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Research paper

New insights on the middle Givetian/middle Frasnian palynofloras from the Phyllite-Quartzite Formation in the Neves-Corvo mine region (Iberian Pyrite Belt, Portugal)

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ABSTRACT

A detailed palynostratigraphic study of two Somincor/Lundin Mining exploration drill holes intercepting the Phyllite-Quartzite (PQ) Formation in the geological basement of the Neves-Corvo mine region (Portuguese sector of the Iberian Pyrite Belt – IPB) allowed to first recognise the oldest ages for this formation in this region, ranging from midGivetian/midFrasnian (base unknown) to late Famennian. The TA Miospore Biozone (*Cristatisporites triangulatus-Ancyrospora ancyrea*) of middle Givetian age (Middle Devonian) was identified in NK30B-1 drill hole (Lombador North mine sector), whereas the BM Miospore Biozone (*Verrucosisporites bulliferus-Lophozonotriletes media*) and IV Miospore Biozone (based in the first occurrence of *Rugospora bricei* and *Diducites* cf. *poljessicus*) of middle Frasnian (Late Devonian) age were both recognised in drill hole SJ32 (Corvo-Semblana mine sector). The common presence of Early-Middle Devonian reworked spores, as well as similar inherited zircon ages may suggest that the lower PQ Formation age is not yet known.

At Neves-Corvo mine, the Volcano-Sedimentary Complex is deposited directly above the PQ basement, spanning different ages, pointing out two major unconformities, a VSC/upper and/or lower PQ sequences and an upper PQ/lower PQ sequences.

A palynostratigraphic correlation of the lowermost Phyllite-Quartzite Formation across the IPB is established. Phyllite-Quartzite Formation palynoassemblage of Neves-Corvo region is compared with lowermost PQ assemblages recovered in the NW sector of IPB (S. Francisco da Serra and Lousal-Caveira mine structures, Portugal) and in E sectors of the IPB in Spain (Gerena-El Garrobo section). The similar palynological record (also including the same reworked taxa signature) and ages obtained, suggests identical sedimentary provenance, close paleogeographic domain and temporal affinity throughout the lowermost IPB Phyllite-Quartzite Formation.

1. Introduction

The Neves-Corvo mine is located in the south-eastern extension of the Rosário-Neves-Corvo NW-SE-trending antiform considered one of the key structures in the central region of Iberian Pyrite Belt (IPB) (Fig. 1). Considering the magnitude of the exploration surveys developed in the area focused on the massive sulphide mineralisation research (Barriga et al., 1997; Carvalho et al., 1999; Relvas et al., 2006a,b; Oliveira et al., 2013a,b), the mine site includes the most complete and studied lithostratigraphic sequence of IPB, investigated by drill holes up to 1500 m depth. The lithostratigraphic sequence comprises from base to top, the Phyllite-Quartzite Formation (PQ), the Volcano-Sedimentary Complex (VSC), and the Mértola Fm. included in the lower unit of the Baixo Alentejo Flysch Group. Seven massive sulphide lenses have been identified so far, including Neves, Corvo, Graça, Zambujal, Lombador, Semblana and Monte Branco deposits (Fig. 1).

Palynological studies have been used as a strategic tool for geological mapping and structural interpretations in the IPB since the 1980s (Oliveira et al., 1986; Cunha and Oliveira, 1989; Pereira, 1997, 1999; Pereira et al., 2006, 2007, 2008, 2010a,b, 2014). The use of detailed palynology for high resolution stratigraphy is nowadays a fundamental tool for near mining exploration purposes in IPB. In the Neves-Corvo area,

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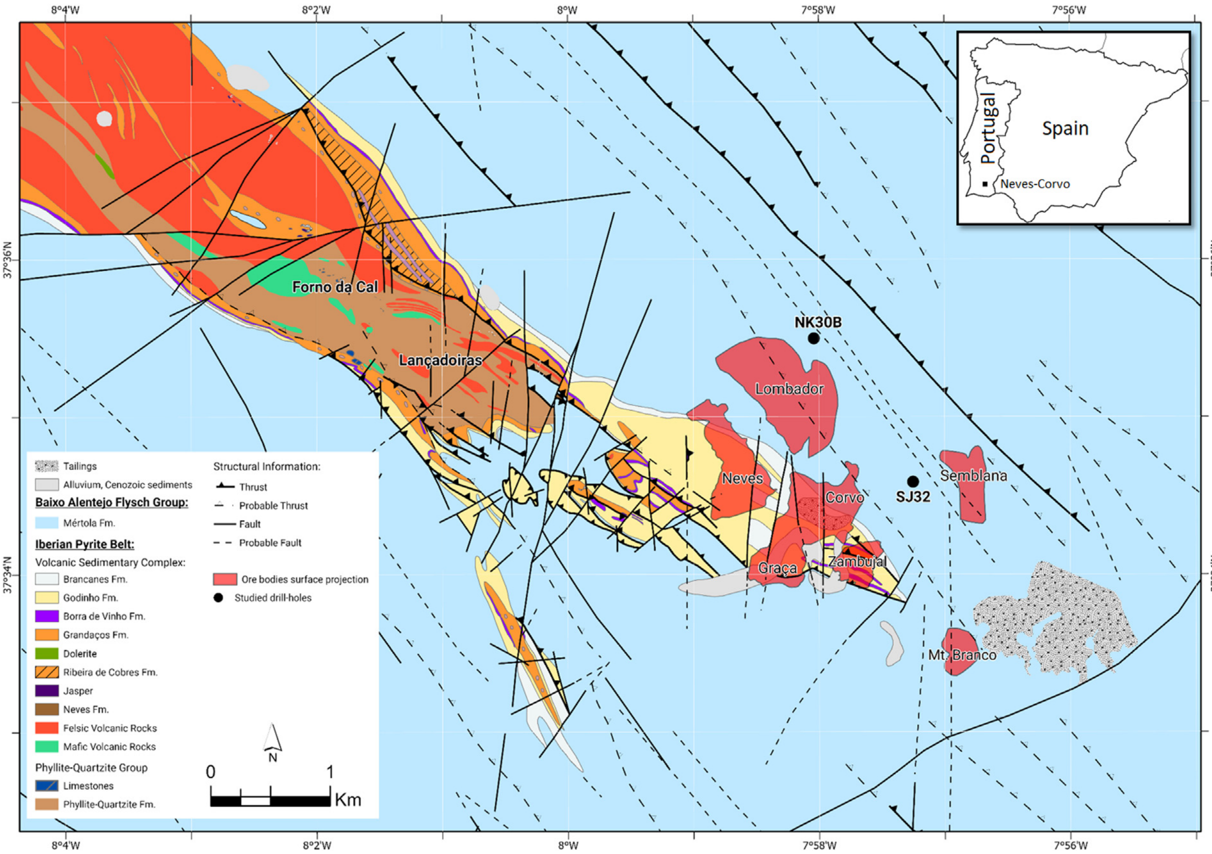

Fig. 1. Simplified geology of IPB with studied drill holes locations. *Geology adapted from* Oliveira et al. (2013a, 2016); Oliveira et al., 2013a and Leca et al. (1983), EXPLORA Project unpub. Neves-Corvo map.

the first palynological studies proved to be useful to determine precise ages of the lithostratigraphic sedimentary units and, to define the age of the black shales that host the mineralisation of late Strunian age (LN Miospore Biozone; Oliveira et al., 1997; Oliveira et al., 2004; Pereira et al., 2004). Recent research projects confirmed previous ages in several IPB locations (Pereira et al., 2008).

Current LNEG – Portuguese Geological Survey and Somincor/Lundin Mining EXPLORA/Alentejo2020 research is focused on a comprehensive age determination of the PQ basement at the Neves-Corvo mine area. For that purpose, a detailed palynological study based on two drill holes located at Lombador North (NK30B-1, 1427.5 m length) and Corvo-Semblana (SJ32, 1130.6 m depth) was conducted for palynostratigraphy, providing new knowledge of the lowermost sediments of the PQ Fm. located in the autochthonous sectors of the mine region. The new data will also be correlated at regional scale across the IPB. A correlation with the north Gondwana palynofloras is established. This research will be a contribution to improve the knowledge on the basal substratum of the IPB stratigraphy, especially in the lowermost PQ Fm., and try to reconstruct the Middle/Late Devonian sediment deposition along the IPB, based on palynoflora and stratigraphic events.

2. Geological setting and IPB stratigraphy

The stratigraphy of the IPB comprises three main units from base to top, the PQ Group (PQG, Schermerhorn, 1971), the Volcano Sedimentary Complex (VSC), and the Mértola Fm. (Baixo Alentejo Flysch Group, Fig. 1).

