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Vanadiferous iron-titanium ores in Gabbroic Series of the Beja Igneous Complex (Odivelas, Portugal); remarks on their possible economic interest

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Palavras-chave: Minérios de ferro titano-vanadíferos, Séries Gabróicas do Complexo Ígneo de Beja; potencial económico

Key-words: *Vanadiferous iron-titanium ores, Gabbroic Series of the Beja Igneous Complex, Economic potential*

Resumo

Na área de Odivelas (Ferreira do Alentejo), as rochas gabróicas bandadas pertencentes ao Complexo Ígneo de Beja integram duas Séries distintas com polaridade normal. O desenvolvimento do bandado não se processa uniformemente e a sua direcção varia usualmente entre NW-SE e WNW-ESE na Série I e entre WNW-ESE e E-W na Série II, apresentando um pendor relativamente constante (< 30°) no sentido SW ou S. A Série I compreende três grandes grupos litológicos: 1) o grupo inferior é predominantemente constituído por leucogabros olivínicos,

Abstract:

In the Odivelas area (Ferreira do Alentejo), the outcropping layered gabbroic rocks of the Beja Igneous Complex form two different Series with normal polarity. The layering is not uniformly developed; it ranges usually from NW-SE to WNW-ESE in Series I and from WNW-ESE to E-W in Series II, displaying a relatively constant dip (< 30°) towards SW or S. The Series I comprises three main groups of layers: 1) the lower group is mainly composed of olivine leucogabbros, troctolites and discontinuous lenses (and/or blocks?) of oxide-rich mafic cumulates; 2) the

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troctolitos e lentículas descontínuas (e/ou blocos?) de cumulados máficos variavelmente enriquecidos em óxidos; 2) o grupo intermédio inclui essencialmente leucogabros e anortositos; 3) o terceiro grupo integra uma sequência relativamente monótona de leucogabros onde ocorrem níveis descontínuos de natureza anortosítica. Na Série II predominam largamente os gabros olivínicos e leucogabros olívinos com bandado incipentemente desenvolvido.

Os minérios titano-vanadíferos de Odivelas ocorrem no grupo inferior da Série I formando massas irregulares de dimensão variável. Estes comportam essencialmente espinelas de ferro magnéticas (que, do ponto de vista químico, correspondem a soluções sólidas entre a magnetite e a maghemite com total catiónico deficiente e enriquecimento em Ti e V), ilmenite e hematite. Nestes minérios, as concentrações em Fe_2O_3 e em FeO variam entre 53,53 e 68,46 wt% e entre 1,44 e 7,03 wt%, respectivamente; os conteúdos em TiO_2 (6,4 a 10,05 wt%) e em V (3514 a 5520 ppm) são claramente anómalos, sublinhando de forma inequívoca o potencial económico dos minérios caso a presença de tonelagens significativas venha a ser confirmada. A necessidade em investigar adicionalmente a região localizada a S-SE dos antigos trabalhos de prospecção mineira via estudos magnéticos e gravimétricos detalhados é colocada em evidência através da distribuição cartográfica dos domínios gabróicos enriquecidos em óxidos e dos resultados de geoquímica de solos. Os indicadores económicos actualmente disponíveis para o vanádio justificam plenamente os investimentos decorrentes da implementação das actividades de prospecção e de pesquisa científica planificadas para a área de Odivelas.

intermediate group includes essentially leucogabbros and anorthosites; 3) the upper group consists of a relatively monotonous sequence of olivine leucogabbros that contains discontinuous anorthositic layers. Poorly layered olivine gabbros and olivine leucogabbros predominate in Series II.

The V-Ti rich ores of Odivelas occur within the lower group of Series I, forming irregular masses of variable size. They chiefly comprise magnetic iron spinels (that chemically are cation-deficient magnetite-maghemite solid solutions Ti-V enriched), ilmenite and hematite. In these ores, the Fe_2O_3 and FeO concentrations range from 53,53 to 68,46 wt% and from 1,44 to 7,03 wt%, respectively; contents in TiO_2 (6,4 to 10,05 wt%) and V (3514 to 5520 ppm) are clearly anomalous, strongly supporting the economic potential of these ores if the presence of significant tonnage is further confirmed. The need to investigate also the region located to the S-SE of the old exploration works by means of detailed magnetic and gravimetric surveys is supported either by the cartographic distribution of the oxide-rich domains of the gabbros or by the available soil geochemistry data. The economic indicators for vanadium justify entirely the investments implicated by the exploration and research activities planned for the Odivelas area.

1. INTRODUCTION

In a recent assessment of the metallogenetic potential of the Iberian Terrane southern border (MATEUS *et al.*, 1998), Ti-V anomalies of potential economic interest in close association with gabbroic rocks belonging to the Beja Igneous Complex (BIC) were predicted. Work since carried out in an area near Odivelas village (Ferreira do Alentejo) corroborate such reasoning. The main objective of the present paper is to characterise the vanadiferous iron-titanium ores identified in the Odivelas area and to discuss the performance of future exploration activities in order to assess their real economic significance. The most relevant data recently obtained in terms of mineral exploration is used to support the advantages to design additional geochemical and geophysical surveys to look for particular domains of the lower gabbroic sequence of BIC. Comprehensive data concerning the Odivelas ore mineralogy, the petrography, geochemical and structural characteristics displayed by the host gabbros, and problems related to the ore genesis, will be the subject of other papers.

2. THE ODIVELAS AREA

2.1. Geological setting

The studied area lies entirely within a gabbroic sequence that belongs to the so called Odivelas Unit of BIC characterised by a remarkable diversity of igneous facies (ANDRADE, 1983, 1984) and is partially covered by

Cainozoic detrital sediments. The geological mapping performed at a 1:15000 scale (figure 1) reveals that the outcropping rocks are often layered and can be grouped in two different Series, and that the anomalous abundance of Fe-Ti-V oxides are limited to the olivine leucogabbros and to the leucograbbros included in the lower one; past mining exploration works for iron can indeed be found in some places.

Series I and II occupy most of the mapped area and their contact is usually gradual. Layering orientation and other structural features allow the determination of the polarity of the magmatic sequence comprising Series I and II, the former corresponding to a lower domain. This reconstructed "stratigraphy" is in contradiction to the one suggested by SANTOS *et al.* (1990), implying that the most recent igneous plutonic members are at SW and not at NE (in the direction of the contact with the late, hipabissal--volcanic rock suites of BIC). However, a simple inspection of the available geological and geophysical maps reveals that shear zones and strike-slip fault zones frequently bring to contact distinct igneous sequences, thus making it extremely risky to connect and to extrapolate data between adjoining compartments of the intrusive complex. Besides, it has also been argued in the literature that the SW reverse polarity in the gabbroic rocks can be inferred from the Fe/Mg ratio displayed by olivine, clinopyroxene and orthopyroxene. Nevertheless, detailed mapping of the Odivelas area show megacyclicity within the gabbros sequence, thus preventing the use of those ratios when very detailed sampling is not available. Finally, it should be noted that granulometric criteria found in some layers of the gabbroic sequence outcropping in the Castelo Ventoso quarry (about 5 km SSE of Odivelas), support the polarity deduced for the Odivelas area. The gabbroic series of Castelo Ventoso corresponds therefore to the uppermost igneous succession that outcrops in the Odivelas - Ferreira do Alentejo area, overlying Series II.

