

Ore-forming systems in the Layered Gabbroic Sequence of the Beja Igneous Complex (Ossa-Morena Zone, Portugal); state of the art and future perspectives

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ABSTRACT: The geological characteristics of the Layered Gabbroic Sequence (LGS) belonging to the Beja Igneous Complex are briefly reported, as well as the available data from geophysical, soil and stream sediment surveys. These are complemented with results obtained via geological, whole-rock geochemistry and mineral chemistry analysis concerning two distinct ore types and respective host rocks identified in the LGS NW sector: 1) massive accumulations of Ti-V rich spinels \pm ilmenite enclosed in the basal group of the lower gabbroic series; and 2) massive $po + cpy + py \pm pn$ aggregates that fill up anastomosed vein arrays within a strong metasomatic halo developed in the upper gabbroic series. The development of these ore-forming systems is intimately related to the LGS evolution. Exploration works in progress strongly suggest that other places of LGS should host similar ore showings, thus expand its metallogenic (and economic) potential.

1 INTRODUCTION

The Beja Igneous Complex (BIC) is a wide curved intrusive belt of approximately 100 Km long bordering the SW domain of the Ossa-Morena Zone in Portugal (fig.1). It records an important syn-orogenic, Variscan magmatic activity from Frasnian-Famennian to Late Visean times (*e.g.* Dallmeyer *et al.* 1993) and can be divided in three major units: 1) the Beja Gabbroic Complex, a layered suite mainly composed of olivine-bearing gabbroic rocks, bordered by heterogeneous diorites resulting of variable extents of magma mixing or crustal assimilation at the margin of the intrusion; 2) The Cuba-Alvito Complex, a more evolved, non-layered, gabbroic to (quartz-)dioritic unit; and 3) The Baleizão Porphyry Complex, younger in age, comprising several types of porphyry rocks emplaced at very shallow crustal levels (Silva *et al.* 1970, Andrade 1983, Santos *et al.* 1990, Jesus 2002). In this work, the Beja Gabbroic Complex will be labeled as LGS.

The metallogenic (and economic) potential of LGS is large, as suggested by the re-evaluation of the available geophysical and geochemical data ob-

tained by the Portuguese Geological Survey (IGM) following criteria resulting from studies recently developed in the NW sector of LGS, between Odivelas and Ferreira do Alentejo. Indeed, there are now several evidences documenting the occurrence of two main ore types within LGS: massive Fe-Ti-V oxide accumulations and anastomosed, Cu(-Ni) sulphide vein arrays. They were originated under distinct physical-chemical conditions achieved in different stages of LGS evolution, being synchronous of the early stages of magmatic differentiation and of late to post-magmatic processes, respectively.

2 GEOLOGICAL CHARACTERISTICS OF LGS

The area located between Ferreira do Alentejo and Odivelas is currently the best-characterized sector of LGS. Here, three main magmatic Series were defined, showing a modal and cryptic layering pattern that is believed to be a result of successive replenishments of the magma chamber (Jesus 2002). In these Series the magmatic layering strikes from NW-SE to WNW-ESE and dips less than 30° to SW

or SSW. The magmatic foliation is sub-parallel to the layering.

The two major Series (I and II) show normal polarity and contact gradually with each other. The lower Series (I) includes three main groups of layers: the lowermost group is essentially composed of olivine leucogabbros but also contains layers and lenses (and/or blocks?) of troctolites, oxide-rich cumulates, and irregular bodies of massive and coarse-grained Fe-Ti-V oxide accumulations; the intermediate group includes leucogabbros and anorthosites; and the uppermost group consists of a relatively monotonous sequence of olivine leucogabbros that encloses discontinuous anorthositic lenses. Series II display a rather massive character and do not show significant oxide enrichment. Its basal portion is mostly composed of olivine gabbros that only occasionally have interstitial oxides; the overlying thick sequence of olivine leucogabbros includes layers of distinct compositional nature that are observed to repeat rhythmically.