2.1. The PQ Group (early Givetian-late Famennian)

The PQG is defined as a siliciclastic open platform mega-sequence (Oliveira et al., 2013a,b, 2019) formed in shallow water environment. The base of PQG is unknown and this Group embraces the following units, from base to top: (1) the PQ Fm., comprising shales with intercalations of interbedded siltstones and quartz sandstones, (2) the Barranco do Homem Fm., including shales, greywackes and quartzwackes and its lateral equivalent, the Represa Fm. (Oliveira, 1990; Oliveira and Silva, 1990; Faria et al., 2015; Oliveira et al., 2019), (3) the Barrancão member, with laminated black shales with siliceous lenses and nodules and dated as late Famennian (Oliveira et al., 2013b), and (4) at the top of PQG, limestones with conodont and crinoid faunas (Boogaard, 1967; Boogaard and Schermerhorn, 1981), are recognized (local names, as Nascedios at Pomarão antiform and Forno da Cal at Rosário antiform, have been used) representing deposition in distinct sedimentary environments (Oliveira, 1984, 1992; Oliveira et al., 2004, 2013b).

The PQG palynostratigraphic age ranges from the early Givetian, AD Miospore Biozone, subzone *lemurata* identified in the northwest IPB region (São Francisco da Serra and Lousal and Caveira antiforms; Pereira et al., 2008, 2010a,b) through the mid-late Givetian (Lake et al., 1988; González et al., 2004; Mendes et al., 2018a,b) to the late Famennian VCo (*D. versabilis-G. cornuta*), VH Biozone (*A. verrucosa-V. hystricosus*) and the latest Famennian (i.e., Strunian) LN Biozone (*R. lepidophyta-V. nitidus*; Oliveira et al., 2004, 2013a; Pereira et al., 2004, 2008, 2010a,b, 2012, 2014) at the top (e.g., Neves-Corvo Mine site;

Fig. 5). At the top of the sequence, Nascedios Fm. limestones lenses in Pomarão antiform yielded conodonts assigned to the *marginifera* Biozone, indicating a late Famennian age (Boogaard and Schermerhorn, 1981), and palynomorphs assigned to the LL Miospore Biozone of latest Famennian (Strunian) age (Oliveira et al., 2006; Oliveira and Silva, 2007; Pereira et al., 2008). In the uppermost part of PQG, limestone horizons are considered as regional geological guides in geological mapping both in Portugal (Oliveira and Silva, 1990; Oliveira, 2016) and Spain (IGME, 2010).

2.2. The VSC (Famennian-Visean)

In Late Devonian, an epiclastic/siliciclastic ocean basin might have evolved to a tectonic extensional regime (Munhá, 1983; Mitjavila et al.,

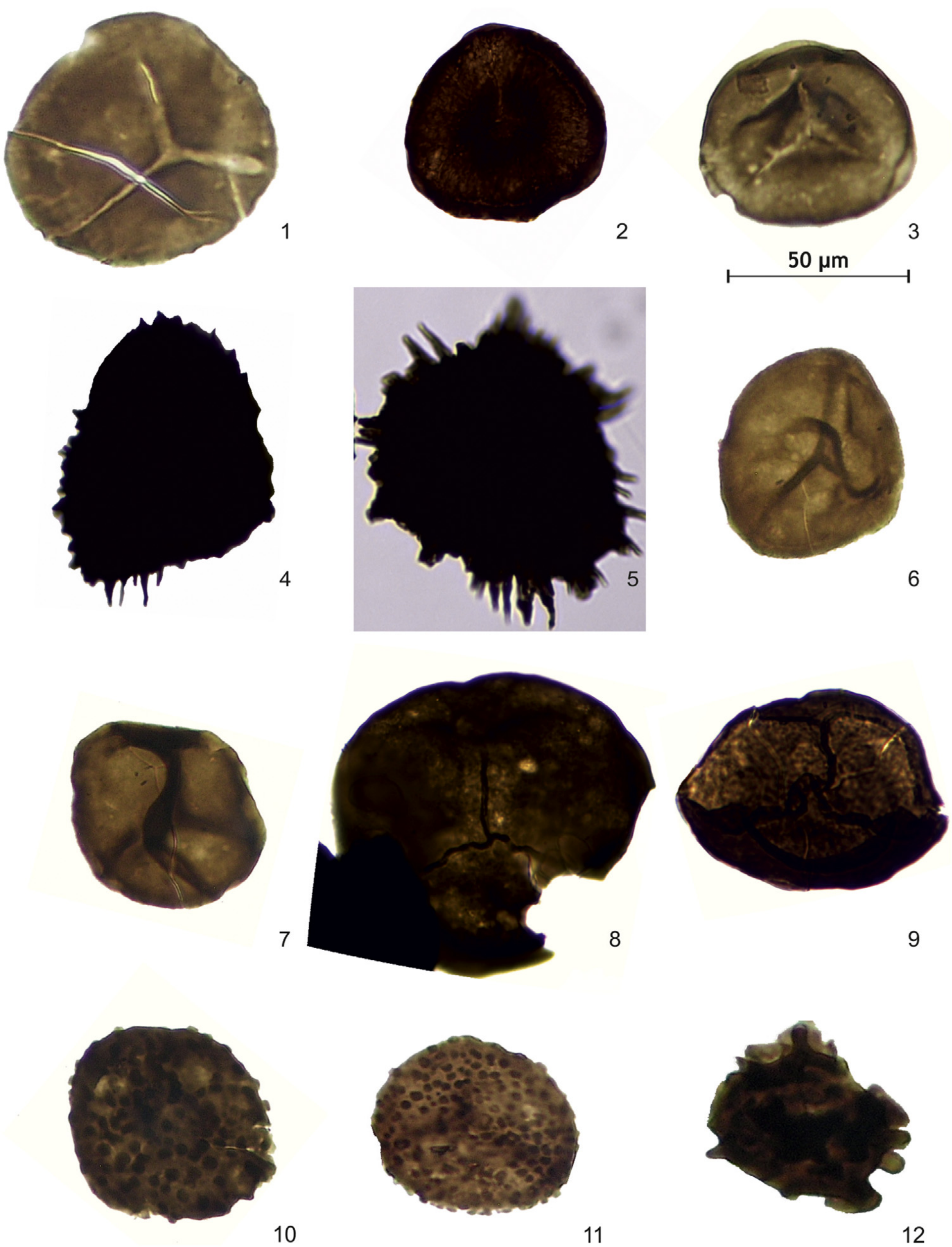

Plate 1. Important taxa selected from drill holes studied in the PQ Fm., IPB. The species name is followed by Formation, drill hole, sample number, slide number, archive image number, and microscope coordinates. All specimens are housed in the collections of LNEG – Portuguese Geological Survey, Portugal. 1. *Punctatisporites* sp.; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2d, MC 1175-125. 2. *Retusotriletes rugulatus* Riegel, 1973; PQ Fm., NK30B-1 drill hole, 1227.6 m sample, slide 2, MC 1100-350. 3. *Retusotriletes triangulatus* (Streel) Streel, 1967; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2d, MC 1275-175. 4. *Acinosporites hirsutus* (Brideaux and Radforth) McGregor and Camfield, 1982; PQ Fm., NK30B-1 drill hole, 1227.6 m sample, slide 1, MC 1120-369. 5. *Acinosporites macrospinosus* Richardson, 1965; PQ Fm., NK30B-1 drill hole, 1227.6 m sample, slide 2, MC 993-453. 6. *Geminospora lemurata* Streel, 1964; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2d, MC 1235-80. 7. *Geminospora lemurata* Streel, 1964; PQ Fm., SJ32 drill hole,910.5 m, slide 2c, MC 1254-135. 8. *Apiculatasporites microconus* (Richardson) McGregor and Camfield, 1982; PQ Fm., NK30B-1 drill hole, 1232.0 m sample, slide 1, MC 1048-298. 9. *Apiculatasporites microconus* (Richardson) McGregor and Camfield, 1982; PQ Fm., NK30B-1 drill hole, 1232.0 m sample, slide 2, MC 1053-148. 10. *Verrucosisporites bulliferus* Richardson and McGregor, 1986; PQ Fm., SJ32 drill hole, 910.5 m, slide 2e, MC 1030-190. 11. *Verrucosisporites bulliferus* Richardson and McGregor, 1986; PQ Fm., SJ32 drill hole, 910.5 m, slide 3, MC 1360-195. 12. *Verrucosisporites premnus* Richardson, 1965; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 1, MC 1045-190. *Note that this species may be confused with morphologically similar Chelinospora concinna* Allen 1965*, but the last generally presents large polygonal to irregular rounded luminae.*

1997; Thiéblemont et al., 1998; Rosa et al., 2006; Silva et al., 2013) disrupting the siliciclastic platform in extensional graben-type basins (Oliveira, 1990). The basin instability was coeval with the emplacement of significant IPB volcanism. This geological setting could have favoured the upwards movement of subaqueous volcanic structures contemporaneous with the deposition of sediments in areas dominated by graben structures. These sediments occur interbedded with felsic and mafic volcanic rocks and are represented by black to dark-grey shales deposited in anoxic environments, by green to purple hematite sediments deposited in near surface environments and transitional facies represented by shales with nodules and siliceous rich sediments, locally associated with volcanogenic sediments, jaspers and cherts. The sediments are dated from Late Devonian (late Famennian) to early Carboniferous (mid-late Visean) based on palynomorphs and rare conodonts ages (Oliveira, 1990; Oliveira et al., 1997, 2004; Pereira et al., 2004, 2008, 2014) whereas the volcanic rocks range from ca. 370–330 Ma, based on zircon geochronology of felsic rocks (Solá et al., 2019). The IPB massive sulphide deposits are commonly associated with felsic volcanic rocks and black shales. VSC comprises two distinct sequences, the Lower and the Upper VSC, initially defined in the Rosário and Neves-Corvo region (Oliveira et al., 2004; Pereira et al., 2008, 2014) and later identified in the Caveira mine (Matos et al., 2015; Dias et al., 2016) and Alvares regions (Faria et al., 2015; Oliveira, 2016). These sequences can be individualised and separated by a sedimentary stratigraphic hiatus embracing the Tournaisian age (Oliveira et al., 2004, 2013b; Pereira et al., 2008, 2014, 2019, in prep.). At the Neves-Corvo mine, the Lower VSC includes the Corvo Fm. (late Famennian age), represented by black shales, carbonate nodules and volcanogenic sediments, and the Neves Fm. represented by black, occasionally pyritic shales, siltstones and black cherts. Both Corvo and Neves formations are coeval with felsic volcanic units. Anoxic conditions during latest Famennian (Strunian) age were favourable to the development of massive sulphide mineralisation deposition. Therefore, latest Famennian

