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ARTICLE

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Stratigraphy of the tectonically imbricated lithological succession of the Neves Corvo mine area, Iberian Pyrite Belt, Portugal

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Abstract Biostratigraphic research, based on palynomorphs and ammonoids, of the tectonically imbricated lithological succession of the Neves Corvo mine, in the Portuguese part of the Iberian Pyrite Belt, has yielded ages for all formerly recognised lithostratigraphic units. These can be assembled in three main lithological sequences: (1) detrital sandy/shale substrate (Phyllite-Quartzite Formation) of late Famennian age; (2) Volcano-Sedimentary Complex, divided into a lower and an upper suite, in which one basic, three dolerite sills and four felsic volcanic units and a mineralised package of massive sulphides are identified with ages which range from the late Famennian to the late Visean; (3) flysch succession (Mértola Formation) composed of shale and greywacke dated as late Visean to early Serpukhovian. Precise biostratigraphic dating of the sedimentrary host rocks of massive sulphide mineralisation constrains the age of the latter to the late Strunian (354.8–354.0 Ma). Three stratigraphic hiatuses, corresponding to early/middle Strunian, Tournaisian and early Visean respectively and a south-westward progressive unconformity were also recognised. Sequences 1 and 2 are related to extensional episodes while sequence 3 marks the beginning of compressive tectonic inversion which gave rise to south-westward flysch progradation in close relation to a foreland basin development. Our results lead to the reinterpretation of the tectonic structure of the Neves Corvo mine, with implications for the interpretation of the regional basin dynamics and metal exploration.

Keywords Palynostratigraphy · Neves Corvo mine · Iberian Pyrite Belt · Portugal

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Introduction

The Neves Corvo massive sulphide deposit is located at the south-eastern termination of the Rosario Antiform in the Portuguese part of the Iberian Pyrite Belt (Fig. 1) and was discovered in 1977 (Leca et al. 1983). The local stratigraphy of the Volcano-Sedimentary Complex (VS), which hosts the massive sulphide mineralisation, was first described by Albouy et al. (1981) and consists of a lower unit of felsic volcanic rocks (tuffs) overlain by black shale and the massive sulphide orebody, a succession of shale and greywacke followed by alternating dark and purple shale, felsic tuffites, and shale and greywacke (Culm type) on top. All these units were considered stratigraphically concordant but no age was ascribed to them. Leca et al. (1983) were the first to recognise the tectonic imbrication of the lithological succession, in which the intercalated shales and greywackes appear to divide the VS Complex into two distinct lithostratigraphic components, later renamed the Upper and Lower sequences of the VS Complex (Carvalho and Ferreira 1994; Carvalho et al. 1997). The age of the lithostratigraphic sequence was still poorly defined and mostly based on lithological comparisons with other regions of the Iberian Pyrite Belt, a method which was subject to many uncertainties and controversies.

Preliminary results of biostratigraphic research based on palynomorphs and ammonoids have finally permitted the age determination of all the imbricate litho-

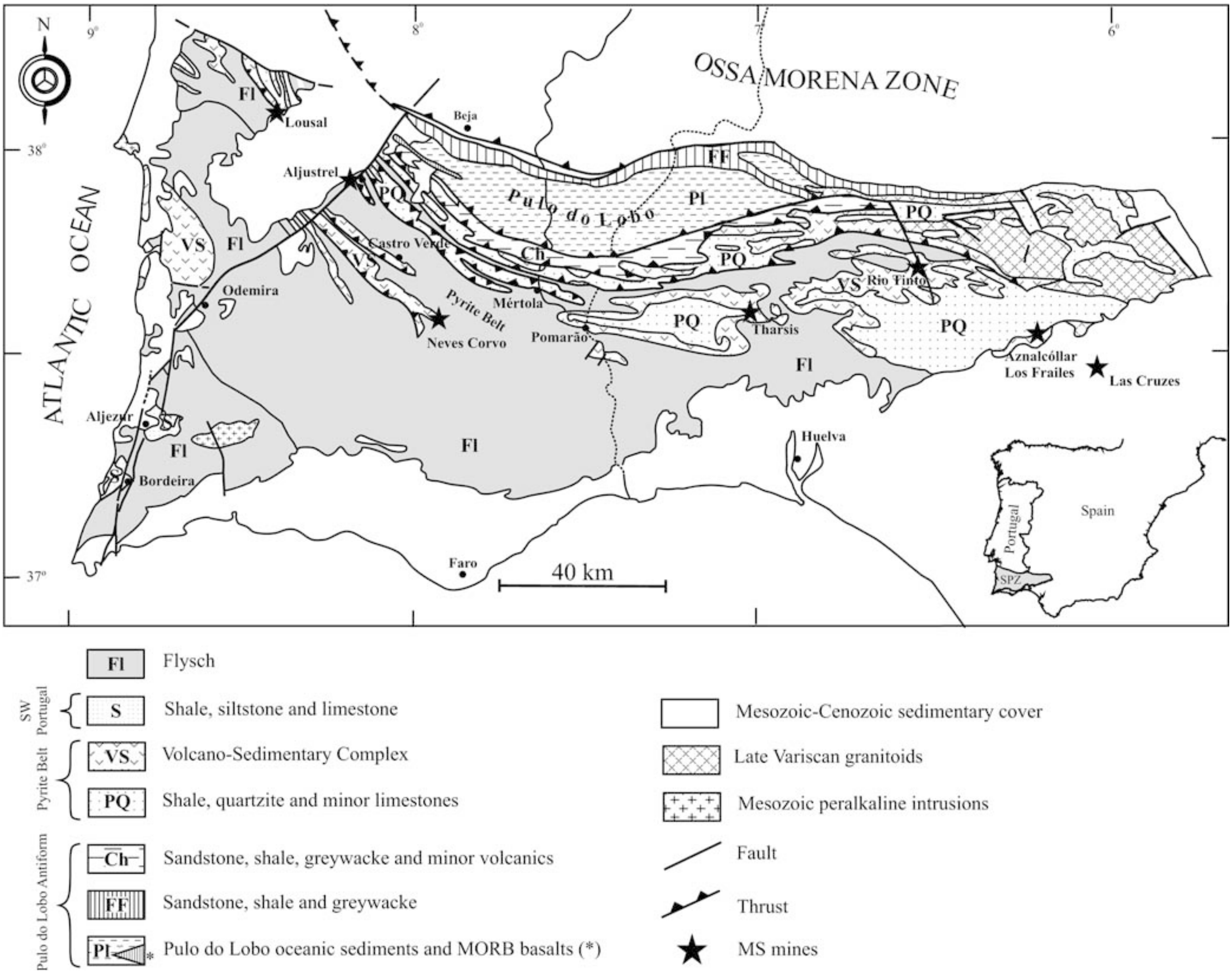


Fig. 1 Geological sketch map of the Iberian Pyrite Belt (adapted from Oliveira 1990and Leistel et al. 1998)

stratigraphic units recognised in the mine (Oliveira et al. 1997a, 1997b; Fig. 2).

Besides the description of the lithostratigraphic units and their ages determined by palynomorphs and ammonoids, the present work focuses on the chronostratigraphy distilled from the imbricate lithological succession, the age of the mineralisation and the tectonostratigraphic development of the mine area in the light of the regional basin dynamics (Oliveira 1990; Silva et al. 1990; Soriano and Casas 2002).

Methods

The stratigraphic sequence of the Neves Corvo mine area was investigated by examination and sampling of 39 boreholes (700 samples). The lithostratigraphic units were already logged by mine geologists.

Biostratigraphic research was based on palynomorphs which were studied using standard palynological laboratory procedures for their extraction and concentration from the host sediments. The resultant residues were mounted as strew slides, under cover slips, using elvacite/cellosize. The slides were examined in transmitted light by a BX40 Olympus microscope equipped with an automatic 35-mm camera. All samples, residues and slides are stored in the Instituto Geológico e Mineiro, S. Mamede Infesta, Portugal.

The miospore zonal scheme used follows the Western Europe Zonation (after Clayton et al. 1977; Streel et al. 1987; Higgs et al. 1988; Clayton 1996; Maziane et al. 2002). For the Upper Devonian, the *flexuosa*-*cornuta* and *fructicosa*-*pusillites* biozones of Richardson and McGregor (1986), modified after Richardson and Ahmed (1988), were used due to the lack of the most important guide species which mark the base of the Streel et al. (1987) and Maziane et al. (2002) zonation (*Apiculatiretusispora verrucosa* and *Vallatisporites hystricosus*).

To complement the palynological study, several ammonoid specimens recovered from productive boreholes and at the surface, near the mine shaft, were determined (Korn 1997).

