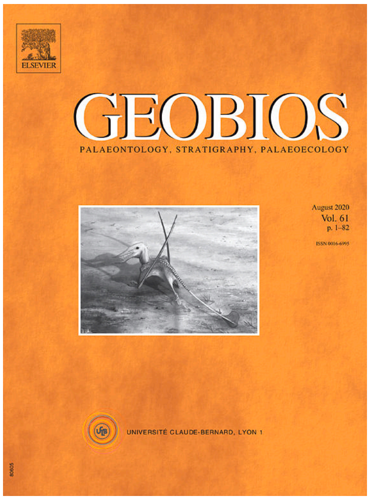

Original article

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Biostratigraphic and structural research in the Guedelhinha–Lançadoiras–Algaré sector in the context of the geology of the Neves–Corvo mine region, Iberian Pyrite Belt ✡

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Abstract

Based on drill hole sampling and sedimentary rock dating by palynology, the present research focuses on the palynostratigraphic events established in the key geological section of Guedelhinha–Lançadoiras–Algaré located in the Portuguese Neves–Corvo mine region, Iberian Pyrite Belt. The age data allow detailing the lithostratigraphic sequence and further understanding the complex structural setting, representing an important contribution to the geological knowledge of this sector located to the immediate WNW of the Neves–Corvo

VMS deposit. The combination of the studied events allows the reconstruction of the Devonian-Carboniferous sedimentation and paleoenvironments along the Iberian Pyrite Belt. Several stratigraphic hiatuses identified in the Neves–Corvo region by the palynological record are confirmed, mainly occurring from the mid Frasnian to mid Famennian, from the early and mid Strunian, and from the early to late Tournaisian, which were mainly coincident with the worldwide extinction events, in particular during Frasnian–Famennian and Late Devonian times. Extensional tectonics and related gravitational faults and local uplift mechanisms could also explain the lack of palynological data and sedimentary hiatus. In this research, the importance of the late Strunian times in the Iberian Pyrite Belt (Miospore Biozone LN of the Neves Formation) is highlighted, confirming the contemporaneity of felsic volcanism, hydrothermalism, sulphide mineralization precipitation and black shale anoxic sedimentation.

Keywords:

Devonian

Carboniferous

Palynostratigraphy

Neves–Corvo VMS deposit

Iberian Pyrite Belt

1. Introduction

The Devonian and Carboniferous were critical periods on Earth´s history marked by important mass extinctions, particularly in the Frasnian-Famennian (Kellwasser event; Late Devonian) and in the Devonian-Carboniferous boundary (Hangenberg event) that impacted both land plants and marine phytoplankton (Kaiser, 2005; Kaiser et al., 2015; Van De Schootbrugge and Gollner, 2013). Focusing on these events and how they affected the biota and sediment deposition during these periods, the study of the Iberian Pyrite Belt (IPB; located in the south of Portugal and Spain) becomes essential, since it corresponds to a well-developed Late Devonian to mid Carboniferous marine basin (Tornos, 2006; Inverno et al., 2015) coincident with a period where the marine realm is affected by an anoxic event marked by the deposition of black shales, felsic volcanics, as well as massive sulphide mineralization (Barriga et al., 1997; Leistel et al., 1998; Carvalho et al., 1999; Tornos, 2006; Oliveira et al., 2013a, 2013b). Here, the Devonian and Carboniferous main extinction events are discussed in the light of the palynological and geochronological record, in close relationship with the stratigraphic hiatus known in the stratigraphic record, particularly in the geology of the Neves–Corvo mine region situated at the southeastern sector of the Rosário antiform, in the IPB (Oliveira et al., 2005, 2013b, 2019; Fig. 1).