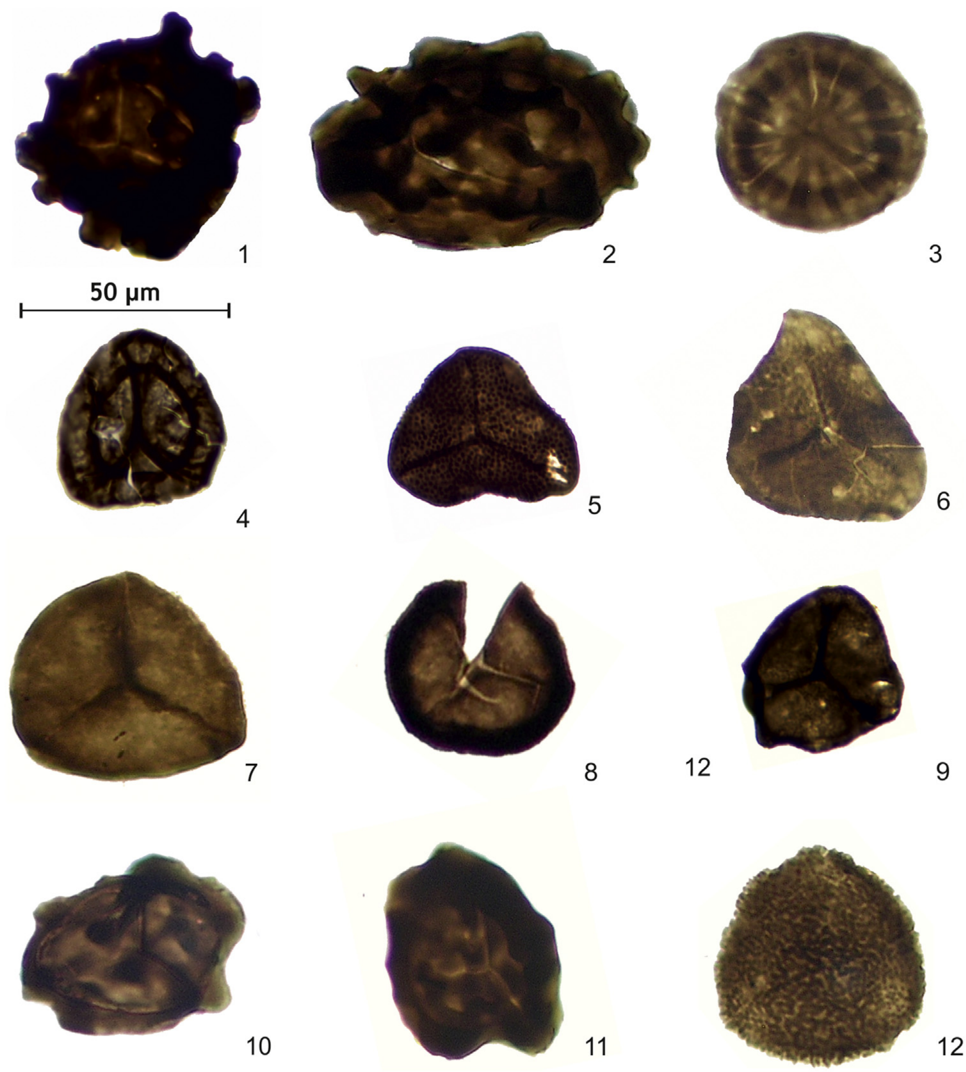

Plate 2. Important taxa selected from drill holes studied in the PQ Fm., IPB. The species name is followed by Formation, drill hole, sample number, slide number, archive image number, and microscope coordinates. All specimens are housed in the collections of Portuguese Geological Survey - LNEG, Portugal. 1. *Verrucosisporites premnus* Richardson, 1965; PQ Fm., NK30B-1 drill hole, 1232.0 m sample, slide 1, MC 1120-247. 2. *Verrucosisporites premnus* Richardson, 1965; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 1, MC 1035-110. 3. *Emphanisporites annulatus* McGregor, 1961; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2b, MC 1345-38. 4. *Emphanisporites annulatus* McGregor, 1961; PQ Fm., NK30B-1 drill hole, 1336.0 m sample, slide 1, MC 1013-288. 5. *Diatomozonotriletes franklinii* McGregor and Camfield, 1982; PQ Fm., NK30B-1, 1232.0 m sample, slide 2, MC 1069-346. 6. *Diatomozonotriletes* sp., 1982; PQ Fm., SJ32 drill hole, 910.5 m, sample, slide 2d, MC 1225-165. 7. *Aneurospora greggsii* (McGregor) Streel, 1974; PQ Fm., SJ32 drill hole, 910.5 m, sample, slide 2d, MC 1220-155. 8. *Archaezonotriletes chulus* (Cramer) Richardson and Lister, 1969; PQ Fm., SJ32 drill hole, 885.2 m sample, slide 1, MC 1374-90. 9. *Archaezonotriletes* sp.; PQ Fm., NK30B-1, 1232.0 m sample, slide 1, MC 942-200. 10. *Lophozonotriletes media* Taugourdeau-Lantz 1967; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 3, MC 1360-205. 11. *Lophozonotriletes media* Taugourdeau-Lantz 1967; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2d, MC 1265-122. 12. *Cymbosporites magnificus* (McGregor) McGregor and Camfield, 1982; PQ Fm., SJ32 drill hole, 850.4 m sample, slide 2d, MC 1178-120.

(Strunian) age black shales and associated felsic volcanic rocks are a key mineral exploration horizon identified in the Neves-Corvo, Lousal-Caveira and Aznalcóllar mines (Oliveira et al., 2004, 2013b; Pereira et al., 2008, 2012, 2014; Matos et al., 2011, 2014).

In the Rosário-Neves-Corvo antiform the Upper VSC includes, from bottom upwards, the following recognised units: Graça Fm. (black shales with dispersed siliceous-phosphatic nodules, hosting felsic volcanic rocks), Grandaços Fm. (dark shales with carbonate nodules, cherts, jaspers and fine-grained volcanogenic sediments), "Borra de Vinho" Fm. (purple hematite rich and green shales sometimes with radiolarians), Godinho Fm. (shales, siliceous shales and fine volcanogenic sediments) and Brancanes Fm. (dark and pyritic shales with thin bedded greywackes to top), all of mid-late Visean age (Oliveira et al., 2004; Pereira et al., 2008).