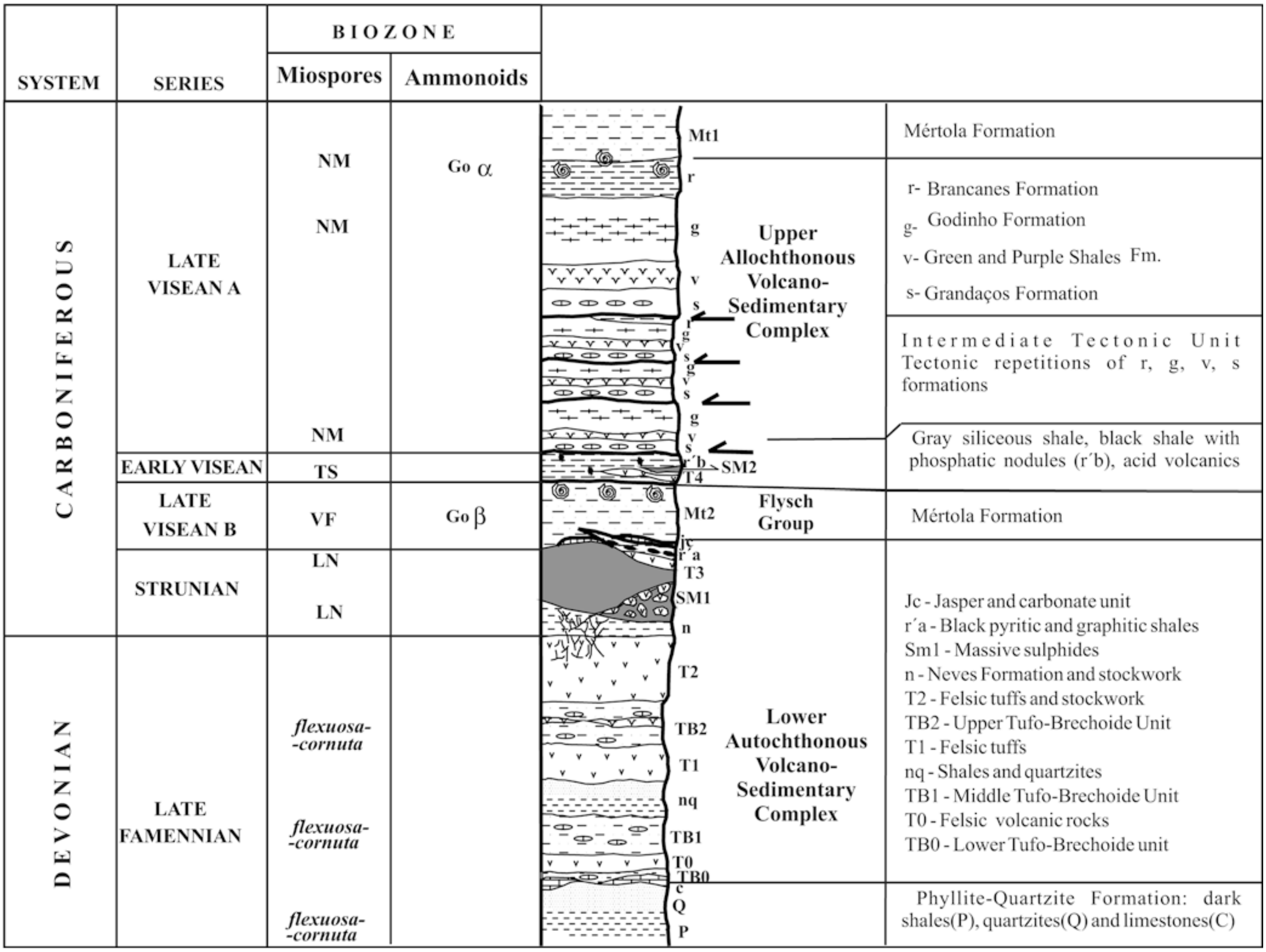


Fig. 2 Tectono-stratigraphic sequence of the Neves Corvo mine area (Oliveira et al. 1997a, 1997b)

The results are discussed in terms of three main cross sections (Fig. 3), selected to include the main boreholes examined and corresponding localisation of the positive palynological samples. These are the Graça–Corvo (Fig. 4), the Lombador (Fig. 5) and the Lombador–PM 2 (Fig. 6) sections, which together illustrate well the existing lithostratigraphic units and their complex geometric relationships. Reference is also made to other palynological productive boreholes not shown in these sections.

The description of the lithostratigraphic units follows in general terms the terminology used by mine geologists, as shown in Fig. 2. However, the nomenclature of some of these units appears confusing (i.e. "Tufo-Brechoide" units, etc.) and in the present work new terms are proposed (Table 1).

All units are affected by the Variscan deformation expressed by syn-orogenic NW-trending and SW-verging folds with associated cleavage and thrusting, and late orogenic NE-trending faults. Due to this deformation, most of the units represented in Figs. 4, 5 and 6 are probably modified with regard to thickness.

Stratigraphic sequence

The following units are currently identified, from base to top.

Phyllite-Quartzite Formation (PQ)

This is the lowermost unit recognised in the mine area, where it has also been termed as the Lançadoiras Quartzites (Boogaard and Schermerhorn 1981). It is composed of dark shale with intercalations of thin-bedded siltstone and quartzite with a total thickness in excess of 100 m (base not reached). These characteristics are comparable to those of the widespread Phyllite-Quartzite Formation of the Phyllite-Quartzite Group (Schermerhorn 1971) which is known across the Iberian Pyrite Belt.

At the top of the PQ Formation, which marks the transition to the Lower VS Complex (see below), limestone lenses up to few metres thick occur interbedded in shale (boreholes SE22', SD6, SD10, SJ17; Fig. 4). Limestone lenses also outcrop underlying Monte Forno da Cal basic and intermediate volcanics (Fig. 3).

