neoproterozoic metasedimentary and metavolcanic succession (Serie Negra or lower part of the Escoural Formation) with black metacherts, metapelites, metapsammites, micaschists, amphibolites and felsic gneisses; (2) Lower Paleozoic metasedimentary and metavolcanic series (upper part of the Escoural Formation, Monfurado Formation, Carvalhal Formation and Xistos de Moura Formation) with marbles, felsic metatuffs and metarhyolites, felsic gneisses, amphibolites, micaschists, metapelites and calc-silicate rocks; (3) Upper Paleozoic sedimentary and volcanic sequences (Pedreira de Engenharia and Cabrela Formations) with limestones, pelites, greywackes, conglomerates, rhyolites, felsic tuffs and andesites;

The selected basic rocks from the EM Lower Paleozoic series that were used in this study, crop out in five different key-areas (see Fig. 1 for location): (1) at Escoural and (2) between Cabrela and Boa Fé, both located within the Montemor-o-Novo shear zone (MNSZ, Pereira *et al.*, (2003); (3) at Casas Novas nearby Boa Fé, within the Boa Fé Fault Zone representing the limit between the MNSZ and the Évora High-grade Metamorphic Terranes (EHMT; Pereira *et al.*, 2003; Chichorro *et al.*, in press); (4) at Valverde and (5) at Arraiolos, both located along the poorly known respectively Northeastern and Eastern limit of the EHMT.

Considering the existence of uncertainties about the protolith ages and the precise stratigraphic position of these metamorphosed basic rocks, this paper aims to show that sampling campaigns for geochemical analysis, controlled by detail field studies, can contribute to identify geological features in common between separate outcrops.

Field and Petrographic descriptions of the EM Lower Paleozoic basic rocks

Fourteen samples of variably deformed and metamorphosed basic rocks from the EM Lower Paleozoic metasedimentary and metavolcanic series, collected in different places from Escoural to Arraiolos regions (see Fig. 1 for location), have been analysed for REE, major and trace elements. As described above, five different key-areas were object of sampling: (1) One outcrop represents a probable metric-scale width sill of medium-grained amphibolite within a sequence of marbles located at a quarry nearby Escoural, belonging to a probably Cambrian volcanic-sedimentary complex described (e.g. Carvalhosa and Zbyszweski, 1994) as the Monfurado formation (sample MOF); (2) Four samples were obtained from fine-medium grained amphibolites with a well-developed S-L fabric, along a kilometric long narrow band of basic rocks associated with metapelites and micaschists, that extends from nearby Cabrela (Silveiras) passing through Relvas, Serra do Conde, to the south of Boa Fé (Corta Braços), described in the literature (e.g. Carvalhosa and Zbyszweski, 1994) as the Carvalhal Formation (samples SLV, REL, SCD, CTB, in order from NW to SE according with an increase in the metamorphic conditions from greenschist to amphibolitic facies). Associated with this group of samples, another one (at vg. Marinha) representing a pebble of a previously metamorphosed and deformed basic rock (sample MAR) was collected from a polygenic conglomeratic level included in the Cabrela Formation, as part of the unmetamorphosed Upper Paleozoic sequences; (3) Two samples from two outcrops of metric-scale width lenses of fine-grained amphibolite (samples CSN-24 and CSN-24DC) associated with cordierite-sillimanite-biotite-rich mica schists, from an intensively deformed fault zone that extends along the MNSZ/EHMT limit, were collected at Casas Novas; (4) A fine-grained amphibolite (sample VAL-1) and a coarse-grained amphibolite (sample VAL-2) with a well-developed S-L fabric were collected from two outcrops located within a narrow band of basic rocks associated with mica schists, felsic gneisses and calc-silicate rocks along the Eastern limit of the EHMT, at Valverde; (5) Two outcrops of metric-scale lenses of amphibolites associated with garnet-rich mica schists and minor calc-silicate rocks where sampled at the Divor dam (samples BDV-1 and BDV-2) and another two samples from kilometric-scale occurrences of amphibolites with minor calc-silicate rocks and mica schists at Arraiolos (samples ARL-1 and ARL-2), all belonging to the Xistos de Moura Formation as described in the literature (e.g. Carvalhosa, 1999).

In general, the principal rock forming minerals of this metabasites are green hornblende and plagioclase whereas quartz can be a major or accessory constituent. Main accessory minerals are K-feldspar, pyroxene, biotite, sphene, opaques, epidote, and the secondary minerals are epidote chlorite, calcite and sericite.