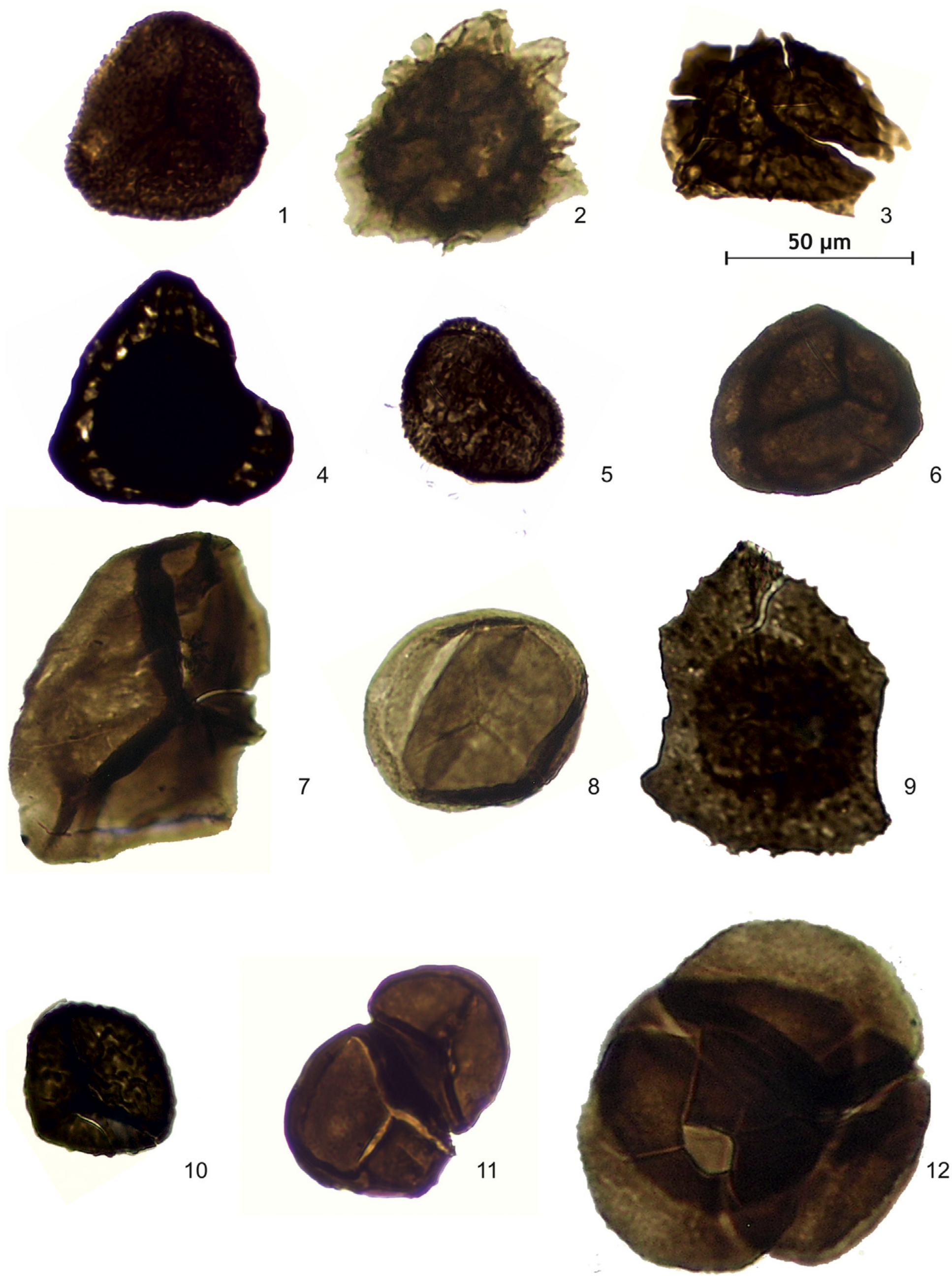

Plate 3. Important taxa selected from drill holes studied in the PQ Fm., IPB. The species name is followed by Formation, drill hole, sample number, slide number, archive image number, and microscope coordinates. All specimens are housed in the collections of Portuguese Geological Survey – LNEG, Portugal. 1. *Cymbosporites magnificus* (McGregor) McGregor and Camfield, 1982; PQ Fm., SJ32 drill hole, 850.4 m sample, slide 2a, MC 1420-125. 2. *Cristatisporites inusitatus* (Allen) McGregor and Camfield, 1982, 1982*;* PQ Fm., SJ32 drill hole, 850.4 m sample, slide 3, MC 1085-65. 3. *Cristatisporites inusitatus* (Allen) McGregor and Camfield, 1982*;* PQ Fm., NK30B-1 drill hole, 1336.0 m sample, slide 1, MC 1025-536. 4. *Cristatisporites triangulatus* (Allen) McGregor and Camfield, 1982*;* PQ Fm., SJ32 drill hole, 850.4 m sample, slide 3, MC 1296-119. 5. *Camarozonotriletes sextantii* McGregor and Camfield, 1976; PQ Fm., NK30B-1 drill hole, 1336.0 m sample, slide 1, MC 1117-304. 6. *Geminospora lemurata* (Balme) emend. Playford, 1983; PQ Fm., NK30B-1 drill hole, 1357.8 m sample, slide 4, MC 957-174. 7. *Rhabdosporites* sp.; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 2c, MC 1285-125. 8. *Diducites* cf. *poljessicus* (Kedo) Van Veen, 1981; PQ Fm., SJ32 drill hole, 850.4 m sample, slide 3, MC 1138-192. 9. *Grandispora libyensis* Moreau-Benoit, 1980; PQ Fm., SJ32 drill hole, 885.2 m sample, slide 2, MC 1144-125. 10. *Rugospora bricei* Loboziak and Streel, 1989; PQ Fm., SJ32 drill hole, 847.4 m sample, slide 5, MC 1155-110. 11. Miospore diad; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 1d, MC 1025-105. 12. Miospore tetrad; PQ Fm., SJ32 drill hole, 910.5 m sample, slide 1, MC 1235-135.

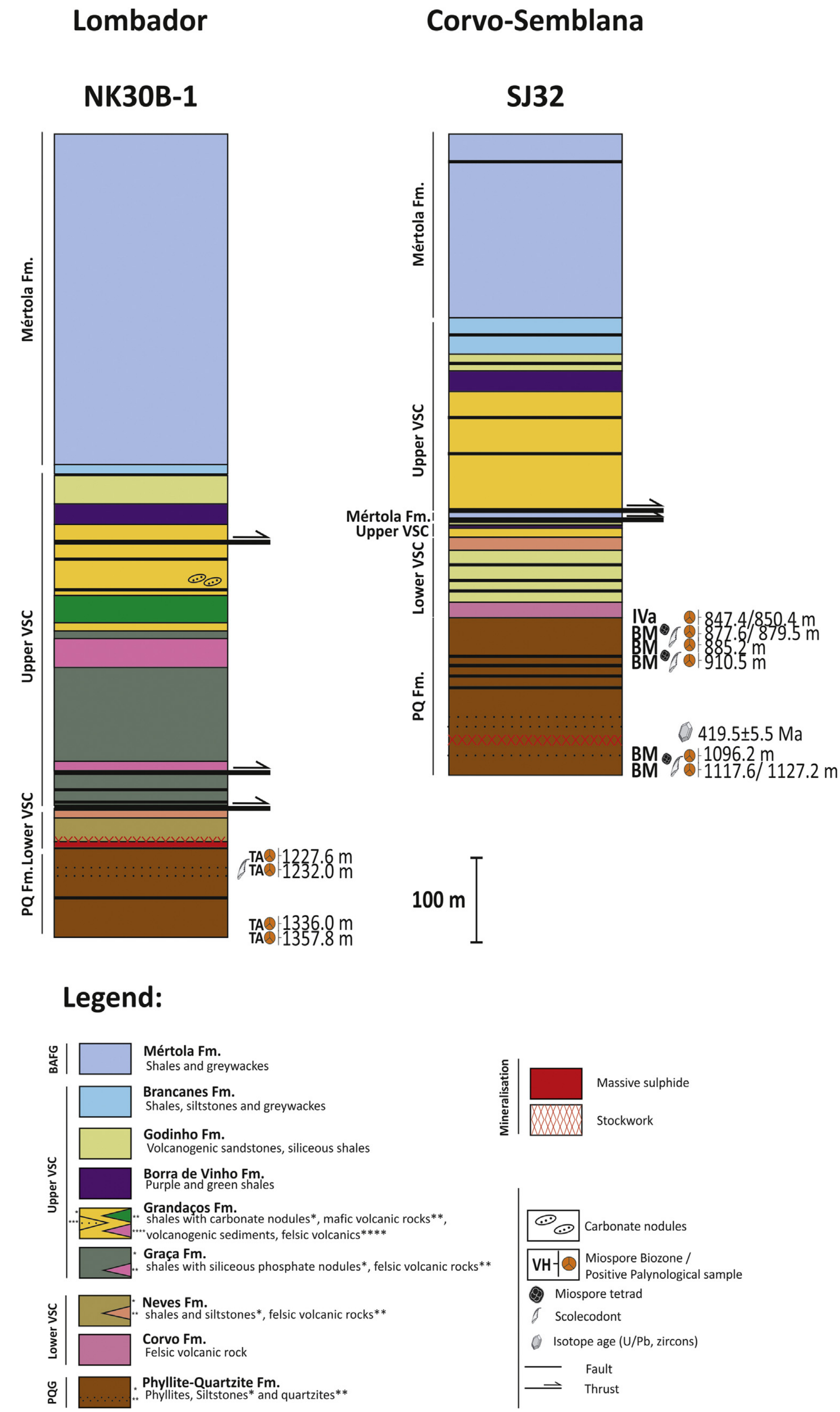

Fig. 2. Simplified logs of NK30B-1 and SJ32 drill holes, including the locations of sampled PQ Fm. sediments.

2.3. *The Baixo Alentejo Flysch Group (Visean-Moscovian)*

The Baixo Alentejo Flysch Group (Oliveira et al., 1979) stratigraphically overlays the VSC units, comprising the Mértola, Mira and Brejeira formations with southwest-younging progradation. The northeasternmost and older Mértola Fm. is the only one identified in the Neves-Corvo study area, representing a turbiditic sequence with intercalations of greywacke beds with shales, siltstones, conglomerates and rare mudflow deposits. This lowermost flysch unit provided goniatite specimens and miospores of the mid-late Visean age, NM Biozone (Oliveira, 1988; Pereira et al., 2007, 2008, 2014).