The Neves–Corvo mine lithostratigraphic sequence is the most studied in the IPB, based mainly on major exploration programs developed by Somincor/Lundin Mining, complemented by research on palynostratigraphy, geochronology and geophysical surveys that involved hundreds of studied drill holes (Oliveira et al., 2004, 2013b; Matos et al., 2020a, 2020b; Mendes et al., 2020; Pereira et al., 2008, 2021). The use of high-resolution stratigraphy based on palynology is a fundamental proxy for near-mine exploration purposes in the IPB, in particular in the Neves–Corvo mine area, where it proved to be a useful tool to precisely determine the relative ages of the lithostratigraphic sedimentary units and to define the age of the black shales hosting the late Strunian mineralization (LN Miospore Biozone; Oliveira et al., 1997, 2004, 2013, 2016; Pereira et al., 2004, 2008, 2014, 2021; Mendes et al., 2017). Encouraged by these results and under the scope of the recent research projects IPB Vectors and EXPLORA, more sections and drill holes were studied and new palynostratigraphic data acquired. Accordingly, this study highlights detailed palynological data collected in eight drill holes located at the Guedelhinha–Lançadoiras–Algaré section (Fig. 1): GU09001, 965 m depth; LC1, 1017 m; CA2, 287 m; CA1, 503 m; NY19, 1934 m; CA3, 890 m; CA11004, 1120 m (Fig. 2); and CA1105, 1085 m depth (Fig. 3). Relog-based interpretative cross-sections were produced based on data provided by palynostratigraphy and geochronology, considering the regional geological setting (Figs. 2, 3). Somincor/Lundin Mining drill hole database and surface geological mapping (Almodóvar 46C 1/50.000 scale Geological Map; Oliveira et al., 2016; Matos et al., 2020a) were essential to produce the presented geological and structural model. Altogether, the analyzed data allow the identification of palynostratigraphic events and paleoenvironments in the Devonian-Carboniferous sediments of the Neves–Corvo NW mine region.

2. Geological setting and stratigraphy of the Neves–Corvo mine succession

The IPB sedimentation began in the late Middle Devonian times, with the deposition of the Phyllite-Quartzite Group in a siliciclastic open platform related to an epicontinental sea environment (Oliveira, 1983, 1990; Pereira et al., 2008, 2021; Mendes et al., 2020). During this period, the basin was subject to extensional processes leading to the strong compartmentation of the IPB basin and the beginning of submarine bimodal volcanism (Oliveira, 1990; Oliveira et al., 2013a, 2019). The VMS deposits and related hydrothermal systems occur in close association with felsic volcanic rocks and black shales that belong to the Volcano-Sedimentary Complex (VSC, late Famennian to late Visean in age; Oliveira et al., 2005, 2013a, 2013b, 2019; Relvas et al., 2006; Inverno et al., 2015). During late Visean, the tectonic regime changed to crustal compression, and the synorogenic Baixo Alentejo Flysch Group was deposited in this setting, overlying the VSC. This flysch sedimentation occurred until late Moscovian times (Oliveira, 1990; Silva et al., 2013a; Oliveira et al., 2019). This compressive stage generated NW-striking folding and thrusting with significant tectonic transport verging to the SW. Stacked thrust sheets are confirmed by drill holes and seismic reflectors (Silva et al., 1990; Oliveira et al., 2013a, Inverno et al., 2015; Carvalho et al., 2017; Matos et al., 2020b; Marques et al., 2022).

Regarding the stratigraphy of the Neves–Corvo mine area (Oliveira et al., 2004; Pereira et al., 2008; Oliveira et al., 2013a, 2013b, 2016; Mendes et al., 2018; 2020; Fig. 1), three main units defined at the regional scale were documented, from base to top (Figs. 1-

3): the Phyllite-Quartzite Group (PQG), the Volcano-Sedimentary Complex (VSC), and the Mértola Fm. (lower unit of the Baixo Alentejo Flysch Group).

The PQG siliciclastic basement comprises phyllites and quartzites of the Phyllite-Quartzite Fm. of mid Givetian-late Famennian age (base unknown), with a total thickness of more than 800 m (Pereira et al., 2008, 2014, 2021; Mendes et al., 2018a, 2018b, 2020). The uppermost part of this formation can locally contain limestones bearing crinoid-rich beds (Forno da Cal quarry limestones; Leca et al., 1983; Mendes et al., 2020).