Anorthosite, leucogabbro and olivine leucogabbro are the main rock types found in Series I, making up three main groups of layers that resemble megacyclic units developed during the fractional crystallisation path (see, *e.g.*, IRVINE, 1987, for an exact meaning of the term used), although the possibility that some anorthosite layers are discontinuous subsists. The lower group is mostly composed of olivine leucogabbros, whereas anorthosites and leucogabbros predominate in the intermediate group. The upper group consists of a relatively monotonous sequence of olivine leucogabbros that contains discontinuous anorthositic lenses. Layers of troctolitic nature can be recognised within the olivine leucogabbro package of the lower group that also contains discontinuous lenses (and/or blocks?) of oxide-rich mafic cumulates (olivine melagabbros, wehrlites and websterites). The oxide ores occur chiefly associated with these domains of the olivine leucogabbro package, forming irregular masses of variable size.

In Series I the layering does not develop uniformly, being sometimes very difficult to discern, especially within some rock domains of the lower group. Nevertheless, it can be shown that the layer dip is relatively constant regardless of the rock type (< 30° towards SSW or SW), ranging in direction from NW-SE to WNW-ESE; near major fault zones anomalous layer orientations may occur.

The basal portion of Series II comprises mostly poorly developed layers of olivine gabbros and olivine leucogabbros. The overlying olivine leucogabbros form a relatively thick package where successions of distinctive compositional layers are observed to repeat rhythmically; rare anorthositic layers may also be identified. In this Series the layer strike ranges between WNW-ESE and E-W and its dip is less than 30° towards SSW or S.

All the above mentioned rock types are variably affected by late metasomatism near important fault zones, leading to the development of mineral assemblages that mostly comprise green amphibole, albite and chlorite; serpentine and talc may be important when the primary mineralogy favours the development of these late metasomatic minerals.

2.2. The oxide enriched gabbroic rocks

According to the available data, the oxide ores are hosted by olivine leucogabbros that belong to the lower group of Series I and occur close to oxide enriched mafic cumulates. A comprehensive characterisation of all these rock types was attempted by collecting 23 samples subsequently examined on the optical microscope. It should be noted that the sampling program was severely constrained by the very low outcrop density of the area, thus leading to a

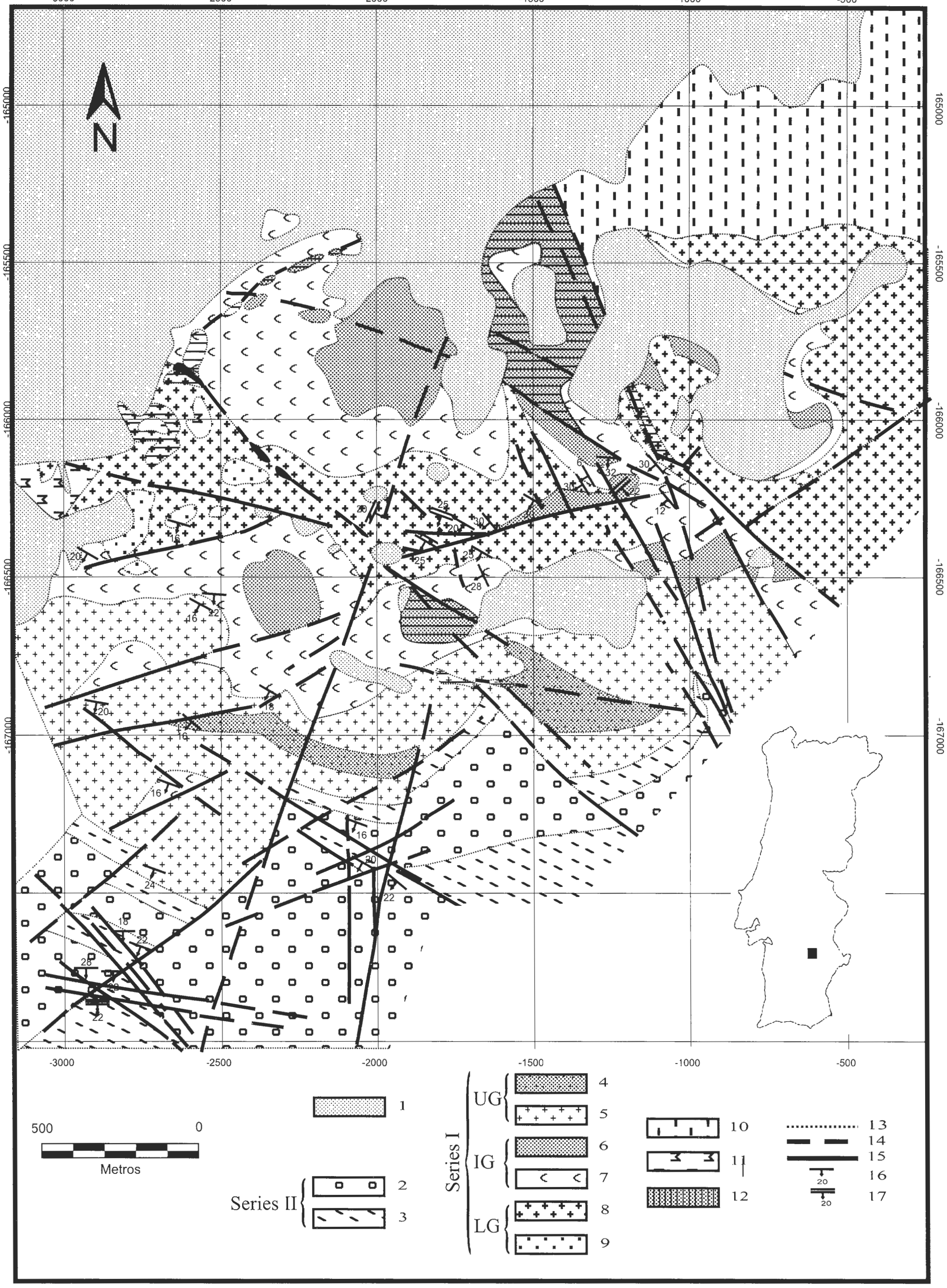

Figure 1 - Geological map of the Odivelas area. 1: *Cainozoic detrital sediments. Series II* - 2: olivine leucogabbros; 3: olivine gabbros. *Upper Group of Series I* - 4: anorthosites; 5: olivine leucogabbros. *Intermediate Group of Series I* - 6: anorthosites; 7 leucogabbros:. *Lower Group of Series I* - 8: olivine leucogabbros; 9: oxide-rich mafic cumulates. 10: Late intrusives; 11: Fe-Ti-V ores; 12: metasomatised rock domains; 13: geological contacts; 14: inferred fault zone; 15: fault zone; 16: magmatic layering; 17: foliation.

strongly heterogeneous spatial distribution of the studied specimens.

