Recent advances in the study of the stratigraphy and the magmatism of the Iberian Pyrite Belt, Portugal

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Abstract: Recent research on the palynostratigraphy and the magmatism (physical volcanology and geochemistry) of the Portuguese part of the Iberian Pyrite Belt (IPB) has provided new results which allow a better understanding of the regional geology. The study was concentrated on the Albernoa, Serra Branca and Mina de São Domingos antiforms and comparisons are made with the Pomarão Anticline and the Neves Corvo mine region.

Palynological data suggest that in the studied antiforms the felsic and mafic volcanism appears to be of late Famennian age and dolerites may be younger, of post Strunian age. In the Pomarão and Neves Corvo structures the felsic volcanism and mafic lavas and intrusions range from the late Famennian to the Viséan. The new palynostratigraphic ages obtained confirm that the antiforms are true tectonic windows, as described in previous structural interpretations.

Reconstructions of the volcanic facies architecture show that the volcanic sequences are dominated by submarine lavas (domes and cryptodomes) and deposits from high-concentration voluminous gravity flow containing abundant pyroclasts. These deposits may have been sourced from explosive eruptions from submarine vents. In the case of the Neves Corvo mine region the volcanic episodes are well constrained by palynological ages.

The lithogeochemistry of mafic rocks from Albernoa and Serra Branca supports an extensional setting for the IPB, with apparent arc signatures being caused by crustal assimilation. The felsic rocks from both areas, but especially from Albernoa, provide a problematic geotectonic classification partially because of their anomalously low high-field-strength element contents, possibly caused by relatively low temperatures of crustal fusion. These relatively low temperatures are confirmed by zircon and monazite saturation models which, in addition, appear to help discriminate VMS-favorable from barren felsic rocks.

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Introduction

During the last two decades the Iberian Pyrite Belt has been the aim of detailed studies, both in Spain and Portugal. Most of these studies are related to lithostratigraphy, petrology/geochemistry, geochronology, structural geology and ore genesis. Varied geophysical techniques were used mainly by private companies in VMS exploration programmes. More recently new fields of research were opened, namely palynostratigraphy and physical volcanology.

Palynostratigraphy has proved to be an important tool to precise the age of the lithostratigraphic units, as demonstrated in recent studies of the tectonically imbricated succession of the Neves Corvo mine region (Oliveira et al., 1997; Oliveira et al., 2004; Pereira et al., 2004). The interpretation of the physical characteristics of the volcanism started earlier in Spain (Boulter, 1993; Soriano and Marti, 1999) and is now a field of intense research in Portugal (Rosa C. et al., 2004 a, b).

Research on the geochemical signature of the volcanic rocks led to distinct geodynamic interpretations, either related to back arc crustal extension (Munhá, 1983), to pull-apart crustal extension caused by oblique collision (Mitjavilla et. al., 1997; Rosa D., et. al. 2004), to partial melting of deep seated accretionary prism (Thiéblemont et al., 1994) or to a northward dipping subduction zone below the Pyrite Belt (Onézime et al., 2003).

This work concentrates on the most recent advances achieved in the Portuguese sector of the Iberian Pyrite Belt in the fields of palynostratigraphy, physical volcanology and igneous geochemistry. The results presented here derive from research currently in progress in five main antiforms, i.e. Albernoa, Serra Branca and Mina de São Domingos located in the so-called north branch and Neves Corvo and Pomarão in the south branch. Although the results are still preliminary, they open room to new geological interpretations of this important crustal segment of the Variscan Chain of Iberia.

Stratigraphy

The stratigraphy of the Iberian Pyrite Belt (Figure 1) consists in two major units, the Phyllite Quartzite Group (PQ) and the Volcano Sedimentary Complex (VSC).

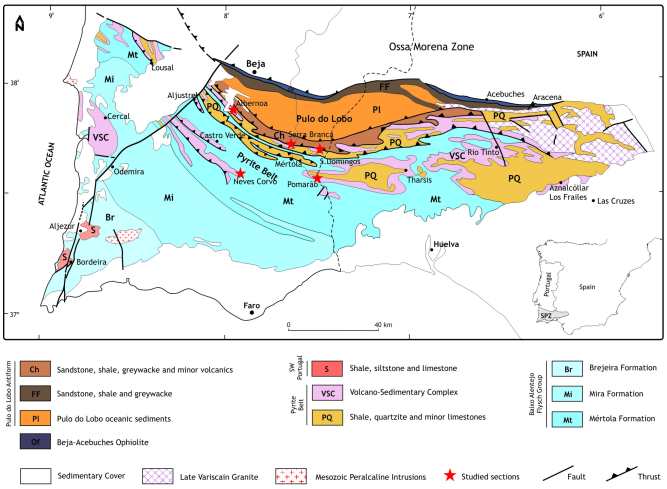
The PQ Group forms the detritic basement and is composed mostly of phyllites, quartzites, quartzwackes and shales with intercalations of limestone lenses and nodules at the upper part which as a whole were laid down in a marine siliciclastic platform. The thickness is in excess of 200m (base not known). The unit is of late Devonian age given by ammonoids, conodonts and palynomorphs (Boogaard, 1963, Fantinet et al., 1976, Cunha and Oliveira, 1989, Oliveira et al., 1997, Oliveira et al., 2004; Pereira et al., 2004).

The VSC includes several volcanic episodes of, either intrusive and extrusive, volcanic rocks dominated by rhyolites, rhyodacites, basalts and minor andesites, and intercalations of black shales, siltstones, minor quatzwackes, thin bedded volcaniclastics, jaspers and purple shales. The thickness is variable, from few tens of meters to more than 1000m. The age, given by rare conodonts and well preserved assemblages of palynomorphs, ranges from the late Devonian to the late Viséan (Oliveira, 1990; Oliveira et al., 1997, Oliveira et al., 2004, Pereira et al., 2004). The VSC was laid down in a submarine environment.

Above the VSC there is a turbidite succession whose designation depends on its position in the belt geographically divided in branches (Oliveira, 1990). In the north branch the succession is named Freixial Formation and occurs usually tectonically imbricated with the VSC lithologies. In the south branch of the belt, the turbidite succession, known as Mértola Fomation, is composed of thick and thin bedded greywackes, conglomerates and shales, with a total thickness of about 3000m.The age of these units is slightly diachronic, the Feixial Fm. being of early late Viséan age, as shown below, while the Mértola Fm. ranges from late Viséan to early Serpukhovian.