Their microtexture is nematoblastic to granonematoblastic. Generally, hornblende crystals are mostly subhedral, prismatic and elongate parallel to their c-axes defining a well-developed mineral lineation, excepting when is preserved in poikiloblastic feldspar grains or in quartz-rich bands that suffered recrystallization. Planar fabrics are defined by observation of metamorphic segregation of mineral phases, compositional changes, granularity variations and textural rearrangements due to dynamic recrystallization.

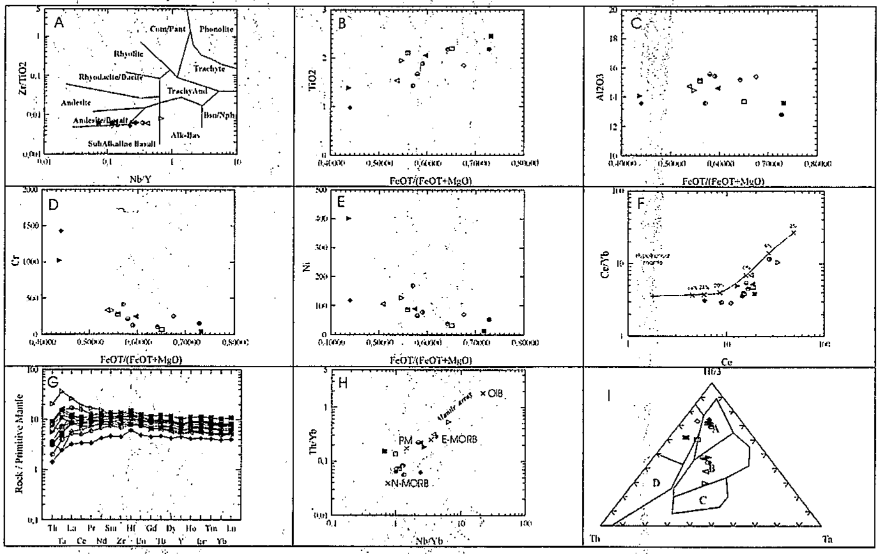

Fig. 2.- EM lower Paleozoic basic rocks geochemistry: (A) – Plot of the analysed samples in the Zr/TiO2 vs Nb/Y diagram, proposed by Winchester and Floyd (1977) and Floyd and Winchester (1978) for the classification of the protoliths of metamorphosed volcanic rocks. (B, C, D, E) – Variation diagrams for TiO_2, Al_2O_3, Cr and Ni using FeOᵗ / (FeOᵗ+MgO) as diferentiation index. (F) – Plot of the Ce/Yb ratios vs the Ce concentrations of the studied samples compared with a equilibrium melting (Shaw, 1970; Pearce and Norry, 1979; Hanson, 1989) curve. + Hypothetical mantle source, assumed to have Ce and Yb contents equivalent to primordial mantle composition (Sun and McDonough, 1989). × Different degrees of partial melting. In the calculations, it was assumed: a mineral composition of 0.55 Ol + 0.25 Opx + 0.15 Cpx + 0.05 Grt for the mantle source; a contribution of 0.10 Ol + 0.20 Opx + 0.40 Cpx + 0.30 Grt for the generated melt. Partition coefficients summarised by Hanson (1980) were used. (G) Primitive mantle (Sun and McDonough, 1989) normalised abundance patterns for immobile incompatible elements in the analysed samples. (H) Plot of Th/Yb vs Nb/Yb. + Compositions according to Sun and McDonough (1989). Mantle array according to Pouclet et al, (1995). (I) – Hf/3-Th-Ta discriminant diagram for basaltic rocks proposed by Wood (1980). A - N-Type MORB; B – E-Type MORB or tholeiitic WPB and differentiates; C – Alkaline WPB and WPB and differentiates; D – Destructive plate-margin basalts and differentiates.