The olivine leucogabbros, mainly composed of An_{47-61} plagioclase (63 to 78 modal %), clinopyroxene (8 to 26 modal %), Fo_{52-60} olivine (5 to 16 modal %) and orthopyroxene (< 4 modal %), comprise always accessory amounts of magnetic iron spinels (< 5 modal %) and ilmenite (< 3 modal %). The olivine melagabbro, apparently the most common mafic cumulate, comprises An_{44-50} plagioclase (25 to 52 modal %), clinopyroxene (20 to 37 modal %), Fo_{42-48} olivine (6 to 14 modal %) and orthopyroxene (< 9 modal %), besides magnetic iron spinels (< 15 modal %) and ilmenite (< 10 modal %). In the examined websterites (≈ 69 % of clinopyroxene, ≈ 10 % of Fo_{43-45} olivine and ≈ 11% of orthopyroxene), the content of magnetic iron spinels and ilmenite did not exceed 6 and 4 modal %, respectively. In wehrlites (≈ 36 % of clinopyroxene, ≈ 27 % of Fo_{47-61} olivine), on the contrary, the amount of magnetic iron spinels and ilmenite increases to around 27 and 11 modal %, respectively. Rare and disseminated sulphide microgloblules mainly composed of pyrrhotite + pyrite + chalcopyrite ± pentlandite can also be recognised in many of the studied samples. Leucogabbros of the intermediate group may also contain significant amounts of ilmenite (2 to 3 modal %) and magnetic iron spinels (3 to 7 modal %); these rocks include mostly An_{47-57} plagioclase (61 to 64 modal%), clinopyroxene (21 to 18 modal %), orthopyroxene (3 to 6 modal %), and badly preserved olivine (< 2 modal %).

In gabbroic rocks of Series I, the modal % of oxide minerals is very variable. These minerals occur interstitially as individual grains or aggregates forming discontinuous clusters or patches, no matter how abundant they may be. The core of oxide aggregates is usually occupied by irregular grains of magnetic iron spinels whose composition correspond to cation-deficient magnetite-maghemite solid solutions displaying significant amounts of titanium and vanadium; very thin discontinuous ilmenite lamellae in the Ti-V bearing iron-spinels can be observed in many oxide patches of the olivine leucogabbros. The iron-spinel grains are often corroded and/or enclosed by large and anhedral ilmenite grains that show tiny hematite lamellae and, sometimes, contain silicate inclusions. It should be noted that the hematite lamellae in ilmenite are relatively well developed in mafic cumulates.

Multi-element chemical composition of 15 representative samples of gabbroic rocks belonging to the lower and intermediate groups of Series I were determined for a research grade of analysis by means of ICP, INAA, ICP-MS and XRF methods at the Activation Laboratories Ltd. (Canada). Results for the anorthosites (3 samples) and the variably metasomatised gabbros (2 samples) will not be considered in the following discussion.

Olivine leucogabbros of the lower group show slightly variable SiO_2 (46,43 to 50,16%), Al_2O_3 (17,85 to 20,28%), CaO (9,27 to 12,11%) and MgO (4,07 to 7,19%) contents; their iron concentration, measured as Fe_2O_3, ranges from 6,91 to 13,85%; TiO_2 and V fall usually below 3,5% and 500 ppm, respectively. This chemical composition is quite similar to that obtained for melagabbros, here represented just by one sample (SiO_2 = 49,72%, Al_2O_3 = 16,01%, CaO = 12,47%, MgO = 7,16%, Fe_2O_3 = 8,48%, TiO_2 = = 0.991% and V = 289 ppm), being worth noting the fact that this specimen has only 2,5 modal % of interstitial oxides. The same is true for the analysed leucogabbro of this group (SiO_2 = 45,99%, Al_2O_3 = 15,43%, CaO = = 11,63%, MgO = 5,68%, Fe_2O_3 = 15,25%, TiO_2 = 2.782% and V = 581 ppm). Leucogabbros of the intermediate group (SiO_2 = 46,74-50,95%, Al_2O_3 = 17,01-21,91%, CaO = 11,87-13,06%, MgO = 4,96-6,81%), being locally richer in interstitial ilmenite and magnetic iron-spinels, show more variable Fe_2O_3 (5,52-12,31%), TiO_2 (0,216-2,122%) and V (56-674 ppm) concentrations.

Considering the available whole-rock geochemistry and mineral chemistry data sets one may conclude that titanium and vanadium are chiefly incorporated in the oxides; this is also shown by the observed TiO_2 *versus* Fe_2O_3 and V_2O_5 versus Fe_2O_3 covariance (figure 2). This also suggests that the spatial distribution of the oxide-rich rock domains can be evaluated on the basis of the modal rock analysis. However, since the collection of the examined 23 samples was very constrained by the outcrop distribution, no guarantee exist about their real representativity for this numerical purpose. This limitation is further constrained by the high values of the ore samples that contribute for the existence of a nugget effect. Although it is possible to establish a model for the spatial correlation of the samples, and these can correlate as far as 1 km, the sampling geometry is responsible for numerical artefacts of the interpolator that do not translate into real values (for example, the

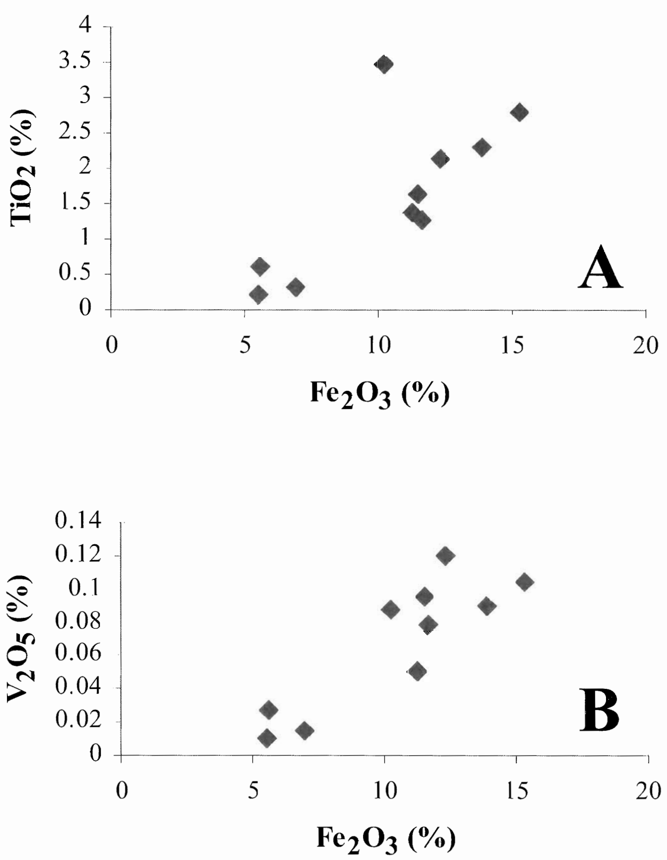

Fig. 2 - TiO_2 *versus* Fe_2O_3 (**A**) and V_2O_5 *versus* Fe_2O_3 (**B**) plots considering the available data for representative samples of gabbroic rocks belonging to the Lower and Intermediate Groups of Series I.