It should be noted that further southwest the Cercal Anticline (Figure 1) constitutes another branch of the Pyrite Belt. The VSC stratigraphic sequence is here overlain also by turbidites, in this case of Sepukhovian age. However, this sequence is far from being well understood and as such is not treated in the present work.

Figure 1. Geological map



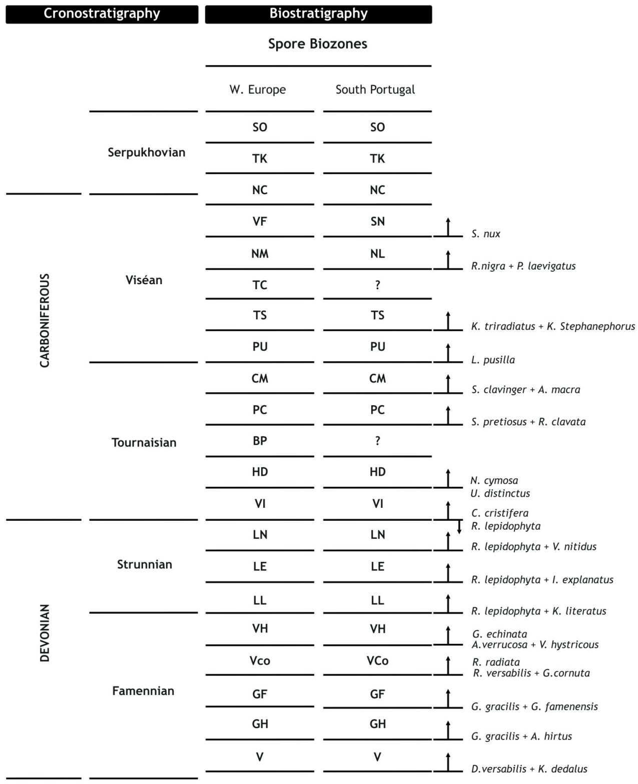
Geological map of the Iberian Pyrite Belt (adapted from Oliveira 1990).

Methods

The study samples were collected in drill cores and in a road track (Serra Branca). The logged lithologies are labelled as informal units which are used only for descriptive purposes. Correlations with well known lithostratigraphic units in the belt are established, depending of existing similarities.

Biostratigraphic research was based on palynomorphs and standard palynological laboratory procedures were employed in the extraction and concentration of the palynomorphs from the host sediments (Wood et al., 1996). The slides were examined with transmitted light, per BX40 Olympus microscope equipped with an Olympus C5050 digital camera facility. All samples, residues and slides are stored in the Geological Survey of Portugal (INETI). The miospore biozonal scheme used follows the standard Western Europe Miospore Zonations (after: Clayton et al., 1977; Streel et al., 1987; Higgs et al., 1988; Higgs et al., 2000, Clayton 1996 and Maziane et al., 2002). The choice of alternative schemes was stated by the presence of very consistent local miospore assemblages in South Portugal (Figure 2). Stratigraphically important and typical taxa are illustrated in Plate 1 .

Figure 2. Miospore zonation schemes used



Western Europe Zonation (adapted from Clayton et al., 1977; Streel et al., 1987; Higgs et al., 1988; Clayton 1996, Higgs et al., 2000, and Maziane et al., 2002); South Portugal Zonation (Adapted from Pereira, 1999).

Figure 1. Stratigraphically important and typical taxa

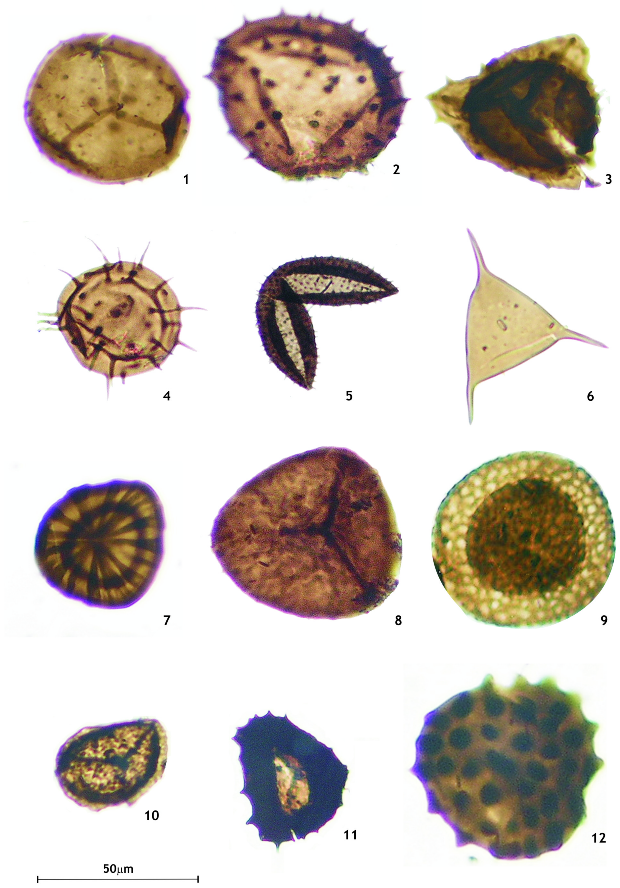


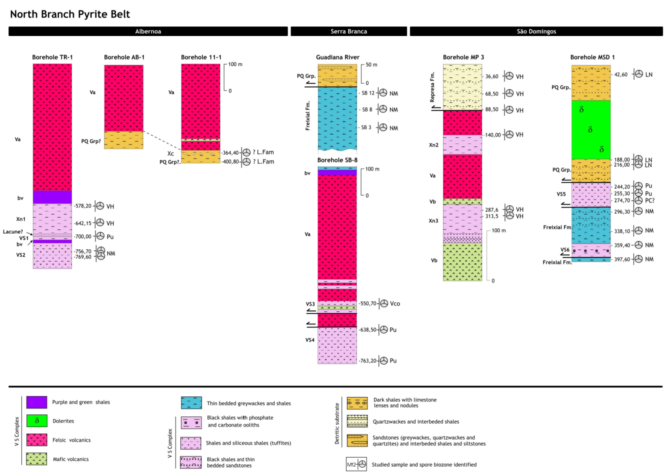
Plate captions list the taxonomic name of the figured specimen, followed by borehole number, sample number, slide number, microscopic coordinates and INETI collection number of the specimen.