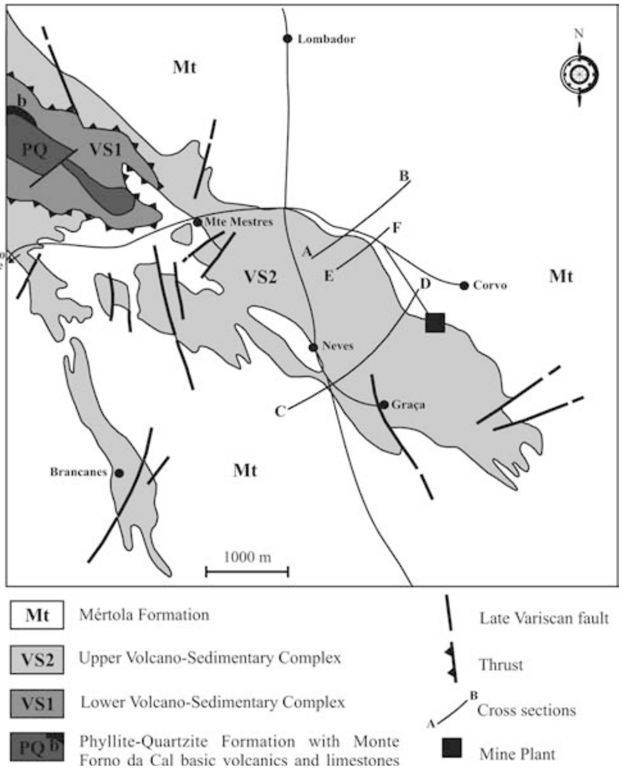


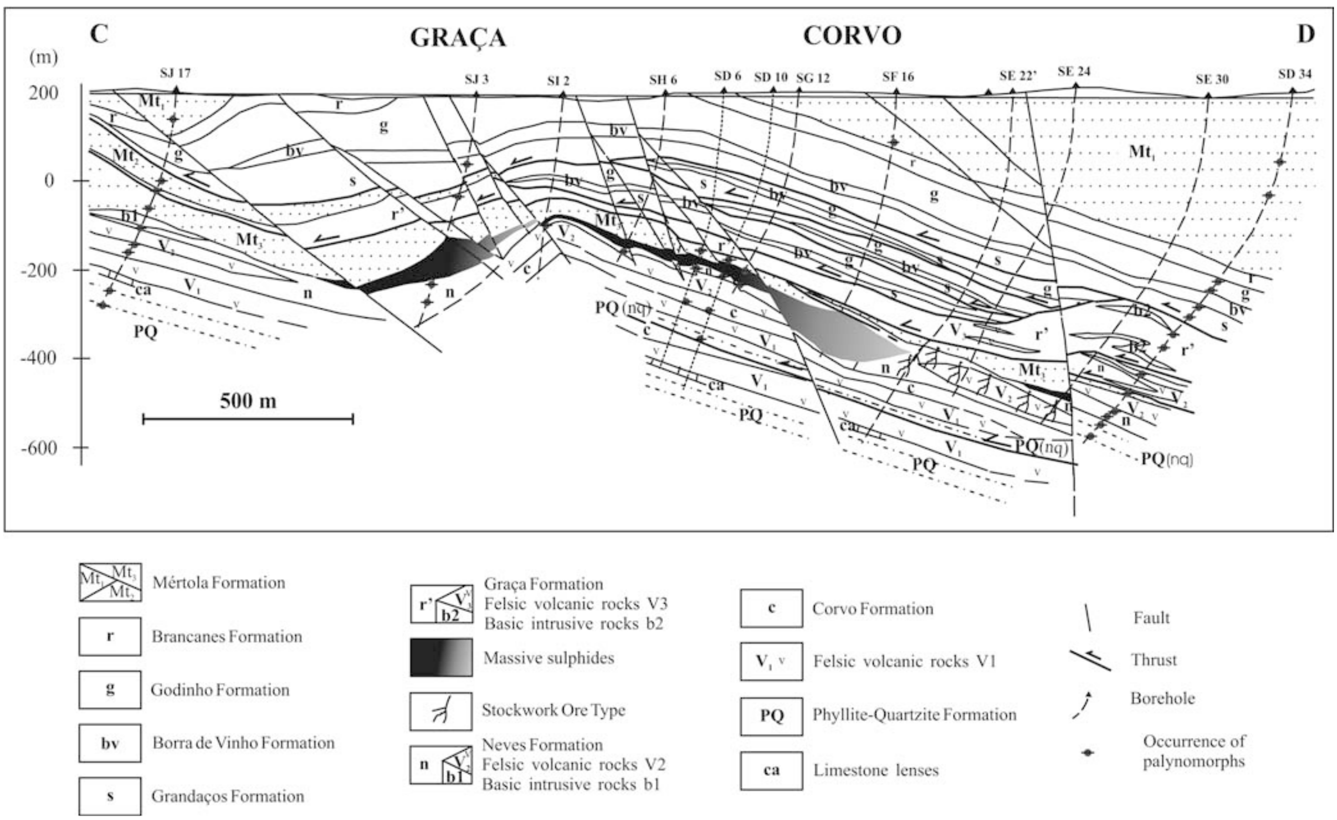
Fig. 3 Detailed geological map of the Neves Corvo mine area (modified from Leca et al. 1983)

Fig. 4 Graça–Corvo cross section (adapted from Carvalho and Ferreira 1994 and Oliveira et al. 1997a, 1997b)

Palynological assemblages recovered from dark shales of the PQ Formation in boreholes SJ17, SD6, SD10 and SD34 of the Graça–Corvo cross section (Fig. 4) are assigned to the *flexuosa-cornuta* Biozone of late Famennian age. The assemblages include abundant species of *Rugospora flexuosa* (Fig. 7a) together with *Emphanisporites annulatus*, *Grandispora echinata* and *G. cornuta* (Fig. 7b). The same miospore assemblages were found in other boreholes not shown in the sections, namely NI18 near the Lombador cross section, SRC744 (Corvo underground) and CA1 (Algaré area, 3 km NW of the Neves Corvo mine). Reworked Givetian and Frasnian spores (*Contagisporites optivus*, *Cristatisporites triangulatus*, *Geminospora lemurata* and *Verrucosisporites premnus*) are well represented in all samples studied.

The limestone lenses intersected by boreholes were not biostratigraphically studied. However, those from Monte Forno da Cal yielded conodonts of the *marginifera* Biozone which indicates a middle Famennian age (Boogard and Schermerhorn 1981). Similar limestone lenses at the same stratigraphic position are quite common in the Iberian Pyrite Belt.

Up to some 75-m-thick beds of shale and thin quartzite occur intercalated in the Lower VS Complex, and were labelled by mine geologists as the "nq" unit (Figs. 2and 4). Palynomorph assemblages recovered from these shales (boreholes SD6, SD10, Fig. 4), NF22 (Fig. 5) and also from boreholes not shown CA1 (Algaré), SO28 (Zambujal) and SRC744 (Corvo underground) are identical to those found within the PQ Formation, including remobilised Givetian and



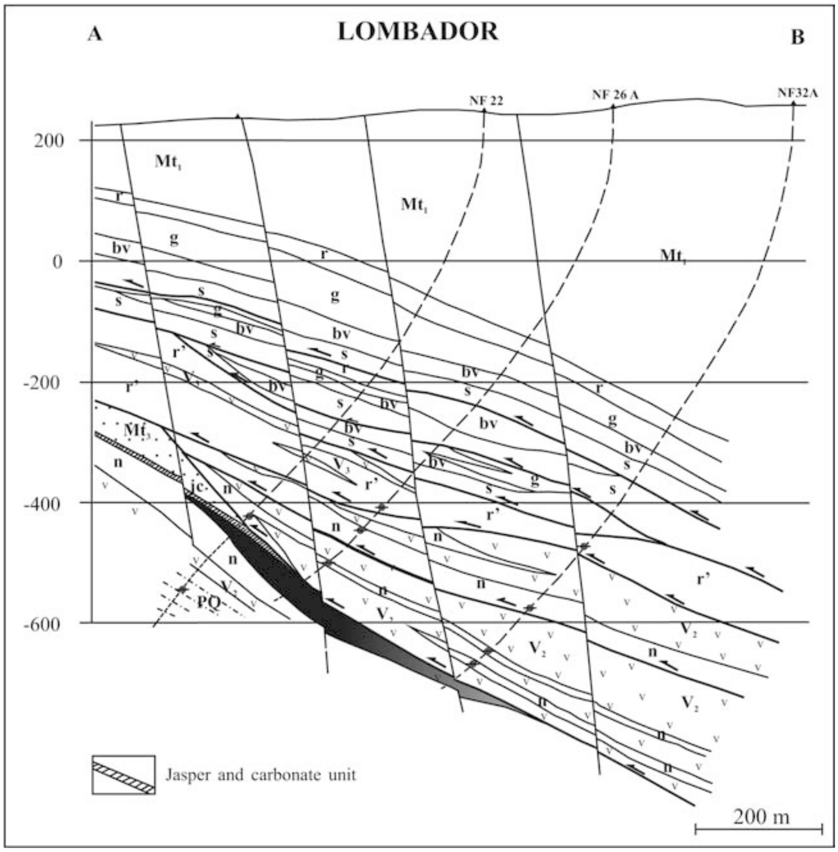


Fig. 5 Lombador cross section (adapted from Pacheco 1994 and Oliveira et al. 1997a, 1997b; symbols as in Fig. 4)

Frasnian spores. The ''nq'' unit is here interpreted as a slice of the PQ Formation, now intercalated in the VS complex due to thrusting (Fig. 4).

Volcano-Sedimentary Complex (VS)

For descriptive purposes this tectonically imbricated complex is here divided into two distinct lithological suites, the Lower and Upper VS Complex. The description of the volcanic rocks follows the traditional nomenclature. Discussion on the type and style of the volcanism emplacement is beyond the aim of this work.

Lower Volcano-Sedimentary Complex

This complex comprises the units formerly assembled in the autochthonous VS Complex (Fig. 2, Table 1) and is well represented at depth, particularly below the Graça and Corvo orebodies where it is unconformably overlain by the Mértola Formation (Fig. 4). It also crops out near Monte Forno da Cal (Fig. 3) in the core of the antiformal structure. The following units have been identified, from bottom to top.

Basic and intermediate volcanic rocks (b)

They are represented by the Monte Forno da Cal spilitic lavas, tuffs, breccias and dolerites (Boogaard and Schermerhorn 1981; Fig. 3). Some of the spilitic lavas and tuffs have an intermediate composition (Leca et al. 1983; Munhá 1983). As these rocks crop out close but

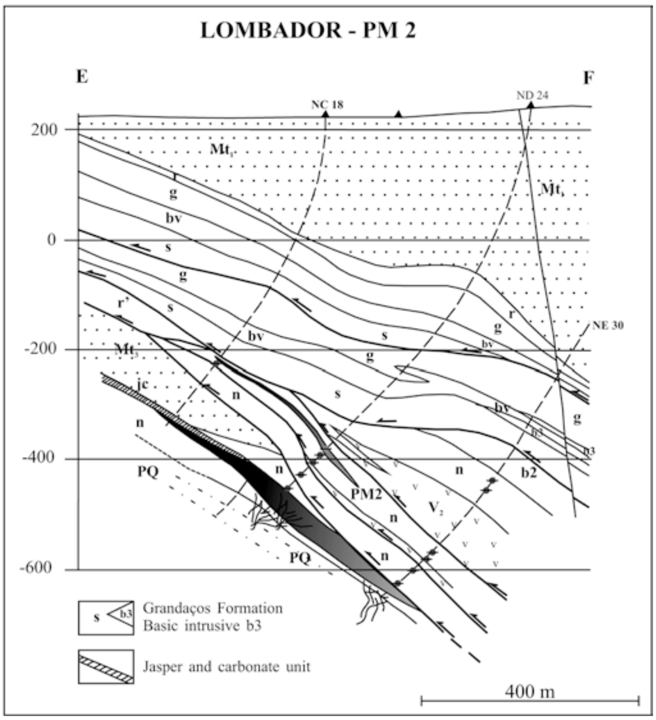


Fig. 6 Lombador–PM 2 cross section (adapted from Pacheco 1994; symbols as in Fig. 4)