3. Materials and methods

Thirty drill core samples were collected for the palynostratigraphic study from two Somincor/Lundin Mining exploration holes: Lombador North/NK30B-1, 10 samples, and Corvo-Semblana/SJ32, 20 samples. Laboratory preparation involved standard chemical treatment to extract and concentrate palynomorphs residues (Wood et al., 1996). Oxidation of the palynomorphs was carried out using Schultze solution, from one and a half hour to two hours. Fourteen samples proved to be productive, containing moderate to well preserved palynomorphs. The selected productive residues were mounted in slides and subsequently examined with a transmitted light microscope Nikon Eclipse Ci. All samples, residues and slides are stored at LNEG. The standard Western Europe Miospore biozonal scheme was used for the Famennian ages (Higgs et al., 2000, 2013; Loboziak and Streel, 1981, 1989; Pereira, 1999; Pereira et al., 2007, 2008; Streel et al., 1987). The list of studied taxa is presented in Appendix A. Selected palynomorphs are illustrated in Plates 1–3 .

4. Drill hole description

The two drill holes studied for the present research were selected considering the depth extension of the PQ Fm. in the Lombador North and Corvo-Semblana sectors (Figs. 1 and 2). The research goals were focused in the characterization of the lowermost sediments of the PQ Fm. in the Neves-Corvo mine area, having in mind the geological models defined by autochthonous rooted PQ blocks, identified by drill holes up to 1500 m depth.

4.1. NK30B-1 (Lombador North sector, Figs. 1 and 2)

NK30B-1 drill hole intersected 1427.5 m into of typical Neves-Corvo mine sequence. The basement unit intercepted from 1427.5 m to 1227.0 m consists mainly of shale and quartzite levels of the PQ Fm. An incipient stockwork and distal stratoid levels (0.1–2.3% Cu) are detected involving both the PQ unit and the overlying VSC Neves Fm. (Fig. 3). Associated to black shales from Neves Fm., massive sulphides (0.3–1.2% Cu) and stockwork mineralisation (0.1% to 0.7% Cu) occur from 1211.7 to 1216.9 m. An important fault is reported in the ore horizon hanging wall. From, 1185.4 to 1211.7 m, there is an interval dominated by Neves Fm. black shales interbedded with siltstones. Upwards, from 1164.8 to 1185.4 m, a felsic volcanic rock unit follows. A characteristic and complete Upper VSC sequence is found from 577.5 to 1164.8 m. From surface to 577.5 m, the Mértola Fm. flysch turbidites are identified.

4.2. SJ32 (Corvo-Semblana mine sector, Figs. 1 and 2)

This drill hole reached a total length of 1130.6 m, finishing in black shales and interbedded siliceous shales of the PQ Fm. (847.5–1130.6 m), with a predominance of quartzite layers, between 847.5 and 916 m (Fig. 3A). Incipient distal stockwork was identified at ca. 1085 m, similar to the stockwork mineralization presently mined in the Lombador Neves-Corvo mine sector (Fig. 3B). The interval from 814.8 to 847.5 m, comprises felsic volcanic rocks and pumice breccia in association to Corvo Fm. From 707.5 until 814.9 m were identified black shales interbedded with millimetric levels of siltstones from Neves Fm. are identified. An important thrust fault occurs, ca. 658 m, carrying the exotic allochthonous flysch Mértola Fm. intersection (658.0–665.0 m) and an Upper VSC repetition sequence (665.0–707.5 m). The interval from 323.8 to 658.0 m comprises the normal Upper VSC sequence (Brancanes, Godinho, “Borra de Vinho” and Grandaços Fms.) though the Graça Fm. is absent. Finally, from the top of the drill hole till 323.8 m, turbidites, shales and greywackes from Mértola Fm. are intercepted.

5. Previous palynostratigraphic studies in PQG

The first research based in palynostratigraphy was performed in the easternmost IPB sector in Spain (Gerena-El Garrobo) and allowed to establish a TCo Miospore Biozone of late Givetian age in the PQ Fm. sediments (Lake et al., 1988). The same Spanish section of Gerena-El Garrobo, and also the Rio Tinto railway and the Jarama River sections were recently investigated, and this age has been confirmed (González et al., 2004, 2005), with PQG ages ranging from late Givetian to late Famennian.

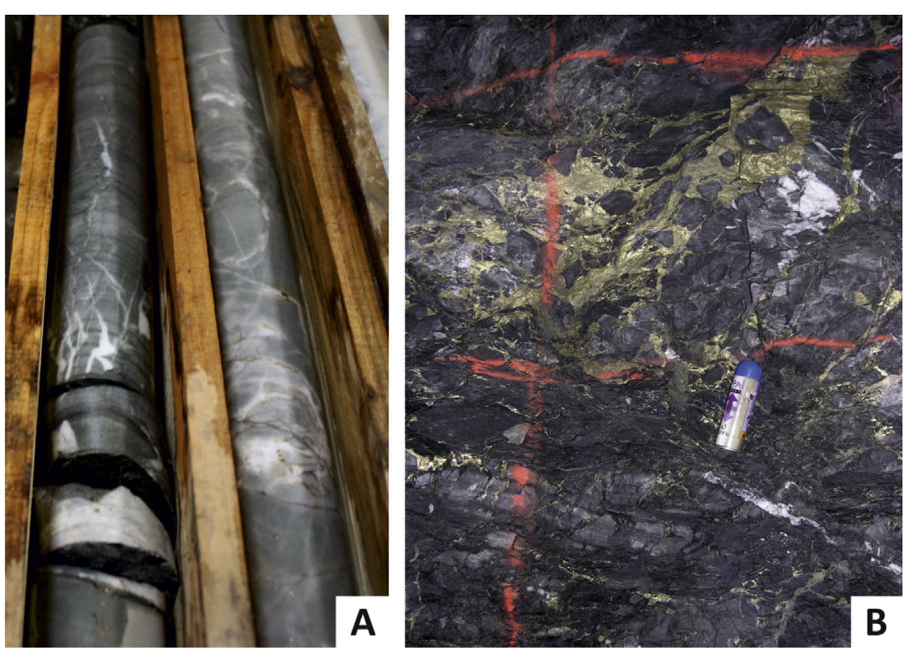

Fig. 3. (A) PQ Fm. quartzites intersected in SJ32 drill hole, 975 m level; (B) Chalcopyrite rich stockwork mineralisation in PQ sediments (quartzites and phyllites) – Lombador Neves-Corvo mine sector.

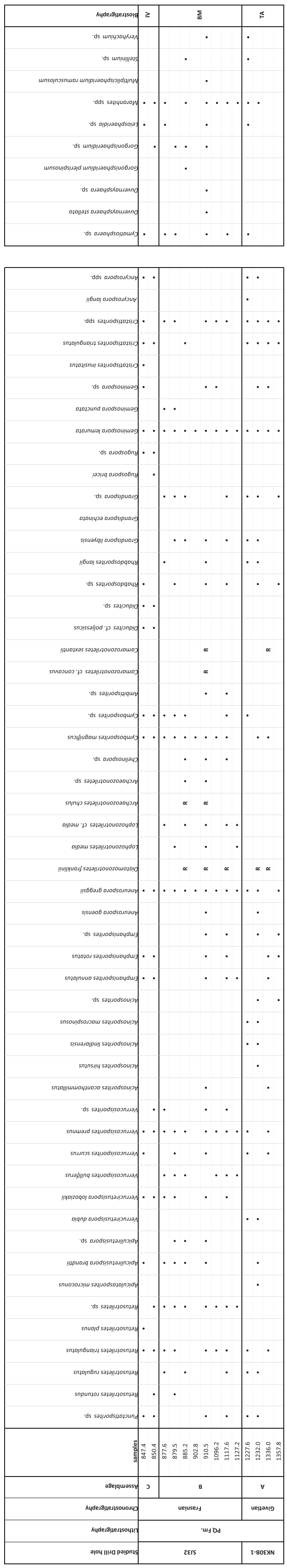

Fig. 4. Chart occurrence from Middle/Upper Devonian palynomorphs assemblages recovered from the NK30B-1 and SJ32 drill holes, Neves-Corvo mine site. R – Reworked taxon.

In the following years more focused projects have been developed in Portugal, allowing a detailed research on PQG, improving the high resolution biostratigraphic knowledge of the entire IPB (Oliveira et al., 1997, 2004; Pereira et al., 2007, 2008, 2012, 2014).

Neves-Corvo mine region typical assemblages in the PQ Fm. are assigned to VCo (the equivalent of *flexuosa-cornuta*), VH and LN Miospore Biozones of late Famennian (Pereira and Oliveira, 2000; Oliveira et al., 2004, 2013a,b; Pereira et al., 2004, 2008, 2014). Reworked Givetian and Frasnian miospores were also documented in all studied samples of this unit (Pereira et al., 2008).

Furthermore, in the sediments below the limestone level with crinoid fossils at the top of the PQ Fm. (Monte Forno da Cal and Lançadoiras sectors), a late Famennian age (VH Miospore Biozone) was documented (Pereira and Oliveira, 2000; Pereira et al., 2014).

At the province scale and along the IPB, in Cercal, Azinheira de Barros, Chaparral, Serrinha, S. Domingos, and Pomarão sectors (Portugal), several PQ Fm. sections and drill holes were investigated based on palynostratigraphy, and a late Famennian age (VH, LL and LN Biozones) was recognised (Pereira et al., 2008; Pereira and Matos, 2012).