1. Grandispora echinata Hacquebard, 1957; Borehole MP 3, Sample 36,60-1, 1244-45, INETI 0501.
2. Grandispora cornuta Higgs 1975; Borehole MP 3, Sample 36,60-1, 1305-225, INETI 0502.
3. Samarisporites triangulatus Allen 1965; Borehole MP 3, Sample 36,60-1, 1090-180, INETI 0503.
4. Gorgonisphaeridium ohioense (Winslow) Wicander, 1974; Borehole MP 3, Sample 36,60-3, 1200-138, INETI 0504.
5. Gorgonisphaeridium plerispinosum Wicander 1974; Borehole MP 3, Sample 36,60-3, 1190-175, INETI 0505.
6. Veryhachium downiei Stockmans and Willière, 1962; Borehole MSD 1, Sample 42,60-1, 1120-110, INETI 0506.
7. Emphanisporites annulatus McGregor, 1961; Borehole MP 3, Sample 36,60-2, 1335-160, INETI 0507.
8. Rugospora radiata (Jushko) Byvscheva 1985; Borehole MP 3, Sample 36,60-1, 1340-148, INETI 0508.
9. Retispora lepidophyta (Kedo) Playford, 1976; Borehole MSD 1, Sample 42,60-1, 1245-100, INETI 0509.
10. Lycospora pusilla (Ibrahim) Schopf, Wilson & Bentall 1944; Borehole MSD 1, Sample 255,30-1, 1155-75, INETI 0510.
11. Densosporites sp.; Borehole MSD 1, Sample 255,30-1, 1095-135, INETI 0511.
12. Raistrickia nigra Love, 1960; Borehole MSD 1, Sample 359,40-1, 1380-180, INETI 0512.

North Branch

This branch extends from Mina de São Domingos (east) until Lagoa Salgada (west), the latter below the Cenozoic sediments of the Sado Basin. The stratigraphic research was carried out in the Albernoa, Serra Branca and Mina de São Domingos antiforms (Figure 1). The units identified in selected boreholes and their corresponding ages based on palynomorphs are shown in Figure 3.

Figure 3. Logs from selected boreholes

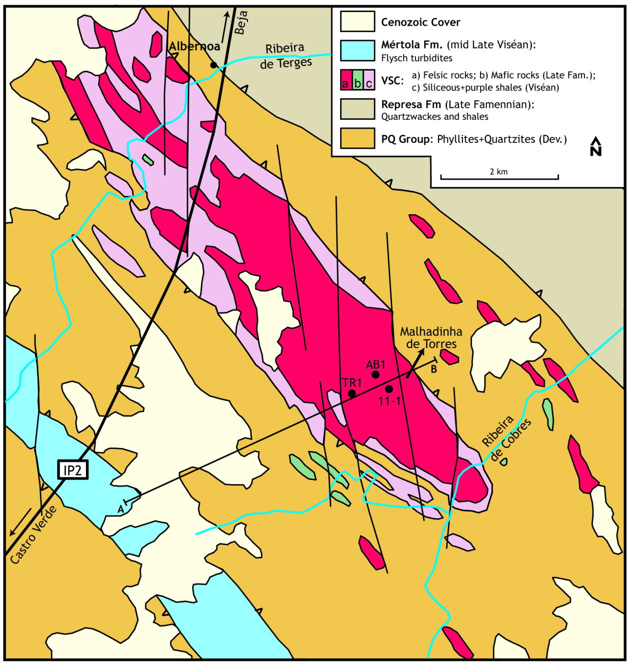


Logs from selected boreholes studied in the North Branch of the Pyrite Belt.

Albernoa

The geological map of this antiform (Figure 4) shows felsic volcanic rocks (rhyodacites) in its core which are overlain by siliceous and purple shales. Phyllites and quartzites ascribed to the Phyllite-Quartzite Group lay geometrically above this sequence.

Figure 4. Detailed geological map



Detailed geological map of Albernoa region (Adapted from Geological Map of Portugal, 1 200 000, Sheet 8).

Boreholes AB1 and 11-1

Boreholes AB1 and 11-1 (Figure 3) put in evidence a lithological succession composed of black shales with carbonate nodules (Xc) followed by felsic volcanic rocks (Va). Unit Xc, which is provisionally correlated with the upper part of the PQ Group, yielded a miospore assemblage that includes Aneurospora goensis, Aneurospora greggsii, Auroraspora sp., Camazonotriletes sp., Crassispora catenata, Densosporites devonicus, Geminospora lemurata, Retusotriletes rugulatus and Verrucosisporites scurrus, indicating an early Famennian age. Younging stratigraphic direction is given by graded bedding, flame structures and load casts in the volcaniclastic sequence immediately above the volcanic rocks, indicating that the stratigraphic sequence corresponds to the upright limb of the antiform (Figure 4).

The lithological succession intersected in borehole TR1 corresponds to the overturned limb of the antiform. The stratigraphic succession consists of felsic rocks (rhyodacites) (Va) overlain by: - purple shales (bv); - black shales (Xn1); - shales, siltstones and tuffites (VS1); - purple shales (bv); - shales, quartzwackes and minor tuffites (VS2).

Unit Xn1 provided miospores of late Famennian VH Biozone. The assemblages include Grandispora echinata, together with Auroraspora sp., Diducites sp., Emphanisporites rotatus, Geminospora lemurata, Grandispora cornuta, Punctatisporites sp., Retusotriletes planus, R. rugulatus and Rugospora radiata. All samples contain abundant acritarchs and prasinophytes.

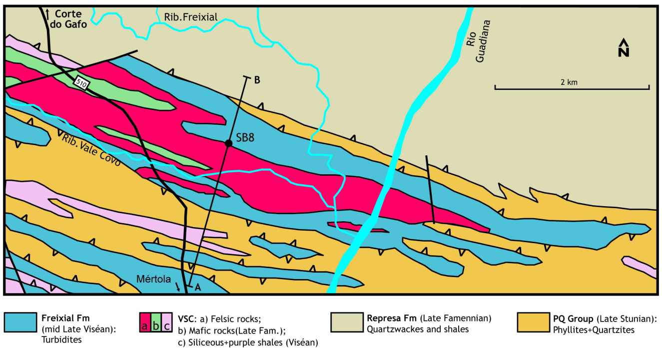
Unit VS1 yielded miospores assigned to the early Viséan, Pu Biozone. The assemblage yielded the zonal specie Lycospora pusilla in association with Auroraspora macra, Convolutispora sp., Densosporites sp., D. spitsbergensis, D. brevispinosum, Dictyotriletes castaneaeformis, Discernisporites micromanifestus, Knoxisporites cf. triradiatus, Vallatisporites pusillites, V. galearis, V. verrucosus and reworked miospores of late Famennian and Strunian age. This unit marks the entry of quartzwackes (turbidites) in the succession.