Table 1 Nomenclature of the lithostratigraphic units

Oliveira et al. (1997a, 1997b)	Present work
Brancanes Fm (r)	Brancanes Fm (r)
Godinho Fm (g)	Godinho Fm (g)
Grandaços Fm (s)	Grandaços Fm (s)
Gray and black shales with phosphatic nodules (r')	Graça Fm (r')
T4 acidic volcanics	V_3 felsic volcanic rocks
Mértola Fm (Mt)	Mértola Fm (Mt)
Jaspers, carbonates and shales (jc)	Jaspers and carbonates unit (jc)
Neves Fm (n)	Neves Fm (n)
T2, T3 acidic volcanics	V_2 felsic volcanic rocks
Dark shales and quartzites (nq)	Phyllite-Quartzite Fm (PQ)
T0, T1 acidic volcanics	V_1 felsic volcanic rocks
TB0, TB1, TB2: "tufo-brechoide" units"	Corvo Fm (c)
Limestones with conodonts (c)	Limestone lenses (ca)
Phyllite-Quartzite Group (PQ)	Phyllite-Quartzite Formation (PQ)

stratigraphically above the limestone lenses mentioned above, they are presumably of middle to late Famennian age.

Strongly altered mafic rocks (dolerites?) also occur at depth, above the V_2 felsic volcanic unit dated as late Famennian (unit b1, borehole SJ17, Fig. 4). Dolerite sills are quite widespread in the Iberian Pyrite Belt, usually in close association to the mafic volcanism.

Felsic volcanic rocks (V_1)

These comprise mostly rhyolitic lavas, marginal quenched-fragmented hyaloclastites and "tuffs" resulting from re-sedimentation of hyaloclastites (Munhá et al. 1997), with a total thickness which can reach 100 m. They correspond to the former T0 and T1 units (Fig. 2, Table 1).

This volcanic unit is conformably interbedded between the PQ Formation and the Corvo Formation (see below). Since both units provided spores of late Famennian age, the V1 volcanic unit must be also of this age.

Corvo Formation (c)

This unit, around 40 m thick, is made up of dark grey and black shale with intercalations of carbonate nodules and locally small clasts of tuffites. The unit is tectonically repeated (Fig. 4) and corresponds to what has been described as "Tufo-Brechoide" units (TB1, TB2, TB3 in Fig. 2; Table 1). This old terminology is now abandoned because it could lead to misunderstandings, since no tuffs and breccias occur.

Shale from boreholes SD6 and SD10 yielded assemblages of spores assigned to the latest Famennian *fructicosa–pusillites* Biozone. These assemblages are characterised by the first occurrence of *Raistrickia variabilis* and *Vallatisporites pusillites*. Other taxa present are *Emphanisporites annulatus* and *Rugospora flexuosa*. Reworked Givetian and Frasnian spores and acritarchs (including *Stellinium micropolygonale*, *Navifusa bacillum*, *Multiplicisphaeridium ramispinosum*) and prasinophyte cysts (*Maranhites brasiliensis*, *M. mosesii*) are present.

Neves Formation (n)

Black pyritic shale and thin bedded siltstone are the dominant lithologies, which as a whole show variable thickness from few to around 100 m.

Shales recovered from many boreholes (Figs. 4, 5 and 6) yielded a very complete spore assemblage of the LN (*Lepidophita nitidus*) Biozone, including the key species *Retispora lepidophyta* (Fig. 7d) and *Vallatisporites verrucosus*(Fig. 7e) which indicates a late Strunian age. Acritarchs and prasynophyts are also very common, particularly the species *Gorgonisphaeridium solidum*, *M. mosesii*(Fig. 7f), *M. perplexus* (Fig. 7c), *Navifusa bacillum*, *Umbellasphaeridium saharicum*, *U. deflandrei*, and *Winwaloweusia ranulaeforma*. Reworked Givetian to Frasnian spores are present in the LN assemblages.

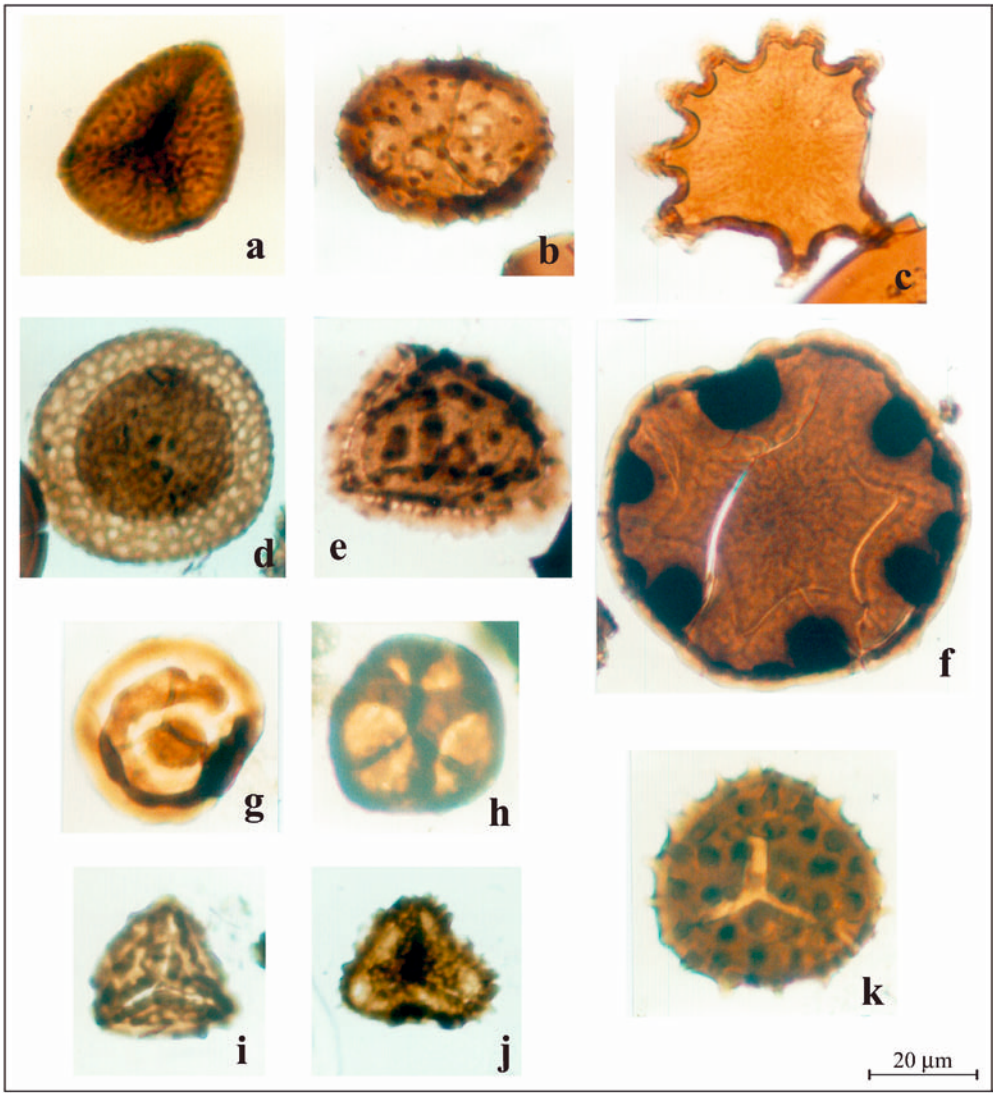
Felsic volcanic rocks (V_2)

This volcanic unit, around 100 m thick, is again mostly composed of rhyolite and tuff showing the same petrological and textural characteristics as those of the V_1 unit. These volcanics are interbedded or interfinger with the Neves Formation and are thus of late Strunian age. However, in the region below the Corvo and Graça orebodies, they rest unconformably on the Corvo Formation (Fig. 4).