Fig. 2.- Geoquímica de las rocas básicas del Paleozóico inferior del Macizo de Évora: (A) – Proyección de las rocas en diagramas Zr/TiO2 vs Nb/Y, propuestos por Winchester y Floyd (1977) y Floyd y Winchester (1978) para clasificación de protolitos de rocas volcánicas metamorfizadas. (B, C, D, E) – Diagramas de variación TiO_2, Al_2O_3, Cr y Ni con indexe de diferenciación FeOᵗ / (FeOᵗ+MgO). (F) – Diagrama Ce/Yb vs Ce comparadas con la curva de equilibrio de un fundido (Pearce y Norry, 1979; Hanson, 1989). + Fuente mantélicas hipotética, con valores de Ce y Yb equivalentes a la composición del manto primordial (Sun y McDonough, 1989). × Distintos grados de fusión parcial. En los cálculos fueron considerados: la composicion mineral 0.55 Ol + 0.25 Opx + 0.15 Cpx + 0.05 Grt para el Fuente mantélica; la contribucion de 0.10 Ol + 0.20 Opx + 0.40 Cpx + 0.30 Grt para el magma generado. Fueron utilizados los coeficientes de partición resumidos por Hanson (1980. (G) Espectros de REE y diagrama multielemental normalizados al manto primitivo (Sun y McDonough, 1989). (H) Proyección de Th/Yb vs Nb/Yb. + Composiciones de Sun y McDonough (1989). Composición del manto propuesto por Pouclet et al, (1995). (I) – Diagramas de discriminación Hf/3-Th-Ta para basaltos, de Wood (1980). A - N- MORB; B – E- MORB o toleitas intraplaca WPB y diferenciados; C – Basaltos alcalinos intraplaca WPB y diferenciados; D – Basaltos de márgenes destructivas y diferenciados.

Geochemistry of the EM Lower Paleozoic basic rocks: major, trace and REE elements

As described in the previous sections, the rocks studied in this work were mainly affected by regional metamorphism, in the amphibolite facies, which completely erased the original magmatic mineral assemblages and textures. Metamorphism processes were probably responsible by changes in the concentrations of the elements with low ionic potential (like the alkaline and the alkaline earth elements), but didn't affect the contents of elements that produce cations with high charge/radius ratios that may have remained essentially unchanged (Pearce and Cann, 1973; Winchester and Floyd, 1977; Humphris and Thompson, 1978; Mason and Moore, 1984; Whitford *et al.*, 1989; Rollinson, 1993). Therefore it is possible, by using the immobile elements, to characterize the geochemistry of the EM amphibolites protoliths and therefore, to constrain hypotheses for theirs igneous petrogenesis and related geotectonic setting.

The range in SiO_2 values (44,2 % to 51,8 %) and the low Zr/TiO_2 ratios (from 0.005 to 0.008) are consistent with a derivation from basic igneous protoliths (basalts and gabbros). Nb/Y ratios are usually low (< 0.41 in all but one sample) denoting the subalkaline nature of the magmas (**Fig. 2A**); The exception is one sample from the Divor dam (BDV-2) with Nb/Y = 0.68, just above the limit proposed by Winchester and Floyd (1977) and Floyd and Winchester (1978) for the separation between alkaline and subalkaline basalts.

By plotting the geochemical data into variation diagrams with FeOᵗ/(FeOᵗ+MgO) as differentiation index (**Fig. 2B, 2C, 2D and 2E**), it results that several elements define correlations that could be explained by fractionation processes from a primitive magma composition. Decrease of MgO with the differentiation index is an expected effect of fractionation of ferromagnesian silicates (olivine, pyroxenes). The plots of Ni and Cr (**Fig. 2D, 2E**)- which have high partition coefficients (Gast, 1968; Rollinson, 1993; Green, 1994) to olivine and clinopyroxene, respectively – also agree with the presence of a significant proportion of those minerals in the fractionating assemblages. High values of Cr and Ni may result from some sort of accumulation (phenocryst concentrations in lavas or cumulus crystals in plutonic rocks) of olivine and clinopyroxene. That could be the case for sample BDV-1 (Ni = 420 ppm; Cr = 1020 ppm). Sample VAL-1 has a high Cr content (1430 ppm) but a comparatively low Ni concentration (118 ppm); Considering both the coarse-grained texture of this amphibolite and its geochemical composition, it is likely that it derives from a gabbroic rock in which the most important cumulus phase was clinopyroxene.