About 40m above the second purple shale intercalation (bv) samples of unit VS2 provided poorly preserved miospores of mid Late Viséan NM Biozone. The miospore assemblage contains the zonal specie Raistrickia nigra and taxa such as Anaplanisporites sp., Crassispora sp. Densosporites sp., D. brevispinosum, D. intermedius, Knoxisporites triradiatus, Lycospora pusilla, Microreticulatisporites sp., Vallatisporites vallatus and Waltzispora sp.

Serra Branca

The VSC of the Serra Branca Antiform (Figure 5) is mostly composed of several felsic units, mafic rocks (mostly spilites), shales and a purple shale horizon at the top of the volcanic sequence. This sequence is overlain by the Freixial Formation turbidites, with a thickness of 200m in the type section, which is well exposed in a road track on the west side of the Guadiana River.

Figure 5. Detailed geological map of Albernoa region



Detailed geological map of Albernoa region (Adapted from Geological Map of Portugal, 1 200 000, Sheet 8).

Borehole SB 8

Borehole SB 8 (Figure 3) intersected the following units from top to bottom: - Freixial Fm. turbidites (Fr); - a purple shale horizon, about 20m thick (bv); - a pile of felsic volcanic rocks with intercalations of dark shales, tuffites and mafic rocks at the lower part (VS3); - black shales, siltstones and siliceous shales (VS4).

The Freixial Fm., in the type section, yielded miospores of the mid Late Viséan NM Biozone as indicated by the following assemblage: Ahrensosporites sp., Anaplanisporites sp., Crassispora trychera, Densosporites sp., D. brevispinosum, Knoxisporites triradiatus, Kraeuselisporites sp., Leiotriletes tumidus, Lycospora pusilla, Microreticulatisporites sp., Vallatisporites cilliaris, V. vallatus and Waltzispora planiangulata, in association to the nominal specie Raistrickia nigra, and taxa such as Emphanisporites rotatus, Geminospora sp., Retispora lepidophyta, Rugospora radiata and Vallatisporites verrucosus, interpreted as reworked miospores of late Famennian and Strunnian age. These assemblages are similar to that described for the unit VS2 identified in theTR1 borehole, Albernoa.

The black shales of unit VS3 gave miospores assigned to the late Famennian VCo Biozone, as indicated by the presence of the zonal specie Grandispora cornuta and Auroraspora sp., Diducites sp., Emphanisporites rotatus, Geminospora lemurata, Punctatisporites sp. and Rugospora radiata, unit VS4 contains a miospore assemblage assigned to the Pu Biozone, identical to that described for unit VS1 of the TR1 borehole.

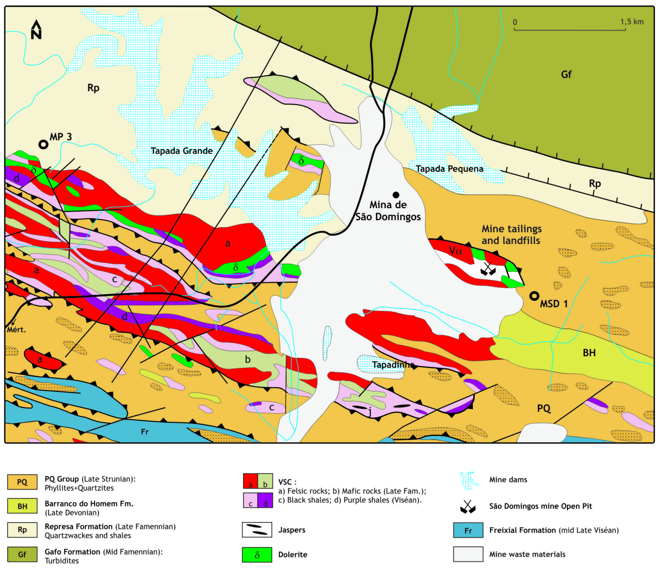
The lithological succession is in normal stratigraphic order until the base of the felsic volcanics which are in turn thrusted over the VS4 unit.

In general terms, the stratigraphic sequences of Albernoa and Serra Branca antiforms share several characteristics in common, particularly concerning the lithologic successions and ages.

Mina de São Domingos Antiform

The stratigraphic sequence of this antiform is composed of felsic rocks (mostly rhyolites), spilites, dolerites minor andesites, shales, tuffites (fine volcaniclastics) and purple shales. The VSC appears to be tectonically overlain by phyllites and quartzites of the PQ Group and is also thrusted by the quartzwackes, siltstones and shales of the Represa Formation, the upper unit of the Pulo do Lobo Antiform, which extends geographically to the north (Figure 6). Two boreholes (MP3 and MSD1) were examined for palynostratigraphic research (Figure 3).

Figure 6. Detailed geological map of Mina São Domingos region



Detailed geological map of Mina São Domingos region (Adapted from Geological Map of Portugal, 1 50 000, Sheet 46-D Mértola).

MP3 Borehole

In the MP3 borehole, four main units were identified, namely: the Represa Fm., silstones and shales (Xn2), felsic (Va) and mafic (Vb) volcanic rocks, black shales (Xn3) and a dolerite.

The Represa Fm. shales yielded rich miospore assemblages of the late Famennian VH Biozone, as indicated by the presence of the taxa Ancyrospora ancyrea, Aneurospora greggsii, Auroraspora sp., A. solisorta, Bauscaudaspora callicula, Crassispora sp., Cymbosporites sp., Diducites poljessicus, D. versabilis, Emphanisporites annulatus, E. rotatus, Geminospora lemurata, Grandispora cornuta, G. echinata, G. famenensis, Punctatisporites irasus, Retusotriletes sp., R. crassus, Rugospora radiata and Samarisporites triangulatus. All samples contain very rich assemblages of acritarchs and prasinophytes.