Massive sulphides (ms)

Five main orebodies are identified in the mine area, namely Neves, Corvo, Graça, Lombador and Zambujal. They consist mostly of pyrite, chalcopyrite, sphalerite, cassiterite, tetraedrite/tennantite, galena, bornite and a large variety of accessory minerals. The ore paragenesis, zonality and tonnage have been well documented elsewhere (Albouy et al. 1981; Gaspar 1991; Oliveira et al. 1997a, 1997b; Pinto et al. 1997; Gaspar 2002). The

Fig. 7a–k Palynomorphs. Each specimen is referenced by collection number and sample number. Scale bar 20 µm, except for **f**, 40 µm.
a *Rugospora flexuosa* (Jushko) Streel 1974; IGM 0301; SD34, 914.6 m: 1410-85.
b *Grandispora cornuta* Higgs 1975; IGM 0302; SD34, 941.8 m: 1282-82. **c** *Maranhites perplexus* Wicander and Playford 1985; IGM 0314; SJ17, 388.1 m: 1225-50. **d** *Retispora lepidophyta* (Kedo) Playford 1976; IGM 0305; SJ17, 388.1 m: 1041-164. **e** *Vallatisporites verrucosus* Hacquebard 1957; IGM 0306; SJ17, 388.1 m: 1450-80. **f** *Maranhites mosesii* (Sommer) Brito 1967; IGM 0315; SJ17, 388,1 m: 1320-45.
g *Knoxisporites stephanephorus* Love 1960; IGM 0317; SO28, 472.5 m: 1473-68.
h *Knoxisporites triradiatus* Hoffmeister, Staplin and Malloy 1955; IGM 0316; SO28, 472.5 m: 1485-200.
i *Savitrisporites nux* (Butterworth and Williams) Smith and Butterworth 1967; IGM 0328; SQ14, 391.6 m: 1228-210. **j** *Bellispores nitidus* (Horst) Sullivan 1964; IGM 0330; SQ14, 391.6 m: 1050-146.
k *Raistrickia nigra* Love 1960; IGM 0325; SD34, 474.5 m: 1198-115



orebodies are interbedded with the black shale of the Neves Formation but are stratigraphically above the V_2 felsic volcanic rocks (Fig. 4).

At the top of the Corvo orebody occurs the so-called rubané ore, composed of thin alternations of massive sulphides and black pyritic and chloritic shales. The thin laminated black shale yielded the same spore assemblage as the Neves Formation. The rubanée mineralisation is thus of late Strunian age. Formerly considered as a distinct stratigraphic unit conformably overlying the massive sulphides (Albouy et al. 1981), it has also been interpreted as a thrust sheet derived from the orebody margin (Barriga et al. 1997; Relvas et al. 1997). The latter interpretation is supported by the present work.

Some 100 m above the Lombador orebody (section AB, Fig. 5), a new distinct massive sulphide occurrence has been identified, referred to by mine geologists as PM 2 (Fig. 6). This occurrence is again interbedded in black shales, in which felsic volcanics are also intercalated. The black shales yielded abundant palynomorphs of the LN Biozone, indicating a late Strunian age. Since the Lombador orebody and PM 2 occurrence are coeval, it is concluded that they were originally in close lateral continuity and that the latter was tectonically transported to its present position. The PM 2 cross section is also important because it shows massive sulphides and black shales of late Strunian age which are tectonically above the late Visean flysch succession of the Mértola Formation (Mt3 beds, Fig. 4). This conclusion may be of crucial importance for further massive sulphide exploration projects.

Jasper and carbonate unit (jc)

At the top of the Neves shales and also directly overlying the massive sulphides (Figs. 5 and 6) and/or the stockwork zone (Fig. 4), a unit a few metres thick, composed of jasper and carbonate (siderite, ankerite) associated with chloritic and sericitic shale, can be found. These chemical sediments appear to be intimately related to the hydrothermal activity (Mirão et al. 1997).

Upper Volcano-Sedimentary Complex

This sequence is well represented in drill cores and partially crops out at surface. It corresponds roughly to what was formerly integrated in the allochthonous VS Complex (Fig. 2, Table 1). From base to top the following units are recognised.

Graça Formation (r′)

This unit, only identified at depth, corresponds to what has been formerly described as "*shales with siliceous–phosphatic nodules*" (Albouy et al. 1981; Leca et al. 1983). It comprises grey siliceous shale and black shale, generally rich in organic matter and dispersed siliceous–phosphatic nodules. The unit is bounded by thrust faults or is unconformably overlain by the Mértola Formation (Mt2, see below), namely west of the Graça orebody (Fig. 4). Samples of shales collected from boreholes SD34 (Fig. 4), NF26A and NF32A (Fig. 5), as well as from boreholes SI31, SF50, MT2, MM3 and SO28 (not shown in figures) all provided spore assemblages containing the guide species *Knoxiporites triradiatus* (Fig. 7h) and *K. stephanephorus* (Fig. 7g) of the TS Biozone, indicating an early Visean age. Reworked Tournaisian palynomorphs (spores and acritarchs) are widespread.

Felsic volcanic rocks (V_3)

These are again mostly rhyolitic in composition and appear interbedded or interfingering with the Graça Shales (Figs. 4 and 5), with variable thickness, from a few up to 50 m. Their age is thus early Visean.

Basic intrusive rocks (b2, b3)

Again, these are strongly altered basic rocks, probably of doleritic composition. They occur at depth intercalated in the Graça Formation (boreholes SD34 and SE30, b2, Fig. 4) and in the Grandaços Formation (borehole NE30, b3, Fig. 6).

Grandaços Formation (s)

This unit has lithological affinities with the Graça Formation, the main difference being the occurrence of dispersed carbonate lenses and nodules instead of siliceous–phosphatic nodules This formation appears tectonically repeated but, at the upper part of the stratigraphic pile, it is conformably overlain by the "Borra de Vinho" Formation (Figs. 4, 5 and 6).

Black shales from the lowermost tectonic sheet (boreholes SD34, Fig. 4 and SO28, not shown) yielded spores ascribed to the NM (*nigra–marginatus*) Biozone, indicating an early late Visean age. The guide species *Raitrickia nigra* (Fig. 7k) is very common in the spore assemblages, together with the species *Savitrisporites nux* (Fig. 7i).

"Borra de Vinho" Formation (purple shales) (bv)

This is a typical formation of the upper part of the VS Complex, and is recognised practically over the entire Pyrite Belt under the name "purple shales". It is made up of interfingering purple and green shales and interbedded lenses and nodules of manganese oxides. The thickness varies from 10 to 40 m. The unit shows rounded white patches ascribed to radiolarians, not yet determined. No other fossils have been found. Deep in the studied sections, the unit is also tectonically repeated but at higher levels it conformably overlies the Grandaços Formation.

Godinho Formation (g)

This formation is made up of tuffites and grey siliceous shales, showing in places interbedded lenses of chert. The thickness varies from 50 to 100 m. Samples recovered from SO28 and SD34 drill cores yielded spores belonging to the NM (*nigra–marginatus*) Biozone of early late Visean age. This unit also appears tectonically repeated but, high in the sections, it conformably overlies the "Borra de Vinho" Formation.

Brancanes Formation (r)

This unit is composed of black shale rich in pyrite and organic matter, and thin layers of graded siltstones and fine greywackes, which mark the beginning of the turbidite sedimentation. The total thickness is of the order of 50 m. The formation crops out in several places around the mine plant where the transition to the overlying turbidites of the Mértola Formation (Mt1) appears gradual. Immediately north of the mine shaft, two faunal horizons in black shale, which are separated by 3 m of unfossiliferous shale, are recognised. The lower horizon yielded *Goniatites hudsoni* Bisat 1934 and *Pronorites*sp. nov., and the upper one *Goniatites*(?) *globostriatus* Schmidt 1925. These ammonoid faunas indicate a late Visean A age which confirms previous determinations (Oliveira and Wagner-Gentis 1983). No spores were recovered from this unit.

Mértola Formation (Mt1/Mt2/Mt3)

This unit, also termed as Culm (Schermerhorn 1971; Moreno and Vara 1985), is the lower unit of the Baixo Alentejo Flysch Group (Oliveira et al. 1979). The lithological succession comprises alternations of greywacke beds, massive or showing Bouma divisions, and dark grey shales. Locally, near thrust sheets, intercalations of conglomerates up to several metres thick can also appear. In the type area (Mértola region), this unit forms a

3,000-m-thick turbiditic sequence of upper Visean age, as determined by ammonoid biozones (Oliveira 1988).

In the mine area, three distinct sequences of turbiditic beds ascribed to the Mértola Formation are identified in the stratigraphic succession, designated as Mt1, Mt2 and Mt3.