The VSC is divided into a Lower and an Upper VSC sequence (Fig. 2), separated by a mid to late Tournaisian sedimentary stratigraphic hiatus (Oliveira et al., 2004, 2013b, 2016; Pereira et al., 2008, 2014; 2021). The Lower VSC sequence comprises bimodal volcanic rocks (essentially felsic volcanic rocks, including coherent and abundant autoclastic rhyolites and rhyodacites, pumice breccias, and minor basalt lava flows and intrusive mafic volcanic rocks, with a total thickness that can reach ca. 500 m (Rosa et al., 2016), dark-grey shales of ca. 40 m thick, the Corvo Fm. (only exposed in underground mine levels) of Famennian age, and black pyritic shales of the Neves Fm., with variable thicknesses from a few meters to ca. 100 m, that interfinger with the felsic volcanic rocks and host the massive sulphide mineralization (Oliveira et al., 2004, 2013; Pereira et al., 2008). The Neves Fm. sediments are late Famennian (Strunian) in age based on the LN Miospore Biozone (*Retispora lepidophyta–Verrucosisporites nitidus*). The Neves Fm. is an important key stratigraphic guide horizon for exploration purposes not only in the Neves–Corvo mine region, but also in other sectors of the IPB (e.g., Lousal, Caveira, Herrerias-Tharsis, and Aznalcóllar areas, according to González et al., 2002; Oliveira et al., 2004, 2013b; Pereira et al., 2008, 2012, 2014; Matos et al., 2011, 2014, 2020b; Saez et al., 2011). On top of this mineralized sequence, a commonly discontinuous unit of jaspers and exhalative carbonates (JC unit) occurs (Oliveira et al., 2004, 2013).

The Neves–Corvo mine VSC volcanic facies have been previously classified based on chemostratigraphic criteria (rhyolites type 1, 2 and 3; Tim Barrett, 2006, 2008 unpub. AGC/Somincor/Lundin Mining report; Albardeiro et al., 2017, 2020) and on physical volcanology features (Rosa et al., 2008, 2016). They range from volcaniclastic transported facies with fiamme, quartz-feldspar crystals and lithic fragments to massive-coherent and autoclastic facies. Rhyolite types 1 and 2 occur associated with the Neves Fm. black shales and the Corvo Fm. shales and in massive sulphides footwall. Rhyolite type 3 occurs in the massive sulphides hangingwall and stockworks (Rosa et al., 2008, 2016) and commonly above these mineralizations.

The geochronology of volcanic rhyolites rocks (U–Pb in zircon) ranges from late Famennian to Tournaisian (ca. 349-363 Ma), i.e., a time span of ca. 14 myr (Solá et al., 2015; Albardeiro et al., 2017, 2020, in press). The late Famennian rhyolites are related to ore-forming hydrothermal activity, and the Tournaisian rhyolites represent a later, barren volcanic episode including exclusive Rhyolite type 3 rocks (Albardeiro et al., 2017). The late Famennian zircon ages overlap (within uncertainty) the cassiterite U-Pb ages of Neves–Corvo early cassiterite mineralization (363-366 Ma; Li et al., 2019).

The Upper VSC (ca. 350-400 m in total thickness) is represented, from the base upwards, by (Oliveira et al., 2004, 2013b, 2016; Pereira et al., 2008, 2014, 2021; Fig. 1): (*i*) shales, siltstones and fine-grained volcanogenic rocks (Ribeira de Cobres Fm., uncertain age); (*ii*) dark-grey shales with siliceous-phosphate nodules (Graça Fm., with miospore assemblages from the TS Biozone of early Visean age to the NM Biozone of mid-late Visean age); (*iii*) grey shales with carbonate nodules, volcanogenic sedimentary rocks and intrusive mafic volcanic rocks (Grandaços Fm., mid-late Visean age based on the NM Miospore Biozone), (*iv*) purple and green shales (Borra de Vinho Fm., mid-late Visean age); (*v*) siliceous shales and volcanogenic sedimentary rocks (Godinho Fm., mid-late Visean age based on the NM Miospore Biozone); and (*vi*) grey and black pyritic shales with minor greywackes (Brancanes Fm., mid-late Visean age based on the NM Miospore Biozone).

The Upper VSC is overlain by the Mértola Fm. (ca. 3000 m thickness in the type-area, Mértola region), the lowermost unit of the Baixo Alentejo Flysch Group (of mid-late Visean age; Oliveira, 1983; Pereira et al., 2008, 2014, 2021; Oliveira et al., 2013b), composed by a turbidite sequence with alternating dark-grey shales and greywackes. In the Neves–Corvo mine area, these turbidite sequences were chronologically distinguished based on palynostratigraphy as MT1 (*Raistrickia nigra*–*Triquitrites marginatus* [NM] Miospore Biozone), MT2 (*Tripartites vetustus*–*Rotaspora fracta* [VF] Miospore Biozone), and MT3 (*Bellisporites nitidus*–*Cingulizonates capistratus* [NC] Miospore Biozone; Oliveira et al., 2004). The Mértola Fm. turbidites outcrops in large areas of the Neves–Corvo region, showing great thickness as confirmed by exploration drilling and geophysics (Oliveira et al., 2013b, 2016; Inverno et al., 2015; Carvalho et al., 2017; Matos et al., 2020a, 2020b).