The black shales intercalated in the felsic rocks (Xn2) and also those intercalated in mafic rocks (Xn3), both gave rich miospore associations of the VH Biozone. This means that at least part of the VSC and the Represa Fm. have the same age. A tectonic breccia that occurs at the base of the Represa Fm. is interpreted in close relationship with a thrust fault which brought the unit over the VSC

Borehole MSD1 intersected the following lithologies, from top to bottom: - sandstones and shales of the PQ Group, which are intruded by a dolerite ; - shales, siltstones and tuffites (VS5); - black shales with interbedded phosphate and carbonate ooliths (VS6); - shales and quartzwackes ascribed to the Freixial Fm.

The shales of the PQ Group provided well preserved miospore assemblages assigned to the LN Biozone of late Strunian age. The assemblages contain Retispora lepidophyta and Verrucosisporites nitidus, the nominal species and the taxa Crassispora sp., Densosporites spitsbergensis, Geminospora lemurata, Punctatisporites sp., Rugospora radiata and Vallatisporites sp. Rare acritarchs and prasinophytes are present.

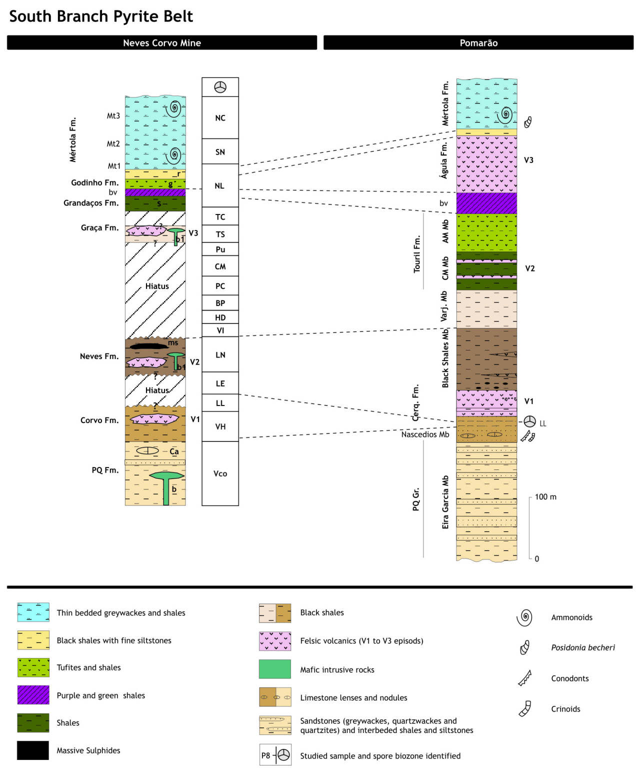
Unit VS5, besides the typical miospore assemblages of the early Viséan Pu Biozone, also yielded one poorly preserved assemblage representative of the late Tournaisian PC Biozone as shown by the occurrence of the taxa Auroraspora sp., Crassispora sp., Retusotrilites incohatus and Vallatisporites vallatus and the zonal specie Spelaeotriletes pretiosus.

The black shales with phosphate and carbonate ooliths (VS6) and the shales of the Freixial Fm have similar miospore assemblages that indicate the mid LateViséan NM Biozone. This borehole, although located close to the São Domingos mine open pit (Figure 6) failed to find any kind of massive sulphides or even felsic volcanic rocks. This is probably due to the highly complicated tectonic structure of the mine region, which is still under investigation.

South Branch

This branch refers to the rooted antiforms where the VSC is conformably overlain by the Mértola Formation turbidites. It extends from the Pomarão Anticline (west termination of the Puebla de Guzman Anticline in Spain) through the Neves Corvo-Rosário Antiform to the Lousal region (Figure 1). The stratigraphic successions of the Neves Corvo mine and the Pomarão Anticline are chosen as examples for discussion (Figure 7).

Figure 7. Stratigraphic columns



Stratigraphic columns of selected structures of the South Branch of the Pyrite Belt.

Neves Corvo

All the lithostratigraphic units recognised in Neves Corvo were palynologically dated which allowed the establishment of the local chronostratigraphic column (Oliveira et al., 2004). On the contrary, the ages of the well defined lithostratigraphic units of the Pomarão Anticline (Boogaard, 1969, Oliveira and Silva, 1990) are still poorly known. Recent palynological research led only to the dating of the upper shales of the Nascedios Formation from where an assemblage of the early Strunian LL Biozone, has been recovered. Limestone lenses and nodules interbedded in the lower part of this unit provided conodonts of middle Famennian age (Boogaard, 1963).

Using the Neves Corvo stratigraphic column as a reference and having in mind the existence of lithological similarities, it seems appropriate to make stratigraphic correlations with the succession of the Pomarão Anticline. These correlations suggest similar depositional settings and tectonostratigraphic reconstructions led Oliveira et al., 2004 to conclude that both regions once belonged to a NW-SE oriented half graben.

It is hopped that research in progress, in Pomarão and other structures, as for instance in Lousal region, will permit the establishment of more stratigraphic correlations across this branch and also the north branch, in order to better understand the paleogeographic and geodynamic evolution of the belt.

Physical Volcanism

Recent physical volcanology studies at Albernoa, Neves Corvo and Serra Branca, allow the reconstruction of the volcanic and sedimentary facies architecture, bringing new advances to the comprehension of the style of volcanism and mode of emplacement of the felsic volcanic rocks.

Reconstruction of the volcanic and sedimentary facies architecture was based on detailed logging on traverses along creeks, rivers and roads with continuous outcrop exposures, or using data from drill-core. In both cases, textural examination of polished slabs and thin sections complemented the study. Original primary volcanic textures are well preserved in areas where the regional and hydrothermal alteration is minimal and away from the strongly cleaved intervals near thrust faults that disrupt the stratigraphic succession.

The volcanic facies are directly related with volcanic activity or contain elements derived from volcanic activity. These facies are all part of the VSC and include primary volcanic facies, syn-eruptive facies, syn-eruptive resedimented volcaniclastic facies and post-eruptive resedimented volcanogenic facies (McPhie et al., 1993). The non-volcanic facies enclose the volcanic facies and consist mostly of mudstone, in some places containing thin intervals of chemical sediments, such as red jaspers and chert.