The contact between Series II and III cannot be directly assessed because of the Cainozoic sedimentary cover. The outcropping portion of the latter Series displays a well-defined layering and is chiefly composed of olivine-pyroxene leucogabbros, olivine leucogabbros and gabbros that are strongly metasomatized in places where late pegmatoid dykes occur and sulphide veins are abundant.

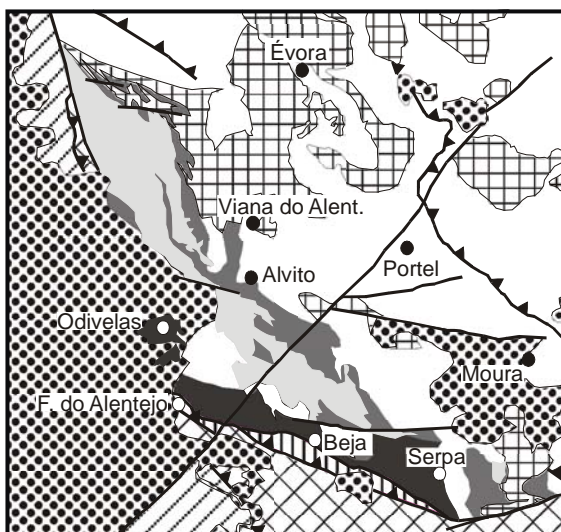
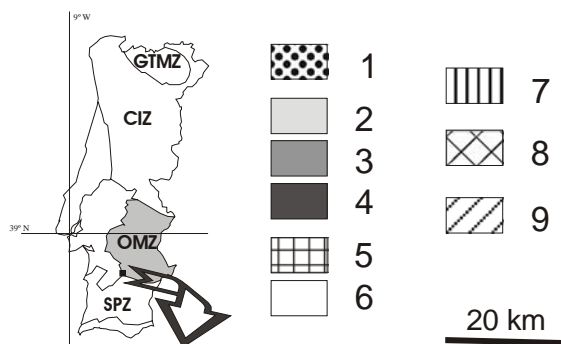


Fig. 1 – Location of BIC with indication of the major geotectonic units of SW Iberia: **CIZ**, Central-Iberian Zone; **GTMZ**, Galicia – Trás-os-Montes Zone; **OMZ**, Ossa-Morena Zone; **SPZ**, South Portuguese Zone. Schematic geological map: 1)

Cainozoic sedimentary cover; 2) Baleizão Porphyry Complex (BIC); 3) Cuba-Alvito Complex (BIC); 4) Beja Gabbroic Complex (BIC). 5) Undifferentiated Variscan Granitoids. 6) Undifferentiated metasedimentary and metavolcanic sequences and ultramafic rocks. 7) Beja-Acebuches Ophiolite Complex; 8) Metasediments and metavolcanics of Pulo do Lobo Group. 9) Metasedimentary and metavolcanic sequences of **SPZ**.

Table 1 summarizes the most relevant data concerning the chemical variation displayed by plagioclase, pyroxene and olivine in all Series, as well as the whole-rock contents of some trace elements in non-metasomatized and non-mineralized samples. Primary orthopyroxene is rare in all the studied gabbroic rocks; usually, this mineral forms coronas around olivine due to late magmatic re-equilibrium processes. The average An, En and Fo contents of plagioclase, pyroxene and olivine, respectively, included in rocks of Series II and III are higher than those displayed by the same minerals in similar rocks of Series I. The Cr and Ni values showed by pyroxene and olivine, respectively, in rocks of Series II and III are also very different of those recorded for rocks of Series I, suggesting that the former two magmatic sequences were fractionated from a melt distinct of that involved in Series I development. The average whole-rock Cr, Ni and Co contents define a similar trend in Series I, II and III and are fairly low (like those of HFSE), as it is typical of magmas generated in subduction environments. The average whole-rock V contents reflect quite well the amounts of interstitial oxides present in each sample and, with the exception of rocks sampled in the lowermost layers of Series II (with maximum V contents of 1120 ppm), they confirm the general oxide-rich nature of rocks belonging to Series I.