A key geological section up to 1,800 m depth and located in the Neves–Corvo WNW region is discussed and illustrated in Figs. 1-3. The section is based on the relogging of eleven exploration drill holes and sampling of eight drill holes. The 4,100 m long cross-section includes from SW to NE the Guedelhinha structure, the Brancanes Antiform, and the Lançadoiras and Cerro do Algaré (Algaré) sectors of the Rosário–Neves–Corvo Antiform (Oliveira et al., 2013a, 2013b, 2016; Fig. 2). Borehole CA1105 (Fig. 3) is located 1 km N of the studied section. Age dating of the sediments by palynology allowed producing an accurate geological and structural model and its correlation with the Neves–Corvo mine sector.

The area is tectonically characterized by southwest verging thrust-sheets (Leca et al., 1983; Carvalho and Ferreira, 1994; Oliveira et al., 1997, 2013b; Oliveira et al., 2013, 2016; Inverno et al., 2015). Late Variscan strike-slip faults with local hectometric horizontal and vertical movements also occur, some reflected on the gravity Bouguer anomaly gradients (Matos et al., 2020a, 2020b) and seismic reflectors (Carvalho et al., 2017) (Fig. 1).

3. Material and methods

Eight drill holes were selected and sampled to investigate the Guedelhinha (GU09001’), Lançadoiras (LC1), and Algaré (CA1, CA2, NY19, CA3, CA1104, CA1105) sectors (Figs. 1-3). Core samples collected for palynology studies were referenced by their corresponding depths along the hole traces (Fig. 2). The total number of studied samples per drill hole, and those that yielded positive results, are listed in Table S1 (Appendix A).

For the palynostratigraphy study, 197 sedimentary samples were collected from all seven drill holes, with 99 productive results. Standard palynological laboratory procedures

(Wood et al., 1996) were performed at the National Laboratory of Energy and Geology (LNEG) to extract and concentrate the palynomorphs. The slides were examined in transmitted light using a BX40 Olympus and Eclipse Ci microscopes. All samples, residues and slides are stored at LNEG facilities in São Mamede de Infesta, Portugal. Table S2 (Appendix A) details the palynomorph assemblages documented in the Guedelhinha–Lançadoiras–Algaré geological section, and selected palynomorphs are illustrated in Figs. 4-6 (see Table S3, Appendix A for detailed descriptions). Fig. 7 shows the range chart of the selected species, with emphasis on the miospore and acritarch events, based on the first occurrence of taxa.

4. Guedelhinha–Lançadoiras–Algaré section

The cross-section of the Guedelhinha–Lançadoiras–Algaré (Fig. 2) results from the combination of a geological section across drill holes GU09001, LC1, CA2, CA1 (off-section, ca. 500 m of CA3 and projected in the same plane), NY19, CA3 and CA1104. Drill hole CA1105, located 1 km NW of the cross-section (Fig. 3), completes the study. The analysis and determination of the lithostratigraphic units in the drill holes were based on their lithological compositions, combined with palynological and geochronological data. All studied drill holes intersect the long-established units that characterize the Neves–Corvo mine region stratigraphic succession (Oliveira et al., 2013a, b; Pereira et al., 2014, 2021). Geological and palynological descriptions for each of the studied sectors is presented below.

4.1. Guedelhinha sector

The Guedelhinha sector is located WSW of the Brancanes Antiform. At surface, it is characterized by large areas where the Mértola Fm. turbidites are dominant (Oliveira et al., 2016). The Guedelhinha sector has an important exploration potential confirmed by EM and TURAM conductors and late-Variscan copper dikes (e.g., Brancanes old copper mine; Marques et al., 2022; Matos et al., 2022a, 2020b). The Somincor/Lundin Mining GU09001' studied hole intersected ca. 350 m of Mértola Fm. turbidites followed by the Upper VSC sequence, both in normal stratigraphic position. From base to top, the Upper VSC is represented by the Grandaços, Borra de Vinho, Godinho, and Brancanes formations. The Grandaços Fm. shows a significant thickness (~460 m) being represented from top to bottom by dark-grey shales with siliceous nodules, dark-grey shales with flake structures (fine sedimentary breccia matrix supported), and black to dark-grey shales with disseminated pyrite. Small metric-scale dolerite intrusions occur. The Grandaços unusual great thickness can be explained by intra-formation thrusting and structural duplexing. Only the VSC sequence was investigated for palynostratigraphy. One sample collected at 954.4 m in the Grandaços Fm. provided palynostratigraphic content that includes *Raistrickia nigra* (key taxon from NM Biozone of mid-late Visean age; Fig. 2). To the northeast of the GU09001 borehole, flysch sediments conformably overlay the Brancanes Fm. dark shales, both associated to the reverse limb of the antiform (Figs. 1, 2).