In the differentiation of basic magmas, the variation of aluminium is particularly sensitive to the crystallization of plagioclase. The diagram Al_2O_3 *vs.* FeOᵗ/(FeOᵗ+MgO) (**Fig. 2C**) shows some spreading, but it can also be seen a slightly positive correlation for samples with FeOᵗ/(FeOᵗ+MgO) < 0.7, followed by decrease in Al_2O_3 in the samples with higher values for the differentiation index. This can be interpreted as result of the presence of in the fractionating assemblages (which explains the absence of a clear positive correlation), but in a proportion not enough, in the first stages of differentiation, to counterbalance the crystallization of the Al-poor ferromagnesian silicates; Only in the most evolved melts the importance of plagioclase would have surpassed that of mafic minerals.

Positive correlations of FeOᵗ and TiO_2 with FeOᵗ/(FeOᵗ+MgO) (**Fig. 2B**) reveal that iron and titanium oxides did not play a major role in the magma differentiation, probably as a result of low oxygen fugacity. This type of behaviour of iron and titanium in subalkaline magmas is typical of the tholeiitic series (Miyashiro, 1974; Miyashiro and Shido, 1975).

Therefore, major element geochemistry together with data on strongly compatible trace elements would support the conclusion that the studied rocks define a tholeiitic suite in which magma evolution occurred *via* fractional crystallization of olivine, clinopyroxene and plagioclase, with increasing role of the Ca-Na-feldspar towards the most differentiated terms.

However, when incompatible trace element data are taken into account it becomes apparent that low-P crystal fractionation cannot explain all the compositional diversity of the protoliths of the studied rocks. In fact, the range of values of the ratios between different incompatible elements is large. For instance, Ce/Yb varies from 2.86 (in sample VAL-2) to 11.5 (in SCD), corresponding to Ce_N/Yb_N values of 0.795 and 3.21, respectively. This variation requires the intervention of, at least, one other process besides crystal fractionation. The most likely hypotheses involve the generation of several primitive magmas, with contrasting Ce/Yb ratios, as a consequence of mantle source heterogeneities or by different degrees of partial melting of a garnet lherzolite mantle source **(Fig. 2F)**.

Besides the variable LREE/HREE ratios – from slightly depleted to slightly enriched – other significant features concerning the incompatible trace element composition must also be pointed **(Fig. 2G)**: values of Th_N/Ta_N are usually (with two exceptions, CSN-24 and VAL-2) below 1.0 what indicates mantle sources typical of anorogenic settings; Ta_N/La_N varies between 0.393 (CSN-24) and 1.39 (BDV-2); Negative Ta anomalies are only present in two samples (CSN-24 and VAL-2); There is a general positive correlation between Nb/Yb and Th/Yb, and all the samples plot within, or very close to, the mantle array in the diagram **(Fig. 2H)** proposed by Pouclet *et al.* (1995). This diagram also shows that incompatible trace element ratios lie mainly between the typical compositions of N-MORB and E-MORB; Only BDV-2 reveals an affinity towards an OIB-like composition. The use of the tectonic setting discrimination diagram of Wood (1980) **(Fig. 2I)** corroborates these conclusions: the majority of the samples plot in the N-MORB and P-MORB fields, with BDV-2 displaying the composition closest to the WPB. Only the samples CSN-24 and VAL-2 plot into the field of destructive plate margin basalts.

Concluding remarks

From the described geochemical features of lower Paleozoic metabasites sampled on distinct key-areas of the EM through different stratigraphic and structural levels (Valverde, Arraiolos, Barragem do Divor, Silveiras, Relvas, Serra do Conde, Corta Braços, Monfurado e Casas Novas) it is possible to get the following conclusions: (1) The studied metamorphic rocks derive from protoliths with tholeiite basalt compositions; (2) Fractional crystallization of olivine, clinopyroxene and plagioclase may have played an important role in the generation of different melt compositions, as revealed by variation diagrams; (3) However it is also necessary to invoke source heterogeneity and/or different degrees of partial melting of a mantle source with garnet lherzolite composition to explain the observed range of incompatible trace element ratios; (4) The most likely sources of the basaltic melts may have varied from depleted mantle (similar to N-MORB sources) to mantle rocks affected by within-plate enrichment.

The magmatic events that originated the protoliths of the studied rocks were probably related to a geotectonic scenario controlled by transtension and the development of clastic and carbonate basin sedimentary sequences. Similar geochemical signatures have been already reported at other areas of the OMZ (e.g. Sánchez-Garcia *et al.*, 2003; Goméz-Pugnaire *et al.*, 2003; Pedro *et al.*, 2003), what reinforces the importance of such anorogenic magmatism in the geodynamic evolution of the Iberian Massif during lower Paleozoic times.

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