Table 1. Summary of the most important EPMA and W-R data for the three LGS Series in Odivelas-Ferreira do Alentejo area.

		Series I	Series II	Series III	
EPMA	Pg	An	50 n=78	62 n=32	60 n=32
		(%)	(45-61)	(58-78)	(59-66)
	Px	En	39 n=87	46 n=25	41 n=21
		(%)	(39-72)	(41-76)	(41-76)
	Ol	Cr	118 n=87	767 n=25	1038 n=21
		(ppm)	(0-688)	(0-2937)	(228-1939)
	Fo	48 n=35	59 n=31	60 n=4	
	(%)	(42-59)	(57-59)	(58-60)	
W-R (ppm)	Ni	76 n=35	490 n=31	270 n=4	
	(ppm)	(0-530)	(15-1000)	(14-700)	
	Cr	83 n=23	165 n=7	511 n=1	
		(32-237)	(22-323)		
	Ni	37 n=23	87 n=7	22 n=1	
	(23-58)	(33-163)			
	Co	39 n=23	38 n=7	32 n=1	
		(10-110)	(11-73)		
	V	313 n=23	224 n=7	166 n=1	
		(9-671)	(13-1120)		

EPMA – electron probe micro-analysis. W-R – whole rock analysis. Average values of the range in brackets; n = number of samples

These magmatic Series display transitional affinities between tholeiitic and calc-alkaline suites (Jesus, 2002). The origin of the melt related to Series II and III development is envisaged as a result of greater depths of magma extraction and/or larger degrees of partial melting. Excluding rocks that are believed to have re-equilibrated in presence of residual magmatic melts or have experienced late metasomatism, there is no evidence of significant enrichment in hydromagmatophile elements for any Series.

3 GEOPHYSICAL, SOIL AND STREAM SEDIMENT SURVEYS

Due to the vast extension of LGS and its ill-known detailed internal configuration, an adequate method for the selection of key-sectors to be further comprehensively investigated was needed. This was carried out successfully through the systematic re-evaluation of the results obtained in old geophysical and soil geochemistry regional surveys on the basis of criteria derived from the studies previously developed in the Ferreira do Alentejo-Odivelas area.

3.1 Vertical field magnetic anomalies

There is a very good agreement between the spatial arrangements of the vertical field magnetic anomalies and the most important geological features mapped at Odivelas (Mateus *et al.*, 2001; Jesus, 2002). In fact, these spatial arrangements discriminate quite well the oxide-rich gabbroic layers and, within them, the location of the massive oxide accumulations surveyed in 1944 (Silva, 1945). In this sector, it can be shown that the most important magnetic anomalies are not limited to the area previously examined in the forties, thus justifying a drilling campaign already designed for a near future.

All along the LGS, a significant number of strong vertical field magnetic anomalies still await for a proper evaluation. A detailed geological mapping and characterization of the gabbroic sequences outcropping in places where the most promising magnetic anomalies are located is currently being performed in order to confirm other exploration guides firstly tested at Odivelas.

3.2 Soil geochemistry data

At Odivelas, seventy-two soil samples were collected along five N-S profiles that went across the old exploration prospects. The data obtained, reported and discussed in detail by Gonçalves *et al.* (2001), show that the anomalous Ti and V thresholds are generally greater than 1.5-2% and 400 ppm, respectively. Following a similar approach, an accurate separation of Ti and V geochemical anomalies would be possible in other LGS sectors carrying oxide mineralizations.

Soil geochemistry Cu data sets available for a large area of LGS (570 km²) are being examined in order to separate the most significant anomalies through multifractal modeling. According to the characteristics displayed by the sulphide mineralizations recognized at Castelo Ventoso (nearby Ferreira do Alentejo), this will enable the separation of the most significant sulphide-rich halos within the gabbroic rocks, regardless of their origin.