4.2. Lançadoiras sector

The Lançadoiras sector represents the inner and SE portion of the Rosário–Neves–Corvo Antiform, characterized by outcropping PQG and VSC units (Oliveira et al., 2013a, 2013b, 2016) both intersected by the LC1 drill hole. The PQG overthrusts the Upper VSC sequence in the SW sector of the Antiform, as shown in the section and surface mapping of Fig. 2 (Oliveira et al., 2016; Matos et al., 2020a; Fig. 1). The Upper VSC sequence is represented by a narrow and limited area located in the SW sector of the Antiform, between Lançadoiras and Forno da Cal.

At the bottom of drill hole LC1 (total length of 1017 m), black shales of unknown origin have been intersected, since no palynostratigraphic data was obtained. The black shales are overlain by a 300 m-thick sequence of felsic volcanic rocks. Upward, these are followed by a ca. 280 m-thick envelope of volcanogenic sandstone beds, followed by grey shales with carbonate nodules and interbedded volcanogenic sedimentary rocks and minor felsic volcanic rocks assigned to the Grandaços Fm. This sequence is repeated by several thrust faults, and no palynostratigraphic data was obtained in this portion of the drill hole. From 398 m to 72 m, the hole intersected PQG shales and siltstones with intercalated thin quartzite beds. The shales provided palynomorphs assigned to the VH Biozone of Famennian age (samples 397.3 m to 132.0 m). A crinoids-rich limestone breccia was intersected at 72.7 m depth (Fig. 2) in the uppermost portion of the PQG. This limestone horizon is commonly found in many drill holes in the Neves–Corvo mine region and elsewhere across the Iberian Pyrite Belt, forming an important key stratigraphic guide (Boogaard and Schermerhörn, 1980, 1981). From 72.0 m to 55.0 m, the VSC comprises volcanic pumice breccias with interbedded dark-grey shales that can be correlated with similar units recognized in the Corvo Fm., Semblana section (NE Neves–Corvo; Pereira et al., 2021). Near-surface black shales occur interbedded with felsic volcanic rocks forming a local syncline (see other folds in the Lançadoiras sector in Fig. 2). These sediments are assigned to the Neves Fm., and dated from the latest Famennian age based on the LN Miospore Biozone (samples 54.7 m and 38.7 m).

4.3. Algaré sector

The Algaré sector corresponds to the NW region of the Neves–Corvo mine (Fig. 1). In this area an old 19th century pyrite–copper small-scale mine named Cerro do Algaré was exploited (Leca et al., 1983; Carvalho, 1991; Matos and Filipe, 2013; Inverno et al., 2020; Matos et al., 2020a, 2020b). The mineralization consisted of veins and minor stockworks hosted in black shales and quartzites. The favorable exploration upside shown by the area in those times was investigated by the Serviço de Fomento Mineiro (SFM) geophysical surveys (electromagnetic TURAM and gravity) that eventually led to the discovery of the western sector of the Neves–Corvo deposit gravity anomaly (Leca et al., 1983; Carvalho, 1991; Matos et al., 2020b).

Six drill holes were investigated to detail the study of the Algaré sector (Figs. 1, 2), namely CA2, CA1 (near Fig. 2 section, and projected in the same plane), NY19, CA1105 (Fig. 3), CA3, and CA1104. Stratigraphic correlations were based on drill hole logs, palynological ages and geochronological data. Besides the Cerro do Algaré mine, other mineralized zones are indicated in Fig. 2, namely stockwork-like veining of ca. 1-2 m wide, hosted both by the

Neves Fm. black shales and felsic volcanic rocks (Fig. 2: drill holes NY19 and CA1104; Fig. 3: CA1105).