The upper sequence of the PQ Fm. is well age-constrained (late to latest Famennian – Strunian) along the IPB, confirming previous conodonts-based age data by Boogaard (1967) and Boogaard and Schermerhorn (1981), in Portugal and in Spain (e.g., Höllinger, 1959).

PQ Fm. basal units were dated in NW IPB São Francisco da Serra antiform and Caveira and Lousal mines (Pereira et al., 2008, 2010a,b, 2012) recognizing AD Miospore Biozone, subzone *lemurata,* indicative of an early Givetian age. Matos et al. (2014) suggest two PQG sequences for this IPB region represented by the Lower Corona Unit (Givetian age) and Upper Corona Unit (late to latest Famennian – Strunian), both represented by phyllites and quartzites. Between the two units an important hiatus was observed in the Lousal and Caveira mines.

In spite of this progress many questions remain to be investigated. Older ages are expected since PQ Fm. is far over 500 m thick in the Neves-Corvo mine area, with unknown base and it is affected by several tectonic repetitions.

6. Palynostratigraphy results

The palynomorph assemblages recovered from NK30B-1 and SJ32 drill holes in PQ Fm. (Figs. 2 and 4) enabled the identification of three fairly preserved assemblages that allowed to identify four miospore biozones. These are characterised by the first occurrence (FO) of particular taxa and the relative abundance of prominent taxa. In stratigraphic order, the palynomorph assemblages and biozones identified are as follows:

6.1. Assemblage A

This assemblage is characterised by a clear dominance of miospores, generally poorly preserved. The recovered assemblage includes common *Acinosporites acanthomammillatus, A. hirsutus, A. lindlarensis, A. macrospinosus, Acinosporites* sp., *Ancyrospora langii, Ancyrospora* sp., *Aneurospora goensis, A. greggsii, Cristatisporites triangulatus*, *Cristatisporites* spp., *Geminospora lemurata, Verrucosisporites premnus* and *Verrucosisporites scurrus.*

Other rare to common taxa complete the assemblage: *Apiculiretusispora brandtii*, *Apiculatasporites microconus*, *Apiculiretusispora* sp., *Chelinospora* sp., *Cymbosporites magnificus*, *Cymbosporites* sp., *Emphanisporites annulatus*, *Emphanisporites rotatus*, *Emphanisporites* sp., *Geminospora* sp., *Grandispora libyensis*, *Grandispora* sp., *Punctatisporites* sp., *Retusotriletes rugulatus*, *R. triangulatus*, *Rhabdosporites langii*, *Rhabdosporites* sp., and rare *Verruciretusispora dubia*, rare to common *Diatomozonotriletes franklinii* and *Camarozonotriletes sextantii* are also present.

Marine palynomorphs were relatively rare, but include *Cymatiosphaera* sp., *Leiosphaeridia* sp., *Maranhites* spp., *Stellinium* sp. and *Veryhachium* sp.

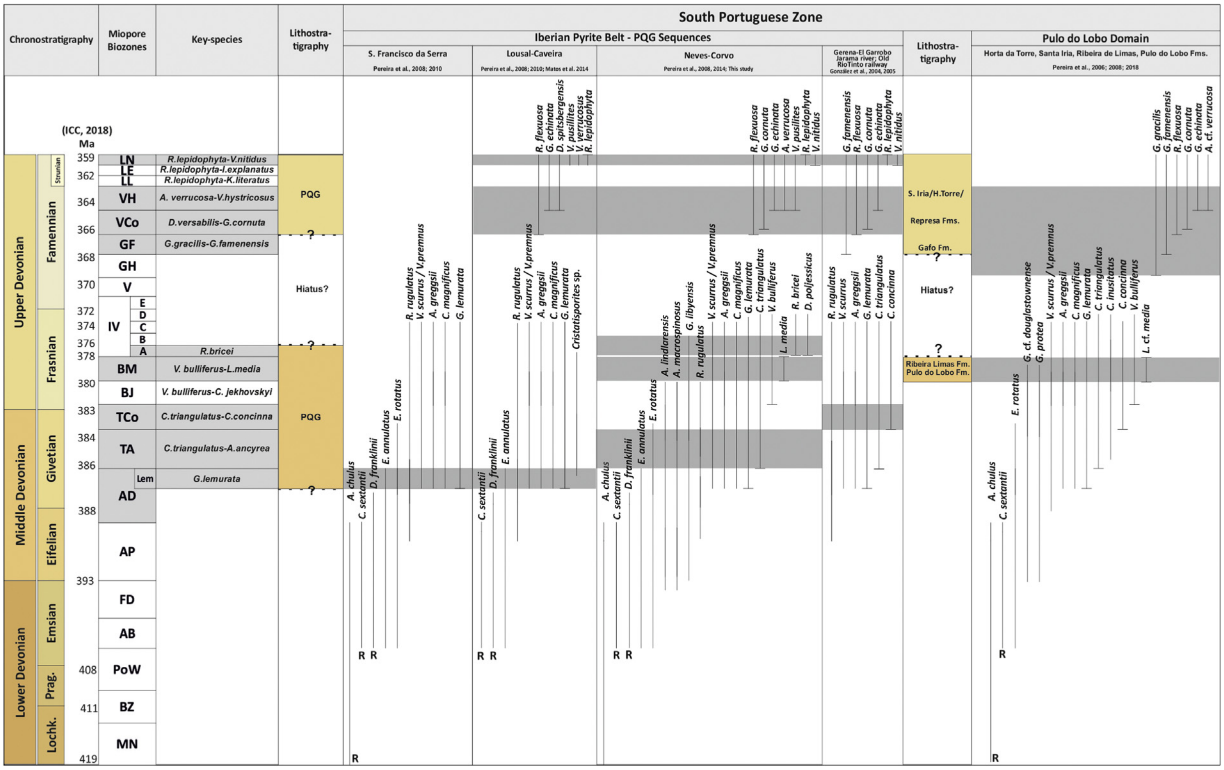

Fig. 5. Zonal scheme and ranges of stratigraphic relevant taxa recovered in this study and correlation with palynoflora data across the South Portuguese Zone. R – Reworked miospores. The zonal scheme follows Higgs et al. (2000, 2013), Pereira et al. (2008), Loboziak and Streel (1981, 1989) and Streel et al. (1987).

Occurrence: Drill hole NK30B-1, sample interval 1227.60–1357.50 m, in PQ Fm. (Fig. 2).

6.2. Assemblage B

Assemblage B is marked by a well-preserved miospore assemblage, with a dominance of miospores and common miospore tetrads.

This assemblage comprehends abundant *Aneurospora greggsii*, *Cristatisporites triangulatus*, *Geminospora lemurata*, *Verruciretusispora loboziakii*, *Verrucosisporites bulliferus*, *V. premnus*, *V. scurrus* and *Verrucosisporites* sp. Common taxa such as, *Acinosporites acanthomammillatus*, *Aneurospora goensis*, *Apiculiretusispora brandtii*, *Camarozonotriletes* cf. *concavus*, *Chelinospora* sp., *Cristatisporites* spp., *Cymbosporites magnificus*, *Cymbosporites* sp., *Emphanisporites annulatus*, *E. rotatus*, *Emphanisporites* sp., *Geminospora punctata*, *Geminospora* sp., *Grandispora libyensis*, *Grandispora* sp., *Lophozonotriletes media*, *L.* cf. *media*, *Punctatisporites* sp., *Rhabdosporites langii*, *Rhabdosporites* sp., *Retusotriletes rotundus*, *R. rugulatus*, *R. triangulatus*, *Retusotriletes* sp., is also common in this assemblage. Moreover, rare *Archaezonotriletes chulus*, *Archaezonotriletes* sp., *Ambitisporites* sp., *Camarozonotriletes sextantii*, *Camarozonotriletes* cf. *concavus*, and *Diatomozonotriletes franklinii*, are found.

Acritarchs and prasinophytes are poorly represented in the assemblage, but *Cymatiosphaera* sp., *Duvernaysphaera stellata*, *Duvernaysphaera* sp., *Gorgonisphaeridium plerispinosum*, *Gorgonisphaeridium* sp., *Leiosphaeridia* sp., *Maranhites* spp., *Multiplicisphaeridium ramusculosum* and *Veryhachium* sp. occur.

Occurrence: Drill hole SJ32, sample interval from 877.60 to 1127.2 m, in PQ Fm. (Fig. 2).

6.3. Assemblage C

This assemblage is marked by low diversity of palynoflora, with miospore taxa generally poorly preserved. Common *Aneurospora greggsii*, *Apiculiretusispora brandtii*, *Cristatisporites inusitatus*, *Cristatisporites triangulatus*, *Cristatisporites* spp., *Cymbosporites magnificus*, *Cymbosporites* sp., *Diducites* sp., *Emphanisporites annulatus*, *Emphanisporites rotatus*, *Geminospora lemurata*, *Geminospora* sp., *Punctatisporites* sp., *Rhabdosporites* sp., *Retusotriletes planus*, *Retusotriletes rotundus*, *Retusotriletes triangulatus*, *Retusotriletes* sp., *Rugospora* sp., *Verrucosisporites premnus*, *Verrucosisporites scurrus*, *Verrucosisporites* sp. and *Verruciretusispora loboziakii* were present. Rare acritarchs and prasinophytes were found.