estimated points may become negative or null although all the closest samples analysed display positive values). However, considering the scarce number of samples analysed and their respective results and the spatial correlation deduced from them, one could still confidently use the modal percentage of the oxides as a guide to define the oxide-rich domains of the gabbros. The definition of the domains closely follows the cartographic pattern obtained by means of macroscopic field criteria, as shown in figure 3.

2.3. Stream sediments

Sediments of tributary streams on both margins of the Odivelas river were collected in 5 places (figure 4). They were dried at room temperature conditions and, after a microscopic examination of all samples, pure mineral concentrates were obtained in the laboratory; the complete sequence of the procedure is schematically represented in figure 5. Particular attention was given to the heavy mineral concentrates, which were separated in magnetic and non-magnetic fractions. After a detailed characterisation of all granulometric fractions by means of stereo microscopy, some portions were analysed by X-Ray diffractometry.

The X-Ray diffraction analysis was conducted with a Philips PW 1710 diffractometer equipped with a graphite crystal monochromator for Cu Kα radiation. The goniometer used a fixed divergent slit and a 0,2 mm receiving slit. Data was collected in a continuous mode with 2θ step increment of 0,02° and 1,25 s counting time for all samples. Oriented and randomly oriented preparations were produced from the clay-size fraction (< 2 μm) by sedimentation on a glass slide and front-loading into Al holders, respectively. One oriented preparation of each sample was solvated with glycerol to allow the identification of expansive phyllosilicates. When needed, the oriented preparations where heated at 550°C for 4 hours in a muffle. Quartz was normally used as an internal standard in the randomly oriented preparations. The phyllosilicates and the other minerals were identified by comparing the X-ray diffraction peak positions to those listed in the PDF cards (ICDD-JCPDS). Table 1 summarises the obtained results, being worth noting the relative abundance of ilmenite, magnetic iron-spinels, amphiboles and pyroxenes, besides the tentative identification of borovskite (Pd_3SbTe_4).

2.4. Soil geochemistry

Seventy-two soil samples were collected along five N-S profiles previously defined in an area that includes the old exploration prospects of Odivelas (figure 4). The collected samples were subjected to a "near-total" digestion in a 4-acid solution of HF, $HClO_4$, HNO_3, and HCl, and analysed by ICP-MS and INAA. All the analyses were performed at the Activation Laboratories Ltd. (Canada).

The profiles are too far away from each other to allow proper correlation of the features observed in each profile. However, a procedure to super-sample the population through kriging provided an adequate mean to analyse the

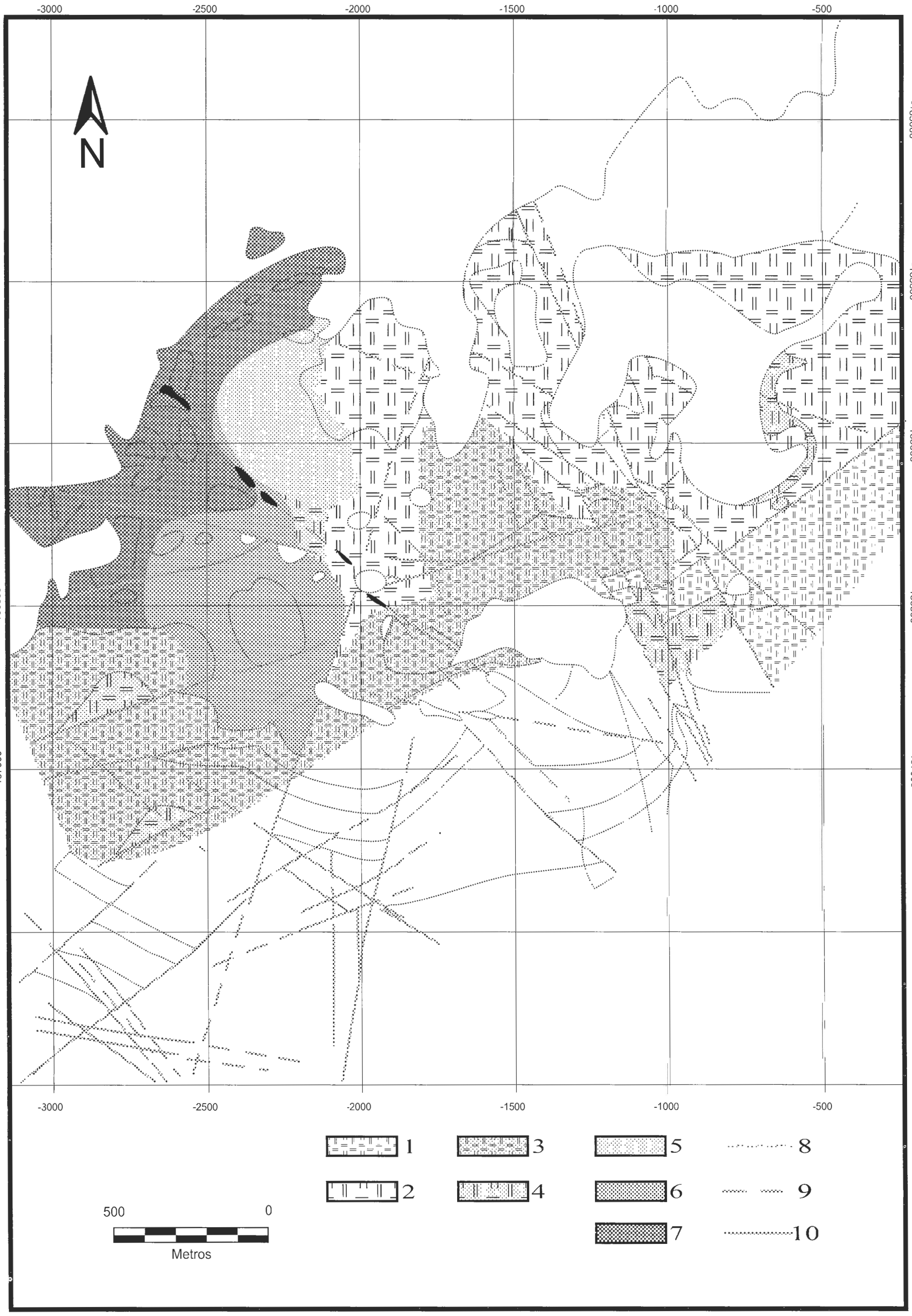

Figure 3 - Interstitial oxides distribution. 1: ilmenite-rich gabbros; 2: ilmenite bearing gabbros; 3: magnetite bearing ilmenite-rich gabbros; 4: magnetite-ilmenite bearing gabbros; 5: magnetite poor gabbros; 6: magnetite bearing gabbros; 7: magnetite rich gabbros; 8: geological contacts; 9: inferred fault zone; 10: fault zone.