In Albernoa area, rhyodacitic coherent facies are subordinate in volume to their autoclastic equivalents, showing gradational contacts with in situ, clast-rotated and redeposited hyaloclastite. Volcanogenic sedimentary facies characterized by thinly, bedded crystal-rich sandstone and mudstone overlie these primary volcanic facies. Along their contact, there is a sediment-matrix volcanic breccia, which could easily be misinterpreted as peperite. The sedimentary component of this breccia is laminated to thinly bedded parallel to the regional bedding. The proportion of the sedimentary component in the breccia increases upwards and passes gradationally to the overlying sedimentary interval with no change of the bedding orientation. We conclude that the breccia was formed by infiltration of sediment into the clast-supported framework of hyaloclastite at the margins of an intrabasinal felsic lava or dome (Rosa C. et al., 2004a).

The principal volcanic facies identified at the Neves Corvo mine are grouped into two facies associations: pumice-rich facies and coherent and monomictic rhyolite breccia facies (Rosa C. et al., 2004b).

The pumice-rich facies association is composed mostly by two pumice breccia units, characterised by lithic-rich coarse bases grading to massive or diffusely stratified intermediate zones and thinly laminated pumiceous mudstone tops. They are interpreted to be deposits from submarine, pumice-rich gravity flows generated by explosive eruptions. Abundant quartz-phyric pumice clasts are preserved in these units. Proximal facies characterised by thick and coarse intervals occur in the south, whereas thinner and finer grained more distal equivalents occur in the central and northern parts of the area. The pumice breccias probably correspond to syn-eruptive pyroclastic deposits. The source vent(s) has not been located but the dominance of lapilli-size pumice and the relatively good hydraulic sorting could indicate that the vent(s) was submarine.

The succession also includes submarine felsic domes or lavas, consisting of massive and flow-banded coherent interiors grading to jigsaw-fit and clast-rotated external zones. Perlitic clasts with planar and curviplanar margins suggest that quenching and autobrecciation were the dominant fragmentation mechanisms. The gradation to overlying sedimentary facies suggests that the rhyolites were extrusive. This facies association corresponds to a near vent setting. The volcanic succession of Neves Corvo also includes a thin clastic interval of rhyodacite that occurs only locally and stratigraphically above the rhyolite facies association. The clast shapes suggest that quenching was the dominant fracturing mechanism.

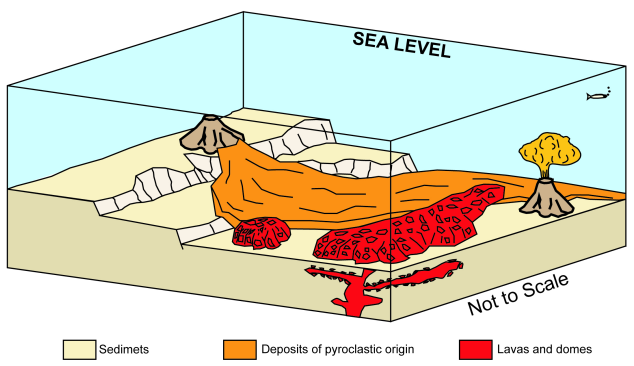
Integration of the volcanic facies associations in the Neves Corvo stratigraphy defined by Oliveira et al., (2004), indicates that the pumice-rich facies association is of late

Famennian age and the rhyolite facies association is of late Strunian age. The rhyodacite age is undetermined but its stratigraphic position suggests that it may correspond to the early Viséan volcanic event reported by Oliveira et al., (2004).

The volcanic sequence at Serra Branca is characterised by a more complex association of facies. Several deposits of pyroclastic origin with rhyolitic composition occur intercalated with thick rhyodacitic lavas. This association representing alternation of effusive and explosive eruptions is disrupted by several small cryptodomes and partly extrusive cryptodomes of rhyolitic composition.

The study areas in the Portuguese part of the Pyrite Belt reveal thick deposits composed of pyroclasts and intrabasinal lavas or domes affected by intense autobrecciation and quench fragmentation (Figure 8). The dominance of lapilli-size pumice in the pumice rich deposits suggests that the source vent was submarine. The rhyolite and rhyodacite facies are constituted by intrabasinal proximal to vent associations.

Figure 8. Simplified schematic representation of the IPB volcanism.



Simplified schematic representation of the IPB volcanism.

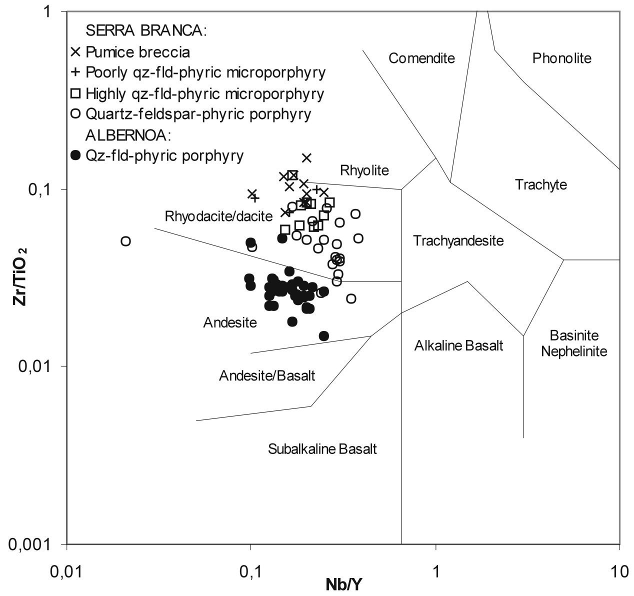
Igneous Geochemistry

The IPB volcanism displays a bimodal distribution with no significant amounts of intermediate rocks and felsic rocks predominating over mafic rocks (Mitjavilla et al., 1997; Munhá, 1983). As shown by Rosa, D. et al., (2004), most intermediate compositions are apparent and reflect silica and alkali mobility and subsequent compositional scatter on major element diagrams. This silica and alkali mobility was focused along fracture networks and within the matrices of hyaloclastic breccias. This is significant for the geotectonic classification of the volcanism, as arc settings are typically dominated by intermediate rocks (andesites), while volcanism generated in extensional settings is generally bimodal.

The felsic rocks present are of calcalkaline affinity. They are represented by pumice-rich facies and coherent or brecciated porphyritic facies. In some areas, only the porphyritic facies has been identified (Albernoa area), whereas in the areas where both facies are present, porphyritic facies can erupt after the pumice-rich facies (Neves-Corvo) or the two facies can alternate (Serra Branca). The felsic rocks have phenocryst populations and compositions corresponding from rhyodacitic to rhyolitic compositions. This is confirmed through their modal classification on QAP space (Streckeisen, 1978). The narrow range of compositions results from some fractional crystallization, namely of feldspar, as indicated by progressive increase in the whole-rock negative Eu anomaly with fractionation.