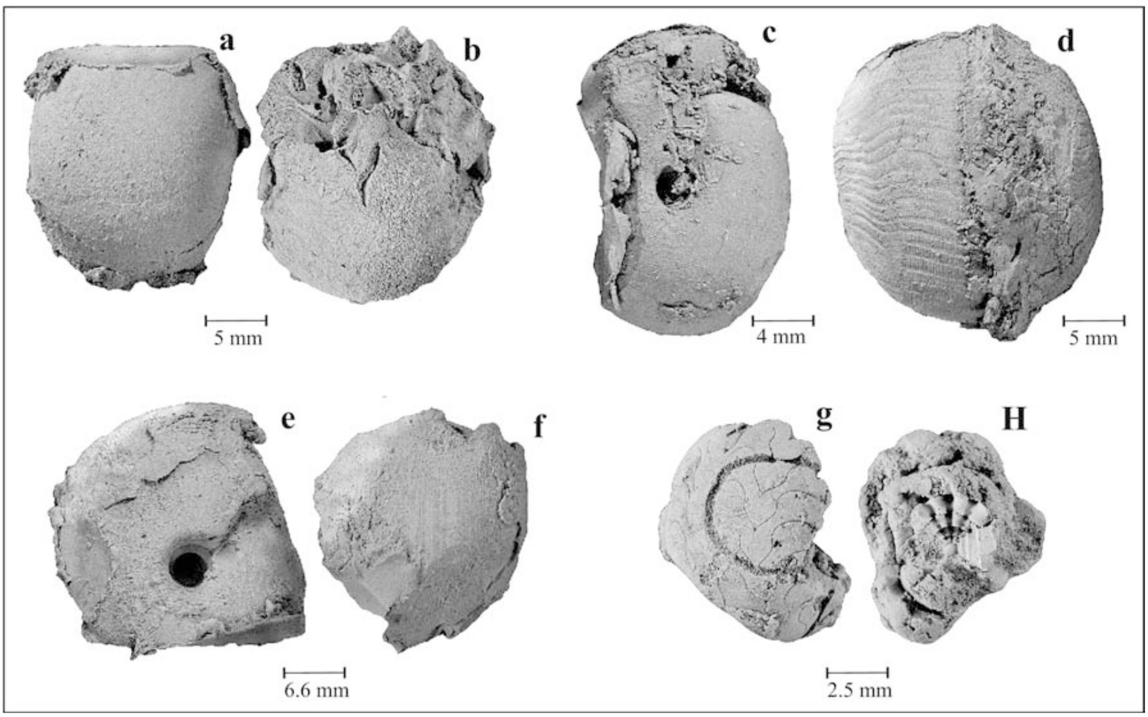
Mt1 beds These correspond to the shales and greywackes which surround the Neves Corvo mine antiformal structure (Fig. 3), with a thickness in excess of 700 m. Samples collected at the base of the unit in boreholes SF16 (Fig. 4), SB18 and SG8 (not shown) provided goniatite specimens of *Goniatites hudsoni* Bisat 1934 and *G.* (?)*globostriatus* Schmidt 1925 which indicate a late Visean A age (Fig. 8a, b). This age determination has been confirmed by spore assemblages of the NM (*nigra–marginatus*) Biozone (boreholes SJ17, SJ3 and SD34 of the Graça–Corvo cross section). Reworked Visean and less-abundant Tournaisian palynomorphs were also determined.

Mt2 beds These beds, only known from drill cores, rest unconformably on the Graça Formation (Fig. 4) and comprise greywackes and shales which show the classic Bouma divisions. Their thickness varies laterally from nil to about 70 m due to truncation by reverse faults. Shales from drill cores SJ17 (Fig. 4) and SI31 (not shown) gave spores assigned to the basal part of the VF (*vetustus–fracta*) Biozone, marked by the occurrence of rare specimens of *Rotaspora fracta*,*Diatomozonotriletes* sp. and *Triquitites marginatus*, together with abundant *Densosporites intermedius*, *D. brevispinosus* and *Raistrickia nigra* and reworked species assigned to the lower TS (*triradiatus–stephanephorus*) Biozone, in particular *Anaplanisporites baccatus*,*Lycospora pusilla*, *Knoxiporites triradiatus* and *K. stephanephorus*.

Mt3 beds These are the lowermost beds of the Mértola Formation and in the present work are used as a stratigraphic marker separating the Lower from the Upper VS Complex (Fig. 4). They are only known from drill cores. The unit thickness changes from nil to about 150 m, this variation being caused by a major reverse fault which cuts the unit at several levels. These beds lie unconformably on the Neves Formation, on the jasper and carbonate unit (jc), and even on the massive sulphides, which demonstrates that there is a time gap between the Mértola Formation and the underlying units, embracing the whole of the Tournaisian and the early and middle Visean. This time gap is probably related to submarine erosion, as discussed below. A particular feature of many greywacke beds is their richness in volcanic clasts and feldspars as compared to normal greywackes. This is also an indication that the turbiditic currents incorporate locally eroded volcanic rocks.

Crushed ammonoid fossils were found in several drill cores (not shown in figures), but only three specimens could be determined, i.e. *Arnbergites arnbergensis* Brunning 1923 from borehole SK2B, *Arnbergites falcatus*Roemer 1850 from borehole NC8, and *Hibernicoc-*

Fig. 8a–h Goniatites from drill cores. Mértola Formation, Mt1 beds: **a***Goniatites hudsoni* Bisat 1934, SB18 at 203.00 m; **b** cf. *Maxigoniatites globostriatus* (Schmidt 1925), SG18 at 153.00 m, latex cast. Mértola Formation, Mt3 beds: **c** *Hibernicoceras* sp., SG26 at 604.90 m, latex cast; **d** *Arnsbergites arnsbergensis* (Bruning 1923), NC18 at 322.50 m, latex cast; **e–h** *Arnbergires arnsbergensis* (Bruning 1923), SK2B at 290.60 m (**e**,**f** latex casts of outer whorl; **g**, **h** silicified inner whorl)



eras sp. from borehole SG26. All these species indicate late Visean B (Fig. 8c–h).

The unit also yielded spore assemblages belonging to the VF (*vetustus–fracta*) Biozone, as indicated by the presence of the index species *Rotaspora fracta* together with common *Convolutispora venusta*,*Diatomozonotriletes sp.*, *Triquitites marginatus* and *Savitrisporites nux* (boreholes SJ17, SD6, SD10 and SD34) in the Graça–Corvo section (Fig. 4) and SI31 (not shown). The base of the NC (*nitidus–carnosus*) Biozone, represented by the guide species *Bellisporites nitidus* (Fig. 7j), was identified in shales collected in borehole SQ14 (not shown). In all studied samples, reworked Strunian and Tournaisian spores are common. These assemblages indicate a late Visean C and early Serpukhovian age, thus fitting the age determinations based on goniatites. It follows that these are the youngest beds of the Mértola Formation known in the mine area.

Regional chronostratigraphy

Based mostly on the spores and to a lesser extent on the ammonoid biozones, complemented by the interpretation of the geometric relationships between the lithostratigraphic units restored to their original position before the tectonic overprint, a chronostratigraphic chart can be devised for the Neves Corvo mine area (Fig. 9).

The examination of this chart reveals three main aspects.

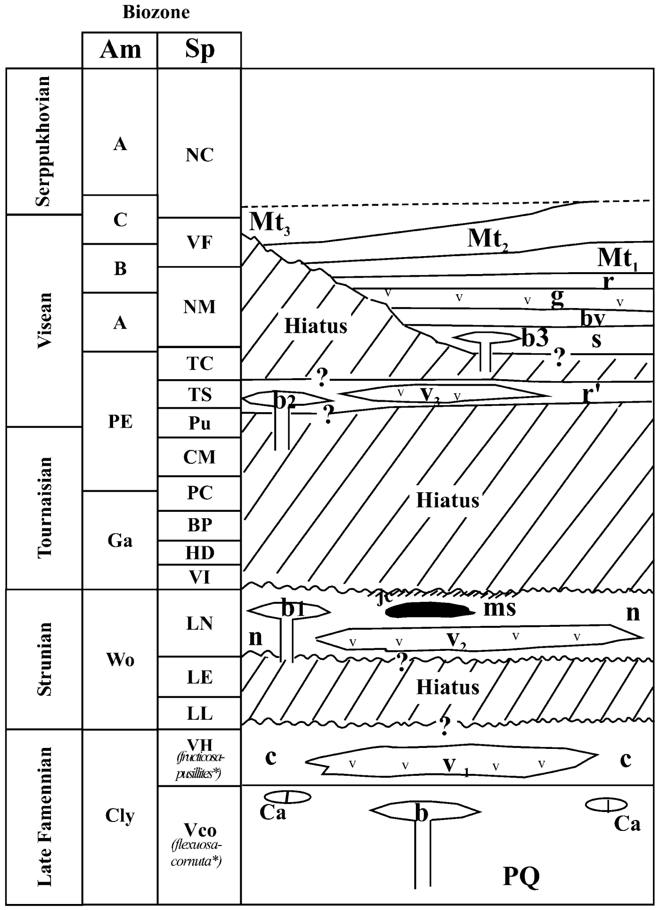


Fig. 9 Chronostratigraphic chart for the Neves Corvo mine (symbols as in Fig. 4). Ammonoid zonation after Korn (1997). Miospore zonal scheme used follows the Western Europe Zonation (after Clayton et al. 1977; Streel et al. 1987; Higgs et al. 1988; Clayton 1996; Maziane et al. 2002; * after Richardson and McGregor 1986, modified after Richardson and Ahmed 1988)