TABLE I

Mineralogical composition of several fractions of sample **B1-5** (*1*) and of the fine fraction of sample **B1** (*2*)

(1)

SAMPLE			B1	B2	B3	B4	B5
COARSE FRACTION	MAGNETIC FRACTION		Ilmenite Hematite Magnetite/Magnesioferrite	Spinel (Magnetite/Cromite) Ilmenite Hematite Pyrite (?)	Ilmenite (very abundant) Quartz	Ilmenite Quartz (traces)	Ilmenite Spinel(Cromite/ Magnesioferrite) Pyrite Hematite
	NON MAGNETIC FRACTION	LIGHT (L)	Quartz	Quartz	Quartz	Quartz	Quartz
		HEAVY (P)	Piroxene (Augite) Ilmenite Simplotite/Wyartite (1)	Ilmenite Piroxene (Augite) Amphibole (Hornblende) Borovskite (2)	Piroxene (Augite) Borovskite (2) Feldspar Tourmaline (Schorl) Hematite Staurolite Amphibole (Tirodite) Andalusite	Tourmaline (Schorl) Andalusite D`ansite (3) Piroxene (Augite) Feldspar Borovskite (2) Amphibole (Tirodite)	Tourmaline (Schorl/Dravite) Andalusite Rutile D`ansite (?) (3) Borovskite (2) Ilmenite

(2)

FINE FRACTION	FINE (F)	Smectite
	FINE 2 (F1)	Smectite Ilmenite Hematite Quartz Maghemite Pyrite

The remaining samples analysed show very similar mineralogical composition
(1)- Simplotite: $CaV^{4+}_4 O_9.5H_2O$; Wyartite: $Ca_3U^{2-}(UO_2)(CO_3)_2(OH)_{18}.3(H_2O)$.
(2)- Pd_3SbTe_4.
(3)- $Na_{21}Mg(SO_4)_{10}Cl_3$

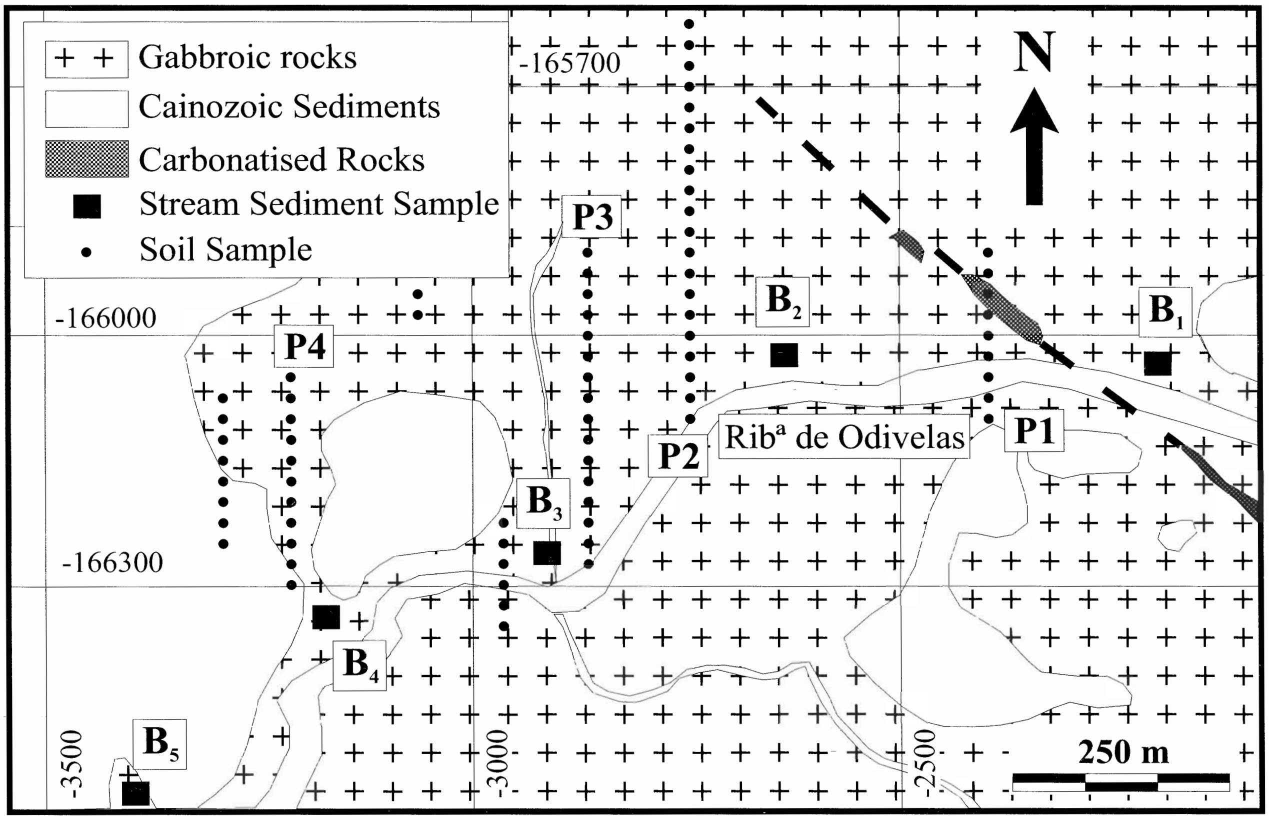

Figure 4 - Location of the analysed stream sediments and soil samples (the latter along five N-S profiles previously defined in the area that includes the old exploration prospects of Odivelas).