Occurrence: Drill hole SJ32, samples collected at 847.4 and 850.4 m, in the uppermost sequence of PQ Fm. (Fig. 2).

7. Discussion

Palynostratigraphic assemblages identified in PQ Fm. sedimentary facies from Neves-Corvo mine are assigned to the mid Givetian to mid Frasnian and late Famennian ages.

Mid Givetian to mid Frasnian PQ Fm. assemblages testify the presence of common reworked spores of Early to Middle Devonian age.

Assemblage A includes the zonal species *Cristatisporites triangulatus* recovered and having the FO at the base of *Cristatisporites triangulatus* – *Ancyrospora ancyrea* (TA Miospore Biozone, defined by Streel et al., 1987 for the Ardenne-Rhenish regions), and indicating a mid Givetian age. Common to abundant *Acinosporites* spp. and *Ancyrospora* spp. confirm the TA Biozone, being characterised by common dominance of these taxa (Streel et al., 1987). Some species such as *Cristatisporites* spp. and *Ancyrospora* spp., present poorly preserved ornamental elements and their taxonomy was left in open nomenclature. The specimens *Diatomozonotriletes franklinii* and *Camarozonotriletes sextantii,* were interpreted as Early to Middle Devonian reworked taxa.

Assemblage B is marked by the presence of the key species *Verrucosisporites bulliferus* and *Lophozonotriletes media* indicating the BM Miospore Biozone of mid Frasnian age (Late Devonian). The basal BM Biozone is marked by the joint occurrence of *Verrucosisporites bulliferus*, which emerged on the base of the previous Biozone BJ (*Verrucosisporites bulliferus* – *Cirratriradites jekhowskyi*) and the FO of *Lophozonotriletes media* (Richardson and McGregor, 1986; Streel et al., 1987; Loboziak and Streel, 1989).

In this assemblage, Archaezonotriletes chulus, Camarozonotriletes sextantii, Camarozonotriletes cf. concavus, and Diatomozonotriletes franklinii, could be interpreted as reworked taxa of Early and Middle Devonian age.

Assemblage C is characterised by the presence of *Rugospora bricei* and *Diducites* cf. *poljessicus,* of mid Frasnian age (Late Devonian). These taxa (and the genus *Diducites*) are common in western Europe and their FO are used to define the base of Biozone IV (Streel et al., 1987; Loboziak and Streel, 1989; Loboziak and Melo, 2002). This assemblage also presents a decrease in taxa diversity and preservation when compared with the preceding BM Miospore assemblages in same drill hole. This is probably related to pos-depositional Famennian felsic volcanic activity and the occurrence of stockwork vein mineralization within the PQ sediments. It is the case of drill hole SJ32 (Fig. 3), where a felsic volcanic pumice breccia unit associated to Corvo Fm. (Lower VSC) and an incipient pyritic-based stockwork mineralisation occur. Identical geology is also observed in NK30B-1.

8. Palynostratigraphic significance and correlation across IPB

The new data recovered in the lowermost PQ Fm. in the Neves-Corvo mine region indicate a palynomorphs-based age of mid Givetian/mid Frasnian. The oldest age identified in the PQ Fm. in the Neves-Corvo mine region is now assigned to the mid Givetian (based on the FO of *Cristatisporites triangulatus*, TA Miospore Biozone).

Considering the environmental deposition of the lowermost PQG sequence of mid Givetian/mid Frasnian silty/shale facies content, with some minor quartzite beds, it may suggest a predominant deep water basin deposition environment with local confined areas with favourable siliciclastic shallower platform deposition. Besides the constraints related to the drill hole information, the quartzite layers present a <10 m thickness and probably not a long extension, as it is common in the upper PQG sequences.

Large quantities of organic material in pristine state were transported into deep waters, as supported by recovered palynological assemblages. These include abundant miospores, miospore tetrads and phytoclasts (proximal organic matter), along with rare acritarchs and prasinophytes, confirming the deposition in a marine deeper water environment. This setting is also confirmed by the sedimentary facies observed during the drill hole logging.

Age correlations could be established with PQ Fm. occurring in the NW and E regions of IPB (Fig. 5), in particular with the studied sections of São Francisco da Serra and Lousal-Caveira antiforms (Matos et al., 2014; Pereira et al., 2008, 2010a,b) and the Gerena-El Garrobo sector in Spain, respectively (González et al., 2004). The same age and similar palynostratigraphic event were identified in the lowermost PQ Fm. in IPB NW sector (early to mid Givetian age is based on the identification of the AD Miospore Biozone, subzone *lemurata*) and in the IPB E sector a mid-late Givetian age is assigned to the TCo Miospore Biozone, based on the FO of *C. triangulatus* and *C. concinna;* (see Fig. 5).

These data display a typical palynoassemblage containing the miospores *A. greggsii*, *Cristatisporites* spp., *C. magnificus*, *G. lemurata*, *R. rugulatus*, *V. scurrus* and *V. premnus* of Givetian age, which are a common feature identified in the lowermost sequence of PQ Fm. throughout the entire IPB. Moreover, all studied sequences contain the same reworked miospores signature. Except for Gerena-El Garrobo case study (González et al., 2004), where reworked spores were not identified possibly due to the poor state of alteration indicated by the authors for the majority of the taxa.

From this point, a detailed microflora correlation along the IPB can be established concerning the Givetian age of the lower sequence of the PQ Fm.

In Neves-Corvo mine region, the lowermost PQ Fm. reaches the mid Frasnian age based on palynomorphs (FO of *L. media* and *V. bulliferus*, BM Miospore Biozone, and based on the FO of *R. bricei* and *D.* cf. *poljessicus*, IV Miospore Biozone) that could correspond to a continuous sedimentary record, even considering a major complex tectonic setting.

Concerning the upper sequence of the PQ Fm., a late Famennian age based on palynomorphs was identified (VCo, VH and LN Miospore Biozone), in several sections across IPB, namely in Lousal-Caveira mines, Neves-Corvo mine, Mértola and São Domingos mine, and in Spain in the Jarama River and Old Rio Tinto Railway (Pereira and Oliveira, 2000; Oliveira et al., 2004, 2013a,b; Pereira et al., 2004, 2008, 2014; Pereira and Matos, 2012; González et al., 2005). A major hiatus could be identified from the mid Frasnian to mid Famennian along IPB (see Fig. 5). This hiatus of about 10 Myr could permit the division of PQ Fm. into two major sequences: lower PQ Fm. dated of mid Givetian/mid Frasnian age and the upper PQ Fm. dated of late Famennian age (and reaching latest Famennian–Strunian age). This upper PQ sequence is coeval with the lower VSC sequence, both formed in a more unstable basin, in a volcano-sedimentary paleogeographic setting.

The Miospore Biozones identified in the lower PQ Fm. sequence displays a sedimentary deposition trend, beginning in early Givetian in NW IPB (S. Francisco, Lousal and Caveira) to late Givetian in the E IPB (Gerena-El Garrobo) sector (Figs. 5 and 6) This regional trend is based on

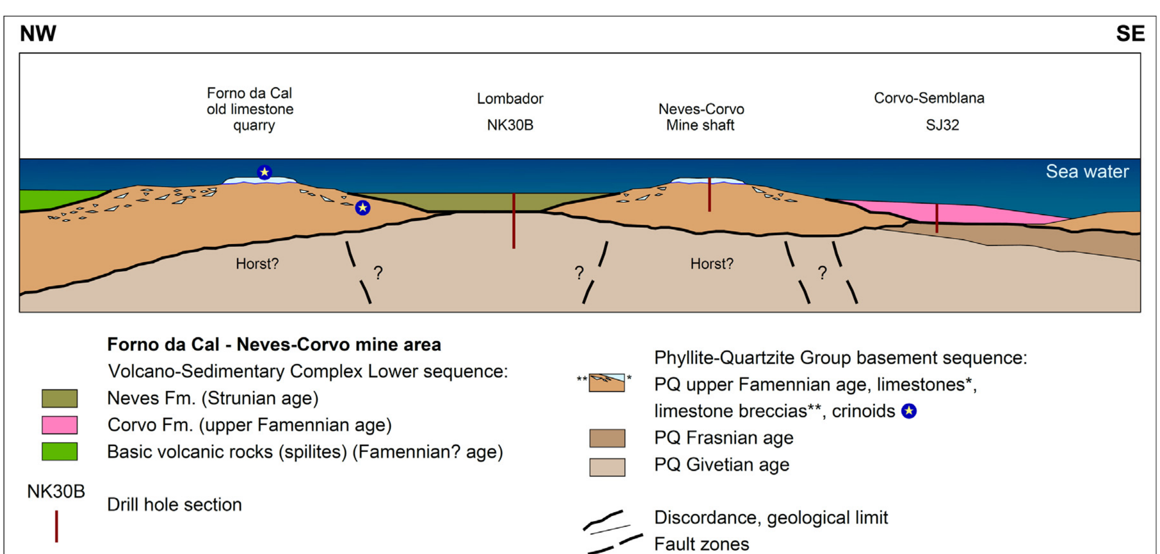

Fig. 6. Conceptual geological model for the deposition of PQ Group basement sediments between Forno da Cal sector and the Neves-Corvo mine area, during Devonian times.

the present data and must be confirmed in future research work. Though this regional trend observed in lower PQ Fm. is almost coincident with the eastwards trend of the subsequent volcanism, which is older in the WNW sector (Cercal area, Alentejo) and younger in ESE sector (Rio Tinto area, Andalusia) (e.g., Carvalho, 1976; Rosa et al., 2009).