The high-field-strength elements (HFSE) systematics of the IPB felsic rocks is variable and their use for the classification of the IPB tectonic setting needs to be carefully addressed. Studies of felsic rocks from Albernoa have shown that these rocks are misclassified when plotted on the Winchester and Floyd (1977) diagram, where they plot as andesites (Figure 9). However, at Serra Branca (Figure 9), the Winchester and Floyd (1977) diagram provides consistent results. The problematic classification of the Albernoa samples is partially caused by their relatively high Ti contents. However, according to Rosa, D. et al (2004), it is also due to their anomalously low Zr contents. In fact, other HFSE are anomalously low at this location. The anomalously low HFSE contents are possibly caused by a decreased solubility of the refractory phases in which these elements reside, during low temperature crustal fusion. This same process has been suggested by Piercey et al. (2001) and Lentz (1999) for felsic rocks from the Finlayson Lake District, Yukon, and Bathurst, New Brunswick, respectively.

Figure 9. Discrimination diagram



Winchester and Floyd (1977) discrimination diagram, displaying the (mis)classification of felsic rocks from Albernoa and Serra Branca.

Crustal Fusion

Rosa, D. et al (2005) looked into the temperature conditions for crustal fusion, determining zircon and monazite saturation temperatures (Watson and Harrison, 1983; Montel, 1993) for one area with anomalously low and one area with normal HFSE contents; Albernoa and Serra Branca, respectively. The zircon and monazite saturation temperatures generally display good agreement between them, confirming their reliability. Outliers, which depart from the TZr=TLREE line, are accounted for by considering that they correspond to samples with significant amounts of inherited zircon and/or monazite, or for which not enough time elapsed for REE saturation before melt extraction. The obtained temperatures are interpreted as being maximum temperatures of crustal fusion and, since there is only limited fractionation, they also provide an upper limit to the emplacement temperature. The zircon thermometer indicates temperatures for the magmas that yielded the porphyritic rocks averaging approximately 780ºC at Albernoa and 820ºC at Serra Branca. At Serra Branca, another magma, which generated the pumice-rich facies, was emplaced at approximately 770ºC, as indicated by the zircon saturation temperature (Rosa, D. et al., 2005).

The zircon and monazite saturation temperatures indicate that magmas at the studied sites were generated at different temperatures, which has exploration implications. At Serra Branca, two different magmas were emplaced, one at a significantly higher and the other at a slightly lower temperature than the temperature recorded at Albernoa. Higher magma temperatures may help develop and sustain hydrothermal convection cells and be a prerequisite for the generation of VMS deposits. Also, in this geological setting, higher temperature fusion occurs under lower pressures, i.e., under shallower conditions, again favoring hydrothermal circulation and VMS formation (Hart et al, 2004). This may explain why Albernoa appears to be barren, while Serra Branca has a gossan, despite sub-economic (Rosa, D. et al, 2005).

If the HFSE concentrations can be anomalously low, the geotectonic settings indicated by diagrams that use these elements, such as the tectonic diagrams of Pearce et al. (1984), should be considered carefully. As pointed out by Rosa, D. et al. (2004), apparent arc signatures in Albernoa samples are the result of low temperature crustal fusion. In fact, considering that Ta, Nb, Yb and Y, similarly to Zr, would have been two or three times more concentrated if fusion had occurred under higher temperature conditions, the studied rocks would plot within or close to the within-plate granites field, instead of the volcanic-arc granites field (Rosa et al, 2004). This is compatible with models invoking partial melting of crustal rocks as a source of silicic magmas in the IPB, proposed by Munhá (1983), Mitjavila et al. (1997) and Thiéblemont et al. (1998).

In the IPB, the mafic rocks are basaltic dykes and flows of tholeiitic and, rarely, alkaline affinity. In the Nb-Zr-Y (Meschede, 1986) and Th-Ta-Hf (Wood, 1980) diagrams, the tholeiitic samples plot in or very close to the VAB field, while the alkaline samples plot as WPB (Rosa et al, 2004). Similarly, in the Zr-Y-Ti (Pearce and Cann, 1973) diagram, in which only tholeiitic rocks can be plotted, the samples plot on or very close to the VAB field (Rosa et al, 2004). However, these tholeiitic samples plot within the MORB +FB field and not on the island-arc field of the Shervais' (1982) Ti-V diagram, considered to be less sensitive to crustal interaction (Pearce, 1996). This is an indication that the Th enrichment and coupled Nb depletion, evident in the Nb-Zr-Y and Th-Ta-Hf diagrams, likely result from the assimilation of continental crust rather than from a true subduction component (Pearce, 1996). Similarly, the Ti and Y depletion in the Zr-Y-Ti diagram is probably due to the magma interaction with relatively Ti- and Y-poor and Zr-rich continental crust. It is not completely clear what the original magma type would have been before assimilation of such continental crust and the described acquisition of an apparent arc signature. Yet the original magma may have had a MORB source, as Mitjavila et al. (1997) argue; a WPB source, in which case it could be represented by the alkaline basalts; or may have had a transitional source between the two.

The developed bimodal volcanism, with possible WPB/MORB transitions and superimposed crustal assimilation is characteristic of magmatism in attenuated continental lithosphere settings, such as the magmatism developed in continental crust by local extensional tectonics. This is compatible with the model proposed by Silva et al. (1990), Quesada (1991) and Solomon and Quesada (2003). In this model, an oblique collision between the South Portuguese and the Ossa Morena plates favoured strike-slip tectonics within the continental crust of the South Portuguese plate. The strike-slip tectonics would have favoured the opening of pull-apart basins where mantle upwelling and subsequent high heat flow would lead to volcanism with the characteristics described above. A similar conclusion was drawn by Mitjavila et al. (1997), who in addition to general geochemical data, also presented isotope data.

Structural Implications

The palynostratigaphic data, although still scarce, allow some considerations on the age of the volcanism and the structural development.