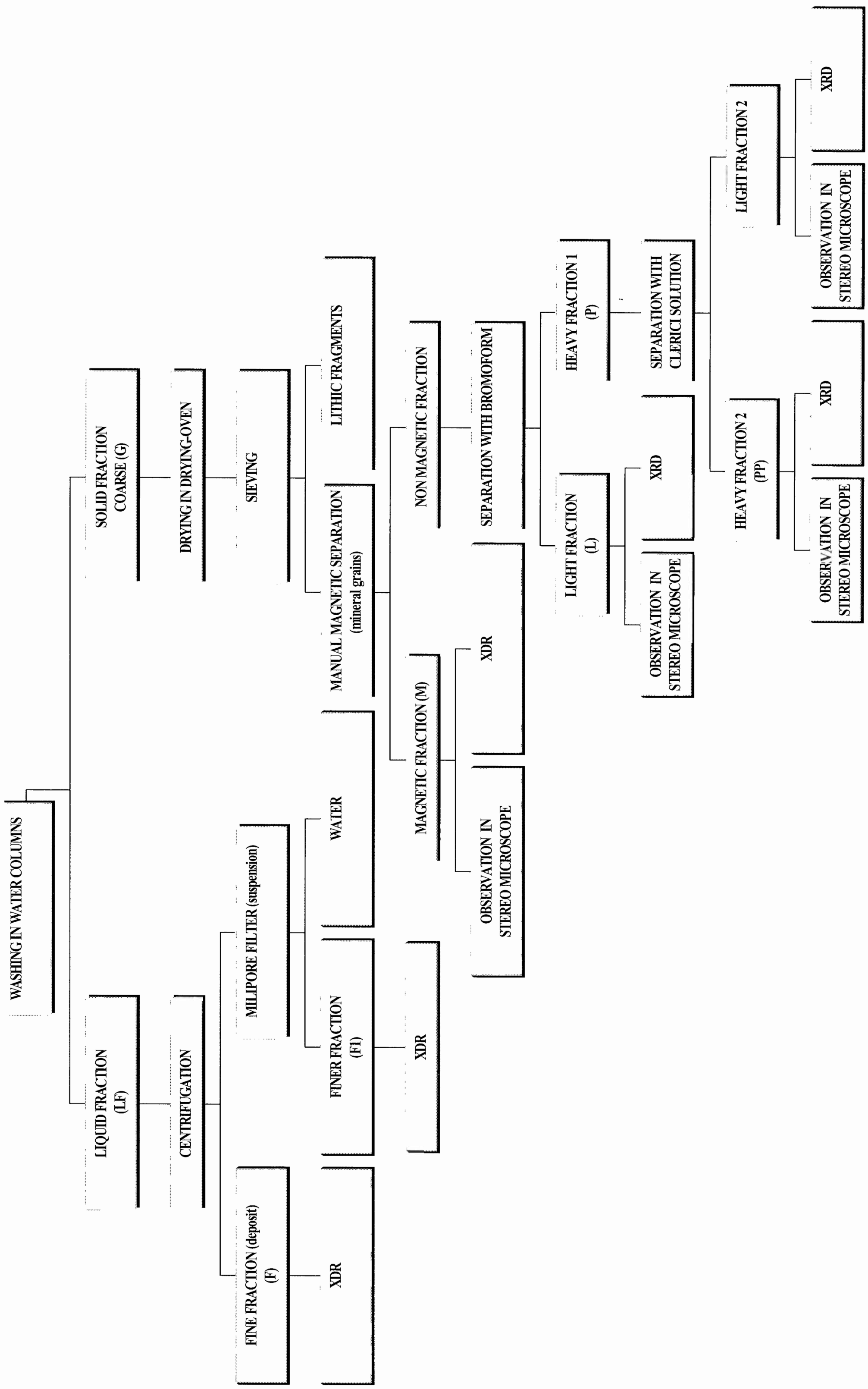

Figure 5 - Schematic representation of the laboratory procedure used in the mineralogical characterisation of the collected stream sediments.

data along profiles P1 to P4 (precisely those with at least 9 samples - GONÇALVES *et al.*, 2001). The diagram in figure 6 reports the obtained results for Ti and V (features concerning the distributions of Cr, Ni and Cu can be found in GONÇALVES *et al.*, 2001). From this graphical representation one may conclude that profile P1 is the only one where V and Ti values are relatively low. Excluding this singularity, the vanadium grades in the sampled soils are clearly anomalous and their gross covariance with Ti strongly suggests that titaniferous mineral phases are the main sources of vanadium, as confirmed by mineral chemistry data. However, the mismatch between some maxima for these metals may also indicate that this is not true for all cases (which also agrees with the available mineral chemistry information - see below) and/or that the dispersion mechanisms for each element in soils are different. The calculated linear length - concentration relation for both metals shows that the anomalous V thresholds are generally greater than 400 ppm, although ranging within 270 and 470 ppm in profile P2. The anomalous Ti threshold values in profile P4 must lie within 1.5 and 2%.

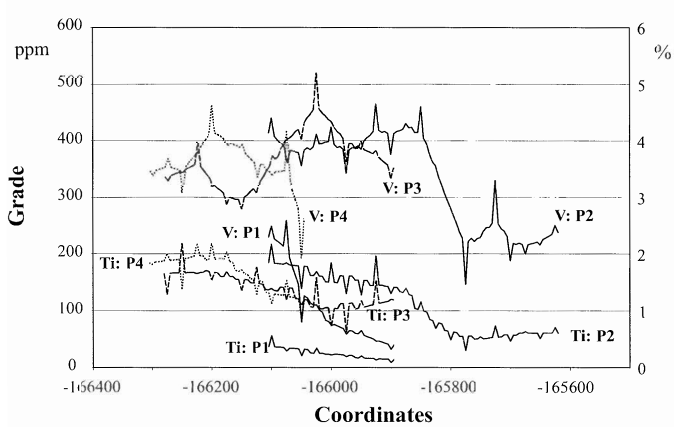

Figure 6 – Grade values for V and Ti for the profiles P1 to P4 in Odivelas area; distance uses the same coordinate system as in figure 4, along the N-S direction. All values in ppm, except for Ti, in % in the right side of the graphic. Lines between sampled points obtained by ordinary kriging, where spikes correspond to the observed values, as kriging is an exact interpolator at these locations. V and Ti in profiles P1 and P2 (solid lines), profile P4 (dotted lines), and profile P3 (dashed lines).

2.5. The Fe-Ti-V ores; synopsis of their mineralogy, texture and chemistry

According to the technical reports of the old mining prospects (mostly concerning 6 shallow exploration shafts), the oxide ores of the Odivelas area form irregular masses of variable size that occur within the olivine leucogabbro package, usually close to the discontinuous lenses (and/or blocks?) of oxide enriched cumulates (melagabbros, wehrlites and websterites).