Having in mind the stratigraphic distribution of the microflora assemblages reported above in several sections across the IPB (Fig. 5), it is evident that similar microflora occurs across the province. This might suggest the same paleogeographic domain, the same temporal sedimentation and probably the same sediment source provenance. Similar interpretation is considered by some authors based in zircon U/Pb data (Pérez-Cáceres et al., 2017 and references therein).

From this research, some important interpretation issues can be stated: (i) An early-mid Givetian to mid Frasnian age could be recognised in basement IPB (PQ Fm.); (ii) A stratigraphic hiatus seems to be present from mid Frasnian to mid Famennian. This hiatus representing ca. 10 Myr has full expression across the IPB (Lousal and Caveira mines, Neves-Corvo mine and Gerena- El Garrobo section). Nevertheless, the complex tectonic setting, sampling restrictions, non-deposition periods or an erosive event, could explain this time gap. Likewise, the basin geometry and development were probably conditioned by extensional faults increasing the erosion rates or/and the sea level changes (Oliveira et al., 2013a,b, 2019; Matos et al., 2014; Martin-Izard et al., 2016). These structures represent the basin instability and would definitively favour the extensional phase coeval with the beginning of the bimodal volcanism in IPB.

Reworked spores of Lower to Middle Devonian age are a common presence in South Portuguese Zone (SPZ) studied sections, in particular the taxa *Ambitisporites* sp., *Archaezonotriletes chulus, Camarozonotriletes sextantii*, *Diatomozonotriletes franklinii*. The source of these reworked palynomorphs remains unclear and suggest that the age of the substrate is not yet fully understood.

U-Pb ages in zircon enforces this concept since inherited ages as old as 414-416 Ma (Lochkovian age, Early Devonian, Solá et al., 2015; Albardeiro et al., 2017) are found in felsic volcanic rocks (Lower and Upper VSC sequences) in Neves-Corvo mine region, and a maximum deposition age of 419 ± 5.5 Ma (Silurian/Devonian boundary) was achieved in PQ Fm. quartzites of drill hole SJ32 (Mendes et al., 2018a, b). These data could suggest that IPB PQ Fm. source(s) basin, could be, at least in the study area, as old as ca. 419 Ma and/or probably older, being contemporaneous of the reworked spores.

The presence of these reworked materials may reinforce the local erosion of older stratigraphic units within the PQ Fm. (basal or other unknown units), further deposited and incorporated in the PQ Fm. older known sediments (mid Givetian to mid Frasnian age).

Future research must be focused in the enlargement of the sampling program covering other case study sites. The understanding of the sedimentary chemistry of the two PQ sequences is also important.

Fig. 6 presents a conceptual model of the Neves-Corvo sector of the basin, showing the different VSC units (basic volcanic rocks and the Neves and Corvo Fms.) deposited directly above the PQ basement represented by sediments of different ages, from mid Givetian to late Famennian. Two major unconformities can be identified, in a VSC/upper and/or lower PQ sequence and in an upper PQ/lower PQ sequences. This model is supported by drill hole studies but also by mapping (e.g. Almodôvar map, Oliveira et al., 2016).

9. Correlation between South Portuguese Zone and North Gondwana

Coeval palynological assemblages of mid Givetian and mid Frasnian age are documented in north Gondwana. The same palynozones, with the same key species identified in IPB and SPZ and presented in this work, were documented in north Gondwana, in Algeria (Moreau-Benoit et al., 1993; Boumendjel et al., 1988a,b), in Saudi Arabia and Tunisia (Breuer and Steemans, 2013), and in Libya (Moreau-Benoit, 1989; Spina et al., 2018). Palynological assemblages referred also present the taxa *Diatomozonotriletes franklinii* and *Camarozonotriletes sextantii,* attributed to Early to Middle Devonian and interpreted as reworked taxa (as for instance in Breuer and Steemans, 2013). These taxa are described in Early Denonian assemblages of Libya (Spina and Vecoli, 2009; Rubinstein and Steemans, 2002). This correlation could sugest that SPZ (Avalonia) and north Gondwana, during Middle Devonian, were in a close paleogeographic realm.

10. Conclusions

The detailed palynostratigraphic study of two sections intercepting the PQ Fm. in the Neves-Corvo mine region (Portuguese sector of the Iberian Pyrite Belt), give the following main results:

- The PQ Fm. palynostratigraphic study provided for the first time the mid Givetian/mid Frasnian age (based on the identification of TA, BM and IV (subzone A), Miospore Biozones), being the oldest ages ever found for this formation sediments in the Rosário-Neves-Corvo region.
- The presence of common Early-Middle Devonian reworked spores and the lowermost Devonian maximum deposition age given by U-Pb geochronology in zircons, suggest that the lower ages of PQG are still an open question.
- A detailed palynological correlation of PQ Fm. sediments along IPB is established, identifying a mid Givetian/mid Frasnian deposition across IPB, with similar palynoflora and reworked taxa, followed by a recognised stratigraphic hiatus of ca. 10 Ma from mid Frasnian to, at least, late Famennian age.
- The palynological record obtained in different areas of IPB suggests close paleogeographic and temporal affinity throughout the lowermost PQ Fm., reflecting similar palynofloras (also including the same reworked taxa), and similar ages. This temporal and palynoflora affinity could suggest identical sedimentary provenance.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Species listed in this work

All spores, acritarchs and prasinophytes taxa recovered from the studied material are listed alphabetically with full author citations.

A.1 Spore

Acinosporites acanthomammillatus Richardson, 1965
Acinosporites hirsutus (Brideaux and Radforth) Richardson and McGregor, 1982
Acinosporites lindlarensis Riegel, 1968
Acinosporites macrospinosus Richardson, 1965
Acinosporites sp.
Ambitisporites sp.

Ancyrospora langii (Taugourdeau-Lantz) Allen, 1965
Ancyrospora spp.
Aneurospora goensis Lele and Streel, 1969
Aneurospora greggsii (McGregor) Streel, 1974
Apiculatasporites microconus (Richardson) McGregor and Camfield, 1982
Apiculiretusispora brandtii Streel, 1964
Apiculiretusispora cf. *verrucosa* (Caro-Moniez) Streel in Becker et al., 1974
Apiculiretusispora sp.
Archaezonotriletes chulus (Cramer) Richardson and Lister, 1969
Archaezonotriletes sp.
Camarozonotriletes cf. *concavus* Loboziak and Streel, 1989
Camarozonotriletes sextantii McGregor and Camfield, 1976
Chelinospora sp.
Cristatisporites inusitatus (Allen) McGregor and Camfield, 1982
Cristatisporites triangulatus (Allen) McGregor and Camfield, 1982
Cristatisporites spp.
Cymbosporites magnificus (McGregor) McGregor and Camfield, 1982
Cymbosporites sp.
Diatomozonotriletes franklinii McGregor and Camfield, 1982
Diducites cf. *poljessicus* (Kedo) Van Veen, 1981
Diducites sp.
Emphanisporites annulatus McGregor, 1961
Emphanisporites rotatus (McGregor) emend. McGregor, 1973
Emphanisporites sp.
Geminospora lemurata (Balme) emend. Playford, 1983
Geminospora punctata Owens, 1971
Geminospora sp.
Grandispora libyensis Moreau-Benoit, 1980
Grandispora sp.
Lophozonotriletes media Taugourdeau-Lantz, 1967
Lophozonotriletes cf. *media* Taugourdeau-Lantz, 1967
Punctatisporites sp.
Retusotriletes planus Dolby and Neves, 1970
Retusotriletes rotundus (Streel) Streel, 1967
Retusotriletes rugulatus Riegel, 1973
Retusotriletes triangulatus (Streel) Streel, 1967
Retusotriletes sp.
Rhabdosporites langii (Eisenack) Richardson, 1960
Rhabdosporites sp.
Rugospora bricei Loboziak and Streel, 1989
Rugospora sp.
Verruciretusispora dubia (Eisenack) Richardson and Rasul, 1978
Verruciretusispora loboziakii Higgs and Finucane, 2002
Verrucosisporites bulliferus Richardson and McGregor, 1986
Verrucosisporites premnus Richardson, 1965
Verrucosisporites scurrus (Naumova) McGregor and Camfield, 1982
Verrucosisporites sp.

A.2 Microphytoplankton

A.2.1 Acritarchs

Gorgonisphaeridium plerispinosum Wicander, 1974
Gorgonisphaeridium sp.
Multiplicisphaeridium ramusculosum (Deflandre) Lister, 1970
Stellinium sp.
Veryhachium sp.

A.2.2 Algae

Cymatiosphaera sp.
Duvernaysphaera stellata Deunff, 1964
Duvernaysphaera sp.
Leiosphaeridia sp.
Maranhites spp.

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