1. The existence of three hiatuses marked by the absence of the early and middle Strunian, LE and LL spore biozones, all biozones of the Tournaisian and the TC Biozone of the early late Visean. Palynostratigraphic research on the stratigraphic sequence of the Iberian Pyrite Belt is still very limited (Cunha and Oliveira 1989; Pereira et al. 1996; Oliveira et al. 1997a, 1997b; González et al. 2002; Rodriguez et al. 2002; Pereira et al. 2003) and biostratigraphic correlations are thus difficult to establish. Having this in mind, we propose the following explanations for these stratigraphic gaps.
   - The oldest hiatus, for the first time identified in the Pyrite Belt, may be of local significance and related to submarine erosion, as suggested by syn-sedimentary slumping identified underground in the mine (Silva et al. 1997).
   - To our knowledge, no lithostratigraphic unit of Tournaisian age has been described in the entire Iberian Pyrite Belt, but reworked Tournaisian palynomorph assemblages were recognised within younger lithostratigaphic units of the belt, particularly in the Graça and Mértola formations, as seen above. Marine terrigenous sediments of Tournaisian age are only known in the southwestern part of the South Portuguese Zone (Pereira et al. 1995; Pereira 1999) where a single spore biozone (CM) is lacking. Therefore, it is unlikely that erosion responsible for the reworking of palynomorphs has taken place in this sector. On the contrary, erosion was very active in the Pyrite Belt, as identified in the Neves Corvo mine area (see below). Indeed, the transtensional tectonic regime (Silva et al. 1990; Quesada 1991, 1998) which prevailed in the Pyrite Belt from the late Famennian until the late Visean, as indicated by the dominant bimodal volcanism (Munhá 1983; Marcoux et al. 1992; Mitjavilla et al. 1997), may have generated marked uplift and block tilting which probably induced gravity sliding responsible for the submarine denudation which locally erased the Tournaisian sediments. The inversion to compressional tectonism started during the late Visean and gave rise to the syn-orogenic flysch sediments of the Mértola Formation (Oliveira 1990; Silva et al. 1990). The latter, as seen above, contain reworked Tournaisian palynomorphs, which indicates that erosion of the substrate continued during this time.

It should be noted that the authors do not preclude the existence of Tournaisian sedimentary rocks in the Iberian Pyrite Belt. At the present state of knowledge, the most plausible explanation for this apparent long gap in the stratigraphic record must be the conjugate results of submarine erosion, still insufficient biostratigraphic investigation, and the impressive tectonism. It is here assumed that the Tournaisian may be preserved in shales, elsewhere in blind grabens or thrust sheets.

– The youngest hiatus, corresponding to the TC spore biozone, is again difficult to interpret, since no term of biostratigraphic correlation exists for this period of time in the Iberian Pyrite Belt. Tectonic erosion at the base of the Graça Formation may be a plausible cause which, however, remains to be proven.

2. A south-westward progressive erosional unconformity between the turbiditic beds of the Mértola Formation and several underlying units (see also Fig. 4).
3. Stratigraphic conformity between the Borra de Vinho, Godinho, Brancanes and Mértola formations (Mt1 beds), all of late Visean age, as shown by the spore and ammonoid assemblages.

Note on the age of the massive sulphide deposits

The Neves Corvo massive sulphide orebodies, apart the stockwork stringers, always appear to be intercalated or interfingering with the black shales of the Neves Formation and are also stratigraphically above the V_2 felsic volcanic episode. Preliminary work (Oliveira et al. 1997a, 1997b) had already suggested that the age of the mineralisation falls within the LN spore biozone.

In order to better constrain the age of the mineralisation, detailed biostratigraphic research of the black shale hosting the Corvo and Lombador orebodies was undertaken. From the samples studied, ten were obtained from thinly bedded (millimetric scale) black shale intercalated within the massive sulphides, and six from samples less than 1 m above and below the shale/massive sulphide boundary. All samples yielded spore assemblages undoubtedly ascribed to the LN Biozone of late Strunian age.

The ore genesis has been linked to leaching of the footwall (mostly felsic volcanic rocks) by hydrothermal fluids associated to convective circulation of seawater (Munhá and Kerrich 1980; Barriga and Kerrich 1984; Barriga and Fyfe 1998), with contributions of magmatic or metamorphic (Moura et al. 1997; Relvas et al. 2001) fluids or even bacteriogenic activity (Tornos et al. 1998). Recent alternative genetic models include (1) direct derivation of fluids from rising magmas in a hot and thinned crust, and final deposition on the seafloor (Marcoux 1998); and (2) deposition in a sill-sediment complex in which the mineralisation episode predates felsic and mafic volcanic intrusions in still wet sediments (Boulter 1993, 1996). The metallogenetic discussion is beyond the purpose of the present work. We emphasise that for the black shale-hosted ores, as is the case of the Neves Corvo orebodies, it is currently admitted that the mineralisation resulted from precipitation and replacement of suphides within euxinic seafloor muds (Barriga et al. 1997; Almodovar et al. 1998; Tornos et al. 1998; Saez et al. 1999). Therefore, the mineralisation event and the black shale sedimentation should be coeval. This is clearly proved in the present work since, as seen above, shales interbedded or immediately above and below the Neves Corvo orebodies provided exactly the same spore assemblage ascribed to the LN Biozone of late Strunian age. Palynological research in the Alznalcollar (Pereira et al. 1996) and Tharsis (González et al. 2002) mining districts has reached the same conclusion regarding the age of the black shales hosting the massive sulphide ore.

It is worth noting that most of the black shale-hosted orebodies (as, for instance, Lousal, Neves Corvo, Tharsis, Alznalcollar, Las Cruces; Fig. 1) are situated in the southern branch of the Iberian Pyrite Belt (Oliveira 1990), where black shale sedimentation was dominant during the late Strunian. The palaeogeographical meaning of this type of sedimentary environment is not yet clearly understood and deserves further investigation. In any case, it seems reasonable to infer that all orebodies of these mining districts were generated in coeval and similarly confined depositional settings, i.e. possibly extension-related half grabens, and this should be taken into consideration when discussing the genesis of the massive sulphide ore.

The three spore biozones (LL, LE and LN) of Strunian age are correlatable with the late *expansa* and the early, middle and late *praesulcata* conodont biozones (Sandberg and Ziegler 1996; Streel and Loboziak 1996; Sandberg et al. 1997; Streel et al. 2000), whose absolute age ranges from 355.5 to 354.0 Ma. According to these authors, the first occurrence of *I. explanatus*, the base of the LE Biozone, can be correlated with the middle early *praesulcata*, with an absolute age of 354.8 Ma. The absolute age for the base of the LN Biozone is not yet well constrained, but the top of the LN is coincident with the Devonian/Carboniferous boundary, with an absolute age of 354.0 Ma. Since the mineralisation episode occurred during the time interval of the LN Biozone, its age should be placed somewhere between 354.8 and 354.0 Ma.

In the Pyrite Belt, recent age determinations have been made using radiogenic isotopes (Marcoux et al. 1992; Mathur et al. 1999; Nesbitt et al. 1999; Relvas et al. 2001; Barrie et al. 2002; Dunning et al. 2002; Table 2). For Neves Corvo the Rb–Sr age of 347 ± 25 Ma (Relvas et al. 2001) has a relative large error margin and can not be used to define the local stratigraphy. U–Pb ages on zircon from other parts of the Pyrite Belt range between 356.0 and 350.0 Ma (Barrie et al. 2002).