3.3 Stream sediment analysis by means of XRD

Sediments of tributary streams on both margins of the Odivelas river and in the northern border of the central sector of the LGS (NE of Beja) were recently collected and examined in detail. The results obtained show that this procedure can be very useful in discriminating different sectors of LGS, enabling also to distinguish the heavy-mineral assemblages intimately related to specific mineralizations (Mateus *et al.*, 2001; Jesus *et al.*, in prep.).

4 MAJOR ORE-FORMING SYSTEMS IN LGS

Although preliminary results from work in progress look very promising, the most important examples of the major ore-forming systems in LGS are located in the Ferreira do Alentejo-Odivelas area.

4.1 Fe-Ti-V oxide ores

At Odivelas, the oxide ores are hosted in olivine leucogabbros of the lower group of Series I (Jesus 2002). The ores do not outcrop but, according to Silva (1945), they form irregular bodies of considerable size (< 50 ton each) that are close to the topographic surface and lie at approximately right angles to the regional layering. These oxide accumulations comprise a coarse matrix of V-bearing titanomaghemite, as equant and quasi-polygonal grains, and of poikilitic V-rich ilmenite, having also accessory amounts of pure maghemite; strongly weathered samples show mineral-textural transformations resulting from fine hematite replacements along fractures of pre-existing spinels, besides late goethite-hematite fracture infillings. None of the spinels in these accumulations display the oxy-exsolution features typically recorded by Ti-spinels included in the surrounding gabbros; hematite exsolutions in the V-rich ilmenite are also very rare. Data concerning the characterization of this mineral assemblage by means of XR diffractometry, Mössbauer spectroscopy, micro-PIXE and EPMA analysis is given in Jesus *et al.* (submitted).

Whole-rock analysis of these ores reveals that about 80% of their mass corresponds to Fe₂O₃ (53.53-68.46 wt%), TiO₂ (6.4-10.05 wt%) and FeO (1.44-7.03 wt%), which is strongly consistent with the mineralogical nature above referred to. The same happens with the high V contents (3514-5520 ppm),

as confirmed by data resulting from micro-PIXE and EPMA analysis (Jesus *et al*, submitted). The Mn (651-3912 ppm), Cr (63-318 ppm) and Co (29-141 ppm) contents suggest also that the ore-forming spinels contain trace amounts of these metals; the presence of Cr and Ni was indeed confirmed by micro-PIXE analysis.

According to Jesus *et al* (submitted), the irregular and discordant shape of the Odivelas oxide bodies must have resulted from localized settling of primary oxide grains (as consequence of magma injection in a chamber where spinel crystallization is already taking place) and/or from gravitic instability of previously formed oxide layers; examples of these kinds of layers were recently discovered in LGS, between Ferreira do Alentejo and Beja. The recorded maghemitization is thus envisaged as a very late but endogenous process, resulting from local and severe oxidation of pre-existent titanomagnetite accumulations under non-equilibrium conditions at $T \leq 650^\circ\text{C}$.

4.2 *Cu(-Ni) sulphide ores*

At Castelo Ventoso (nearby Ferreira do Alentejo), Cu(-Ni) sulphide ores occur within an important metasomatic halo developed in gabbroic rocks of Series III (Jesus, 2002). The ores are mostly composed of massive *po* + *cpy* + *py* ± *pn* aggregates that fill up anastomosed vein arrays of centimetric thickness. The available analytical chemical data, although limited to a very reduced number of samples, reveal the expected whole-rock metal contents in face of the observed mineralogy (Cu = 1774-14060 ppm; Ni = 1420-1526 ppm; Co = 1220-2130 ppm).

The metasomatic halo is chiefly the result of different textural-mineralogical transformations experienced by gabbroic rocks, involving heterogeneous hydration of primary olivines and pyroxenes and plagioclase hydrolysis that are, at least partly, correlative of sulphide deposition. These chemical processes took place under a decreasing path of temperature conditions, initially positioned below 600°C (Jesus, 2002). During this evolution, the early, coarse-grained *po* aggregates exsolved small amounts of *pn*, *py* and *cpy*. This is complemented by the late deposition of *py* and *cpy* along inter- and trans-granular micro-fractures. Trace amounts of mackinawite were also identified as reticular aggregates resulting from exsolution processes lately experienced by *cpy* and *po* at $T \leq 250^\circ\text{C}$.