In the north branch of the belt, the felsic and mafic volcanism appears to be mostly of late Famennian age, at least in the studied antiforms, while the mafic intrusions, although with an uncertain age may be younger, possibly emplaced in a post Strunian age. This would suggest that the volcanism has been originated in similar geodynamic conditions (along the same crustal tectonic lineament ?). In the south branch volcanic episodes can reach younger ages even the early Late Viséan. Does this mean that volcanism progressed southward in time, as suggested by Oliveira, 1990 (?). Further research is still needed to reach a definitive conclusion.

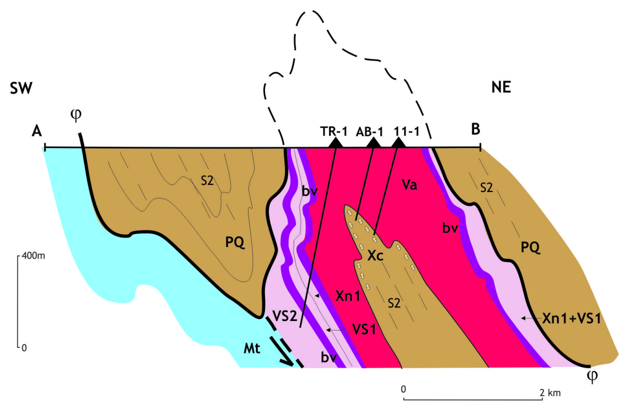
The structure of the Albernoa Antiform is schematically depicted in Figure 10. It shows the lithologies of the PQ Group and the VSC in conformable stratigraphic order, thrusted by shales, quartzites and quarzwackes ascribed to the PQ Group. The thrust was generated during the first NE-SW compressional episode of latest Viséan age and later refolded in the same sense during the Upper Carboniferous (post Moscovian) time.

The Serra Branca Antiform shows a similar tectonic style with the VSC conformably overlain by the Freixial Fm. and the latter thrusted by the PQ Group and VSC lithologies (Figure 11).

The structure of the Mina de São Domingos Antiform has, in general, the same tectonic style. However, in detail it is complex and the existing data preclude, for the moment, any definitive structural interpretation.

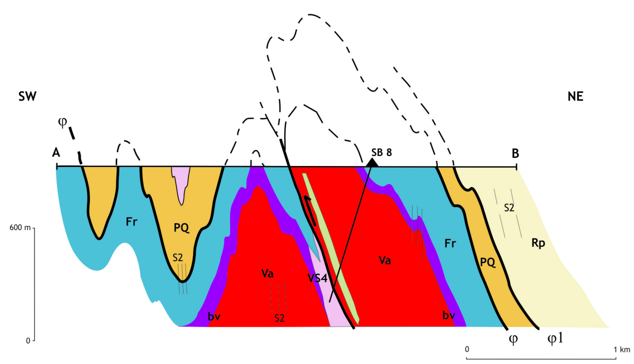
These structural interpretations, now supported by palynostratigraphic age determinations, confirm previous tectonic modelling for the Portuguese part of the Pyrite Belt (Ribeiro et al., 1983; Oliveira, coordinator 1988; Silva et al., 1990; Oliveira and Silva 1990).

Figure 10. Tectonic structure



Tectonic structure of the Albernoa Antiform (schematic).

Figure 11. Tectonic structure



Tectonic structure of the Serra Branca Antiform (schematic).

Conclusions

Undergoing research dealing with palynostratigraphy and magmatism (physical volcanology and geochemistry) provided new insights to the Portuguese part of the Iberian Pyrite Belt geology. These are particularly relevant for the stratigraphic, magmatic and structural knowledge. The work was concentrated on the Albernoa, Serra Branca and Mina de São Domingos antiforms that belong to the so-called north branch (Oliveira, 1990) and geological comparisons are made with the better understood structures of Pomarão and Neves Corvo mine.

Felsic and mafic volcanic episodes are intercalated in fine terrigenous and volcanogenic sediments. Purple shales, usually used as marker beds for mapping purposes appear having distinct stratigraphic positions and ages in the VSC. The volcanic episodes are restricted to the late Famennian in the north branch, while in the south branch they have younger ages reaching the late Viséan. Dolerites are intrusive at several levels in the stratigraphic sequence of both branches. At a first glance, it seems that the volcanism progressed southward in time, as already suggested by Oliveira, 1990. However, owing to the still scarce existing ages, this conclusion must be seen has preliminary.

In terms of physical volcanism, research was mostly concentrated in the felsic rocks. The Albernoa volcanic sequence consists of rhyodacitic lavas or domes represented by coherent and their autoclastic equivalents, grading upwards to bedded volcanogenic sediments. The age of this volcanism is placed between the early and the late Famennian.

At the Neves Corvo mine region three distinct volcanic facies associations, with intrabasinal and near vent characteristics, constitute the VSC. The pumice-rich facies constitute the V1 felsic volcanic episode of late Famennian age while the rhyolitic coherent and autoclastic facies correspond to the V2 felsic episode of Strunian age. Autoclastic rhyodacitic facies may correspond to the V3 volcanic episode.

The volcanic architecture at Serra Branca is composed of rhyodacitic lavas intercalated with deposits containing abundant pyroclasts and relatively small cryptodomes and partly extrusive cryptodomes. The dates obtained for the enclosing sedimentary facies suggest a similar age for this and the Albernoa volcanic successions.

In the Mina de São Domingos antiform the felsic volcanism has not been studied in detail. Nevertheless indications from one borehole and several outcrops suggest that rhyolitic autoclastic facies and volcaniclastic rocks deposited by gravity flows dominate the sequence. Late Famennian ages have been determined.

The more recent lithogeochemistry results supports a geotectonic setting for the IPB involving extension and not subduction, with apparent arc signatures in mafic rocks being caused by crustal assimilation and apparent arc signatures in felsic rocks being, partially at least, caused by anomalous HFSE systematics. Furthermore, studies into the causes for the anomalously low HFSE contents of felsic rocks has confirmed that they are caused by relatively low temperatures of crustal fusion. Additionally, the temperatures of crustal fusion, indicated by zircon and monazite solubility models, may have exploration implications in this world-class VMS province.

Lithostratigraphic units identified in the studied boreholes and their ages, together with outcrop data confirm that the antiforms of Albernoa and Serra Branca are true tectonic windows where the VSC stratigraphic succession is truncated by overthrust nappes. These were generated during a first NE-SW compressional episode of latest Viséan age, refolded in the same sense in the Upper Carboniferous (late Moscovian). The Mina de São Domingos antiform has the same style of tectonic deformation but shows in detail structural complications which are still under investigation.

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