Table 2 Absolute ages from selected Iberian Pyrite Belt orebodies

Author	Method	Samples	Study area	Age (Ma)
Marcoux et al. (1992)	$^{206}Pb/^{204}Pb$	Ms ore	IPB, Spain	368 ± 26
Mathur et al. (1999)	Re/Os	Ms ore	Rio Tinto, Spain	346 ± 26
			Tharsis, Spain	353 ± 44
Relvas et al. (2001)	Rb/Sr	Ms ore	Neves Corvo, Portugal	347 ± 25
Nesbitt et al. (1999)	U/Pb zircons	Dacitic tuff	Los Frailes, Spain	345.7 ± 4.6
Dunning et al. (2002)	U/Pb zircons	Rhyolite	Zufre, Spain	347.5 ± 1.5
		Rhyolite	Nerva, Spain	353 ± 2
Barrie et al. (2002)	U/Pb zircons	Rhyolite	Rio Tinto, Spain	349.76 ± 0.9
		Dacitic tuff	Las Cruces, Spain	353.97 ± 0.7
		Green tuff	Aljustrel, Portugal	352.9 ± 1.9
		Rhyolitic tuff	Lagoa Salgada, Portugal	356.2 ± 0.73

Geodynamic setting

The tectonic structure of the Neves Corvo mine area is characterised by a stacked pile of thrust sheets composed of varied lithostratigraphic units which were affected by gentle NW-trending folds and cleavage, with tectonic transport towards the SW, as shown by the vergence of folds and thrusts (Albouy et al. 1981; Leca et al. 1983; Silva et al. 1997).

Taking into account the unconformities, hiatuses and geometric relationships described above, and restoring the lithostratigraphic units to their original position, the geodynamic evolution of the region can be visualised (Fig. 10). As commented above, extension during the late Famennian and Strunian gave rise to bimodal volcanism to which, in some way, the mineralisation must be linked. Extension continued until the

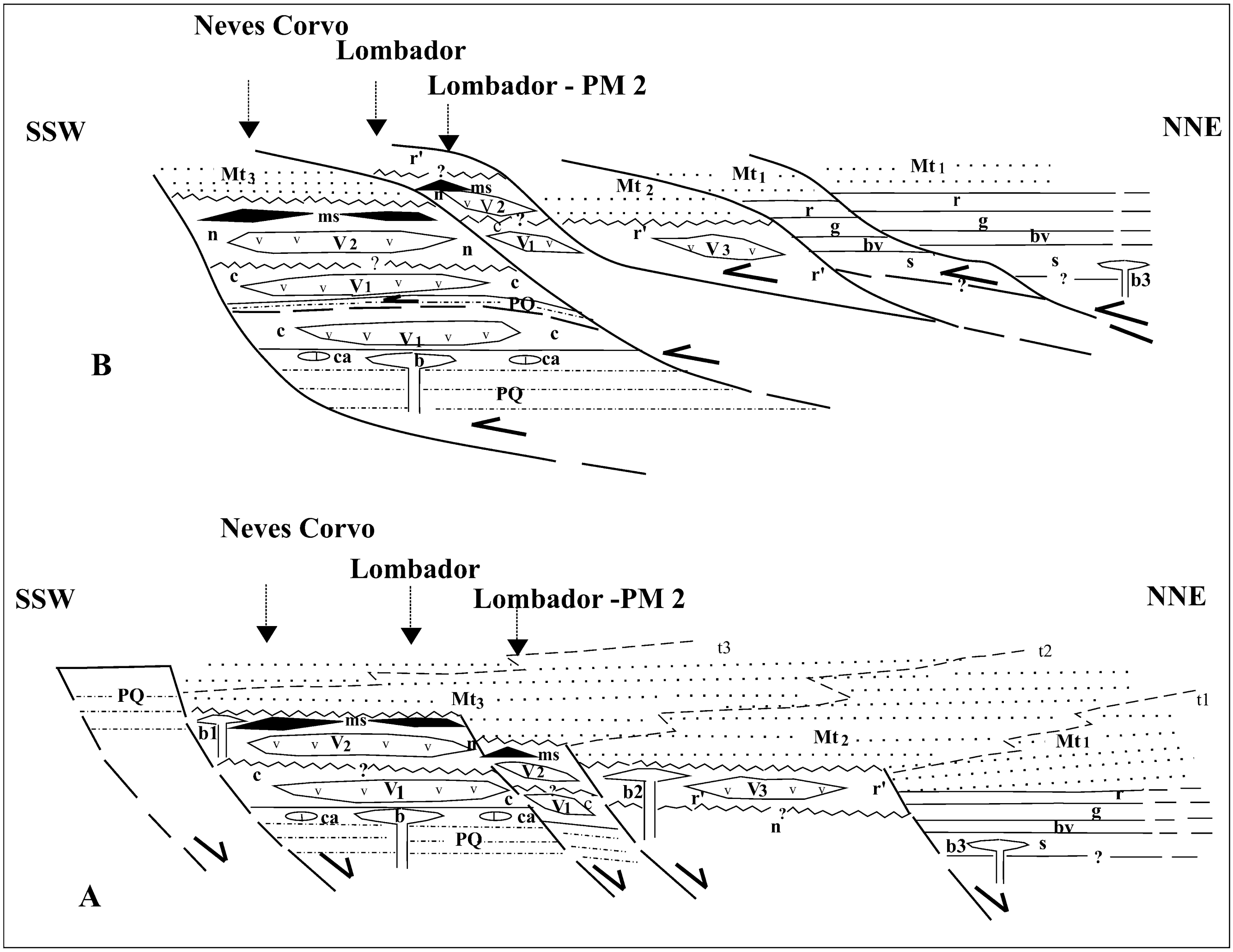


Fig. 10A, B Cartoon to illustrate the regional basin dynamics. **A** Late Famennian to Visean A: dominantly extensional regime; **B** Serpukhovian to Moscovian: dominantly SW-verging fold and thrust regime. Symbols as in Fig. 4; *t1*, *t2*,*t3* inferred time lines late Visean A and caused uplift, block tilting, submarine erosion and volcanism (early Visean). The scenario during the late Visean/early Serpukhovian may have been close to that devised in Fig. 10A. The unconformities and stratigraphic relationships between the sedimentary rocks of the Mértola Formation (Mt1, Mt2 and Mt3 beds) and the underlying substrate are indicative of a half graben structure deepening eastwards before the arrival of the turbiditic sediments. The conformity between the Mt1 beds and the underlying units of the Upper VS Complex (right end of Fig. 10A) is similar to that observed in the stratigraphic sequence of the Pomarão Anticline (Boogaard 1963; Oliveira and Silva 1990, Fig. 1), including the late Visean A age for the beginning of the turbidite sedimentation provided by ammonoids of the *hudsoni* Biozone in Neves Corvo and the *crenistria* Biozone in Pomarão (Oliveira 1988; Korn 1997). From this lateral stratigraphic correlation, it can be concluded that during the final stage of the extensional regime a half graben some tens of kilometres in width may have existed in this area.

The flysch sedimentation started in front of thrust sheets moving southwards, intimately related to the development of a foreland basin (Oliveira 1990; Oliveira and Quesada 1998). The thrusts probably resulted from the reactivation of former gravity or strike slip faults (Oliveira 1990; Quesada 1998). The first stage of this tectonic inversion in the Neves Corvo area is illustrated in Fig. 10B. One important structural achievement of the present work is the identification of tectonic duplication of lithostratigraphic units in the so-called autochthonous sequence, proving that the complete stratigraphic pile is involved in the fold and thrust sheet complex which characterises the tectonic structure of the Iberian Pyrite Belt. This conclusion should open new perspectives for mineral exploration.

Conclusions

Biostratigraphic research undertaken in the Neves Corvo mine area, mostly based on palynomorphs and ammonoids, allows four main conclusions.

1. Palynology and ammonoid biozonation precisely date the lithostratigraphic units of the Neves Corvo mine area and permit a better understanding of the local geodynamic basin development. The pre-volcanic detritic basement is dated as late Famennian, the age of the Volcano-Sedimentary Complex ranges from late Famennian to early late Visean, and the flysch sedimentation started during late Visean and reaches early Serpukhovian age.
2. All Neves Corvo massive sulphide orebodies are intercalated or interfingering with the black shale of the Neves Formation, indicating a late Strunnian age for the mineralisation episode (interval 354.8–354.0 Ma).
3. Three hiatuses were identified in the lithostratigraphic succession one embracing the LL and LE spore biozones of the Strunian, the second the entire Tournaisian, and the third the TC spore biozone of the early Visean. Progressive unconformities of the flysch sediments on an already lithified VS substrate were also identified. Reworked Tournaisian palynomorphs in one unit of the Upper VS Complex, dated as early Visean, and in late Visean flysch sediments show that Tournaisian sedimentation may have occurred in the Pyrite Belt proper and the sediments were later eroded. This erosion may be related to gravity slumping and sliding generated in response to tectonic uplift and block tilting. This process probably caused widespread submarine denudation.
4. The tectonic regime changed from extensional to compressive during late Visean times, and this inversion gave rise to a pile of thrust sheets which affected the entire lithostratigraphic succession. This means that no rooted autochthonous stratigraphic sequences exist in the mine area, a conclusion which opens room for further exploration targets.

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