The ores are massive and mainly composed of relatively coarse (1-3 mm) equant grains of Ti-V bearing maghemite (73 to 81 modal %) that originate an isotropic matrix locally included in anhedral and bigger grains of ilmenite (11 to 22 modal %). Hematite is an important accessory mineral phase (4 to 15 modal %), most of the times filling late dilational veinlets that display zoned development; the latest growth bands of these veinlets usually comprise fine intergrowths of hematite and goethite. There is no evidence for ilmenite lamellae in maghemite, and hematite lamellae in ilmenite are very rare. The border of maghemite grains, however, display distinct variations in reflectance and in colour (increase of the brownish tint), showing abundant red and reddish-orange internal reflections as well. The reason for the observed optical changes is currently under detailed investigation. However, as a work hypothesis, the genesis of the Ti-V enriched maghemite matrix is tentatively envisaged as a result of an incomplete and probably non-equilibrium subsolidus oxidation process over a pre-existent aggregate of magnetite--ulvospinel composition below *circa* 600°C. Indeed, the development of ilmenite-hematite lamellae is expected to form as a consequence of the oxidation of earlier magnetite-ulvospinel aggregates during magmatic cooling if subsolidus equilibrium occurs (LINDSLEY, 1991). Conversely, metastable cation-deficient magnetite-maghemite solid solutions and ilmenite will developed, and the presence of significant amounts of Al^{3+} is believed to be the main cause to suppress completely the tendency of maghemite inversion to hematite (WAYCHUNAS, 1991; BANERJEE, 1991). The role played by vanadium in this process is presumably similar to that of aluminium; the available experimental data reveal that Ti^{4+} should not inhibit this irreversible crystallographic transition (BANERJEE, 1991). This prediction agrees totally with the chemical composition obtained for the maghemites of Odivelas by means of electron microprobe analysis, for which $Al_2O_3 < 10$ wt%, $TiO_2 \leq 27{,}04$ wt% and $0.11 \leq V_2O_3 \leq 2{,}70$ wt%; minor amounts of ZnO (≤ 0.86 wt%), MnO (≤ 0.66 wt%) and Cr_2O_3 (≤ 0.14 wt%) were also recorded.

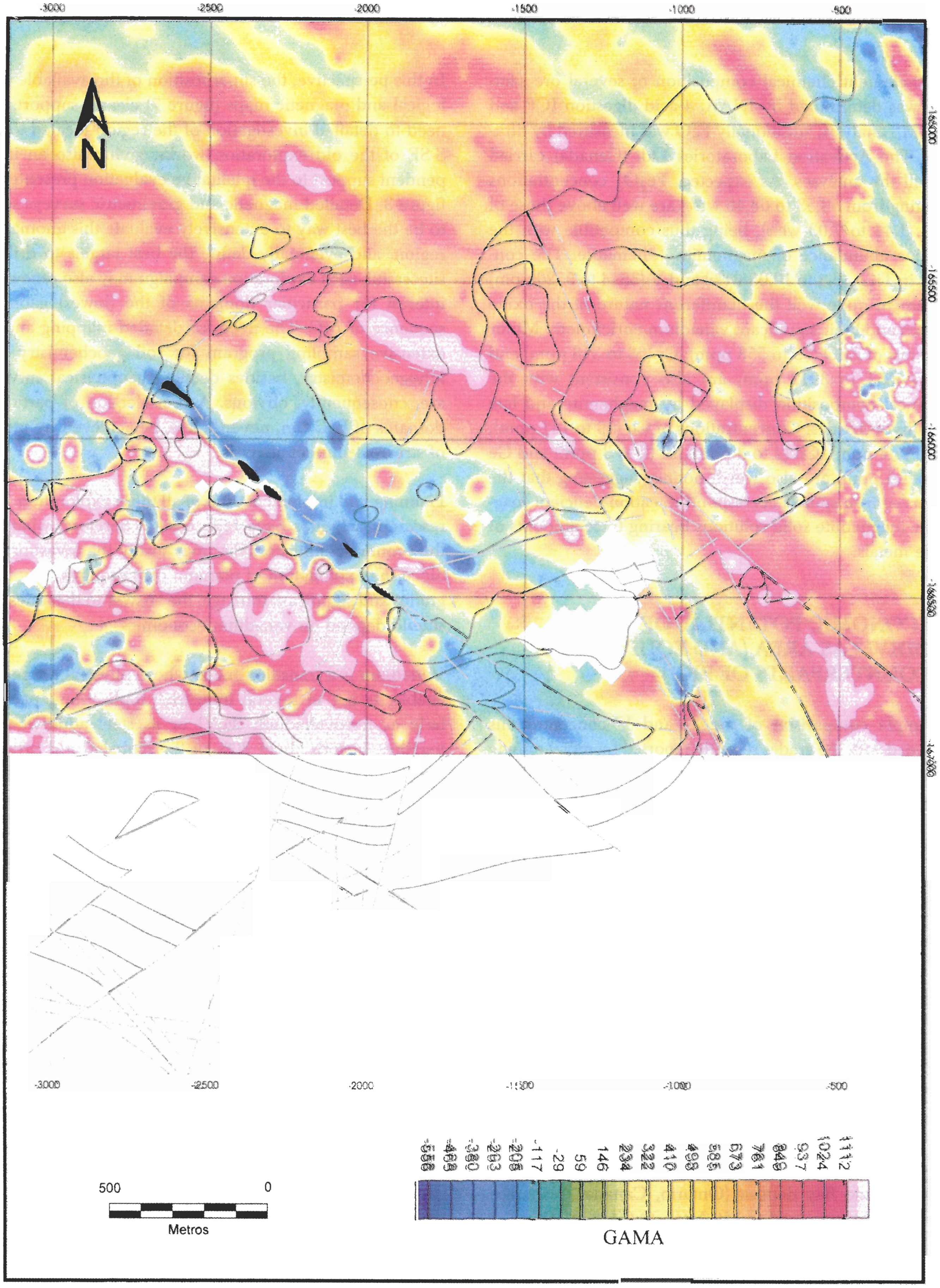

Figure 7 - Vertical field magnetic anomalies of the Odivelas area (adapted from FONSECA, 1999).
Note the coincidence between the magnetic anomalies and the oxide enriched gabbros of Series I.

Multi-element chemical composition of several ore samples was determined by INAA, 4-acid digestion ICP and ICP-MS analysis; additionally FeO was measured by titration. The Activation Laboratories Ltd. (Canada) carried out all the analyses. As expected, Fe_2O_3 concentrations (ranging from 53,53 to 68,46 wt%) are well above those of FeO (1,44 to 7,03 wt%), being thus compatible with the relative abundance of maghemite + hematite. The contents in TiO_2 (6,4 to 10,05 wt%) and V (3514 to 5520 ppm) document quite well the titaniferous nature of the oxide masses and their significant vanadium enrichment. Minor amounts of ZnO (75 to 558 ppm), Cr (63 to 318 ppm) and MnO (651 to 3912 ppm) are also consistent with the chemical composition displayed by maghemite and late iron (hydr-)oxides. Concentrations of Co (29 to 141 ppm), Se (5 to 6 ppm), Cd (2 to 3 ppm), Bi (2 to 3 ppm) and Ge (1 to 1,6 ppm) are also worth noting, suggesting that the observed iron spinels correspond to cation-deficient magnetite-maghemite solid solutions bearing trace amounts of these metals.