Metasomatic processes and sulphide deposition are envisaged as a result of late fluid circulation within fractured gabbroic sequences, probably during the late stages of their cooling, taking up fluids evolved from mixtures of residual magmatic 'waters' with crustal, sulphur-rich hydrothermal solutions. This explains also the whole-rock increase in LILE contents (Rb, Th, U and LREE) revealed by the metasomatized gabbroic rocks. Similar occur-

rences in other sectors of the LGS were already recognized and are currently under investigation.

5 FUTURE PERSPECTIVES

According to the present-day knowledge, the metallogenic (and economic) potential of LGS is large but the detailed characterization of the most promising targets, as revealed by the geophysical and soil geochemistry data, is needed to fully evaluate their real importance. This is valid both for Fe-Ti-V oxide and Cu(-Ni) sulphide ore-forming systems, which are believed to developed during the early stages of magmatic differentiation and of late to post-magmatic processes, respectively. However, essential issues concerning the lifetime, cooling history, extent of crustal contamination during ore genesis, and the nature of the main causal relationships involved in ore deposition still await adequate solution. In order to bring some light to these issues, mineral and whole-rock isotopic signatures using relevant radiogenic isotope systems will be determined soon in representative samples of each target. For the sulphide ore-forming systems in particular, this approach will help additionally to unravel the main metal sources, providing also critical constraints on the major fluid pathways as recorded by the effects of the strong interaction between the circulating mineralising fluids and the gabbroic rocks.

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REFERENCES

- Andrade, A.S. 1983. *Contribution à l'analyse de la suture Hercynienne de Beja (Portugal), perspectives metallogéniques*. Ph.D. thesis, INLP, Univ. Nancy, France.
- Dallmeyer, R.D., Fonseca, P.E., Quesada, C. & Ribeiro, A. 1993. $^{40}\text{Ar}/^{39}\text{Ar}$ mineral age constraints to the tectonothermal evolution of the Variscan Suture in SW Iberian. *Tectonophysics* Vol. 222: 177-194.
- Gonçalves, M.A., Mateus, A. & Oliveira, V. 2001. Geochemical anomaly separation by multifractal modelling. *Journal of Geochemical Exploration* Vol. 72: 91-114.
- Jesus, A.P. 2002. *Fe-Ti-V mineralizations and sulphide occurrences in gabbroic rocks of the Beja Igneous Complex (Odivelas - Ferreira do Alentejo)*. M.Sc. thesis, Univ. Lisbon.
- Jesus, A.P., Mateus, A., Waerenborgh, J.C., Figueiras, J., Cerqueira, L. & Oliveira, V. submitted. Hypogene Ti-V maghemitic accumulations in a layered gabbroic complex (Odivelas, Beja, SE Portugal). *Canadian Mineralogist*.

- Mateus, A., Jesus, A.P., Oliveira, V., Gonçalves, M.A. & Rosa, C. 2001. Vanadiferous iron-titanium ores in gabbroic series of the Beja Igneous Complex (Odivelas, Portugal); remarks on their possible economic interest. *Est. Notas e Trab. Inst. Geol. e Mineiro* Vol 43: 3-16.
- Santos, J.F., Andrade, S.A. & Munhá, J. 1990. Orogenic magmatism in the meridional border of the Ossa Morena Zone. *Comun. Serv. Geol. Portugal* Vol. 76: 91-124.
- Silva, J.M. 1945. Notas acerca do depósito de ferro de Odivelas. *Est. Notas e Trab. Serv. Fom. Min.* Vol. 1: 286-292
- Silva, L.C., Quadrado, R. & Ribeiro, L. 1970. Previous notes about the existence of a zoned structure and of anorthosites in the gabbro-dioritic massif of Beja. *Bol. Mus. Lab. Min. Geol. Univ. Lisboa* Vol. 11: 223-232.