3. ECONOMIC POTENTIAL OF THE ODIVELAS AREA (AND EQUIVALENT COUNTERPARTS OF BIC?)

A simple comparison of the Ti and V concentrations obtained with the grades recently reported by many mining companies for several exploitations and promising prospects included in similar geological settings (banded gabbroic complexes - see, *e.g.,* the web sites for Vanadium), reveals that the oxide ores of the Odivelas area may have economic interest. In fact, vanadium values in the studied massive ores are scattered between 0,63 and 0,99% V_2O_5, although they rarely exceed 0,10% V_2O_5 in the host rocks; additionally, TiO_2 concentrations give added value to these oxide ores (ranging from 6,4 to 10,1 %) since they are very close to the economically acceptable titaniferous ore grade. This means that the major goal of further exploration attempts should be the recognition of the most anomalous rock domains of the gabbroic lower group belonging to Series I. If the presence of significant tonnage is confirmed, the Odivelas area would be potentially economic, because of the low cost usually involved in dressing of these ores. Taking, for instance, the Mckenzie Bay deposit (Ontario, Canada), resources were crudely estimated as 350 Mton @ 0,45% V_2O_5.

In this perspective, the superposition of the available geological and magnetic maps (figure 7) clearly supports the need to detailed investigation of the region located to the S-SE of the old exploration works, giving also an independent support to the qualitative evaluation presented in figure 3. Detailed magnetic and gravimetric surveys seem to be the best way to extensively evaluate this anomalous region, and eventually define the best targets to drill. If successful, such exploration campaign may also renew the interest for particular domains of the (lower) gabbroic sequence of BIC. The need for detailed mapping and an extensive sampling program for soil geochemistry and lithogeochemistry, besides detailed geophysical surveys, are, consequently, obvious. A pre-selection of particular domains of BIC can, nevertheless, be achieved by means of stream sediment analysis.

Planning and implementation of all these exploration (and research) activities have high costs. Therefore, what are the economic indicators that may justify the investments? Since the exploitation of titanium ores requires very high grades and significant tonnage, the answer to that question should depend on vanadium economics.

Vanadium is a transition metal whose physical properties enable its use in several industrial applications, particularly as ferrovanadium (FeV) or as steel additive that, together, absorb about 80% of the global world production of this element. This means that vanadium prices depend mostly on steel trading, and on the global supply/demand balance of metals (such as columbium, manganese, molybdenum, titanium and tungsten) that are to some degree interchangeable with vanadium as alloying elements. Nevertheless, the predictable need for stronger and lighter steels, the increasing necessity of maleic anhydrite (an important chemical component of polyester resins and fibreglass), and the current believe that there is no acceptable substitute for vanadium in the manufacture of titanium alloys for aerospace industry, strongly suggests that, in the following years, vanadium should maintain, at least, its present position in the international market. An important increase of vanadium demand may however be expected if new, environmental sustainable, hydroprocessing catalysts driven by pressure on oil refiners were soon accomplished, and/or if redox batteries were successfully developed at lower costs in the near future.

At present, vanadium world resources exceed 63 million tons, but considering that this metal is usually recovered as a by-product or a co-product, the amounts reported in official bulletins (*e.g.* U.S. Geological Survey - Mineral Commodity Summaries, February 2000) are not fully indicative of the available supplies. The main reserves of this metal are located in the Republic of South Africa (45%), Russia (24%), United States of America (13%) and China (9%), and an excess of vanadium production of 3-4% for the next two years is predicted assuming present day consumption and supply of this metal. However, a long-term price of US$2,5 per lb of V_2O_5 can be expected on the basis of the above mentioned projection of vanadium needs. This represents a slight increase of the V_2O_5 prices relatively to those performed in 2000 (US$1,85/lb), although not so different of the average market value in the last ten years (US$2,60/lb - excluding the abnormally high prices recorded in 1988 as a consequence of a significant reduction in vanadium supply due to the political and economic crisis in Russia). The FeV prices, usually higher, reached US$9,50/lb in 2000.

4. CONCLUSIONS

In the Odivelas area, the outcropping gabbroic rocks of BIC form two different Series with normal polarity. The layering displayed by these rocks is not uniformly developed, but it can be shown that it ranges usually from NW-SE to WNW-ESE in Series I and from WNW-ESE to E-W in Series II, dipping in both cases less than 30^o towards SW or S.

Three main groups of layers can be recognised in Series I: 1) the lower group is mainly composed of olivine leucogabbros, although the presence of troctolites and discontinuous lenses (and/or blocks?) of oxide-rich melagabbros, wehrlites and websterites is believed to represent a distinct feature of this igneous sequence; 2) the intermediate group is essentially made of leucogabbros and anorthosites; 3) the upper group consists of a relatively monotonous sequence of olivine leucogabbros that contains discontinuous anorthositic layers. In Series II, poorly layered olivine gabbros and olivine leucogabbros predominate.

The studied V-Ti rich ores occur within the lower group of Series I, forming irregular masses of variable size. They chiefly comprise coarse (1-3 mm) equant grains of magnetic iron spinels whose chemical composition can be generally settled as cation-deficient magnetite-maghemite solid solutions Ti-V enriched. Minor and accessory amounts of ilmenite and hematite, respectively, complete the mineral ore paragenesis. This mineralogical signature is compatible either with the obtained Fe_2O_3 and FeO concentrations (ranging from 53,53 to 68,46 wt% and from 1,44 to 7,03 wt%, respectively) or with the anomalous contents in TiO_2 (6,4 to 10,05 wt%) and V (3514 to 5520 ppm), strongly supporting the economic potential of these ores if the presence of significant tonnage is further confirmed. Regarding this feature, it should be noted that the cartographic distribution of the oxide-rich domains of the gabbros and of the magnetic anomalies, clearly supports the need to detailed investigation of the region located to the S-SE of the old exploration works. This is also suggested by the available soil geochemistry data, from which one may conclude that the anomalous V and Ti thresholds are generally greater than 400 ppm and 1.5%, respectively.

Detailed magnetic and gravimetric surveys seem to be the best way to extensively evaluate the area that comprises the old exploration works and the most promising magnetic anomalies at S-SE, leading eventually to the identification of the best targets to drill. If successful, such exploration campaign may also renew the interest for particular domains of the (lower) gabbroic sequence of BIC. The available economic indicators for vanadium justify entirely the investments implicated by the exploration and research activities planned for the Odivelas area.

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