At the bottom of the sequence, the shales and thin bedded quartzites of the PQG, sampled in drill hole NY19 (from 1650.0 m to 1394.7 m), provided poorly preserved miospores assigned to an early-mid Frasnian age (BJ/BM? Biozones). The uppermost PQG sediments are intruded by felsic volcanic rocks and the interbedded Lower VSC sediments assigned to the Neves Fm. (NY19 drill hole: 1362.0 m and 1353.7 m samples). The Neves sediments provided a moderately preserved assemblage assigned to the LN Biozone of the latest Famennian age (Strunian).

Above this level, the allochthonous PQG occurs in tectonic thrust zones from 1025.5 m to 1201.2 m and represented by shales, siltstones and minor quartzites (NY19 drill hole: from 1201.2 m to 1025.5 m). These sediments yielded poorly preserved palynomorphs allocated to the latest Famennian age (LN Biozone, Strunian age) and identified for the first time in this sector. The age and assemblage are similar to those found in the Neves Fm., although showing lower preservation and less diversity (Fig. 7). Higher in the NY19 drill hole (from 905.6 m to 693.70 m), older PQG sediments were noted, probably mid Frasnian in age (BM? Miospore Biozone) based on the presence of *Verrucosisporites* cf. *bulliferus* and *Lophozonotriletes* cf. *media*. Although showing similar palynomorph assemblages, the preservation and diversity of the allochthonous PQG is lower (drill hole NY19: BJ/BM? Biozones) when compared with the same assemblage recovered from the autochthonous PQG (drill hole NY19: BM? Biozone) (Fig. 2). In the uppermost part of the PQG (drill hole NY19), a crinoid level occurs at 618.3 m, associated with sediments of probable Famennian age (no key species were documented). Laterally, the upper PQG shales and quartzites (drill hole CA01) can be assigned to the late Famennian VH Miospore Biozone.

The Lower VSC sequence is characterized by the Corvo Fm. (drill holes CA1003, CA1 and NY19) represented by grey shales and intercalated pumice volcanic breccia, and the Neves Fm. formed by black shales (intersected in CA2, CA1003, CA1, NY19 and CA3 drill holes). The Corvo Fm. palynostratigraphic signature is limited to NY19 hole. The Neves Fm. sediments show a well preserved and diverse palynomorph assemblage assigned to the latest Strunian LN Biozone (drill holes CA2, CA1 and NY19). Felsic volcanic rocks occur associated with the Neves Fm., providing geochronological ages of 365.5 ± 7.4 Ma and 366.0 ± 4.2 Ma in the drill hole NY19.

The drill hole CA1004 bottommost section is defined by a Lower VSC sequence represented by felsic volcanic rocks, the Corvo Fm. sediments, and the Neves Fm. black shales (sample 1075.5 m provided a moderately preserved assemblage from the latest Famennian age (Strunian) LN Miospore Biozone). The referred felsic volcanic rocks provided similar geochronological Late Famennian ages of 357.5 ± 3 Ma, 360.5 ± 2.1 Ma, and 361.4 ± 3.2 Ma. The PQG overlays this sequence from 1056.0 m to 779.5 m (see limits by thrust faulting in Fig. 2). The PQG sediments provided a palynomorph assemblage assigned to the VH Biozone (*Grandispora echinata*) of late Famennian age (samples 1056.0 m to 779.5 m). Above the PQG a Lower VSC sequence was identified and characterized by the Corvo Fm. grey shales and intercalated pumice volcanic breccia (no palynostratigraphic record), followed by the Neves Fm. black shales (samples 750.9 m to 697.2 m provided an assemblage from LN Miospore Biozone of late Strunian age) and related felsic rocks (rhyolites) with stockwork mineralization.

On top of the VSC sequence, the Neves–Corvo Main Thrust with SW vergence separates the Lower and Upper VSC sequences, being intersected in the CA1103, CA1, NY19, NAA11’, CA3 and CA1104 drill holes (Fig. 2). This regional thrust panel can be related with seismic reflectors and EM anomalies in the Neves–Corvo NW mine sector (Carvalho et al., 2017; Matos et al., 2020; Marques et al., 2021; Donoso et al., 2022). This tectonic setting includes the presence of fine (<30 m thick) and discontinuous alloctonous blocks of Mértola Fm. flysch sediments identified in the CA1102, CA1103, CA1, NY19, NAA11’ and CA3 drill holes. At NY19 hole, the flysch sediments were dated from mid-late Visean (sample 388.4 m: probable VF Miospore Biozone). In the Neves–Corvo mine these flysch alloctonous blocks are referred as the MT2 Mb. (Oliveira et al., 2004, 2013).

In the NE sector of the Algaré section the Upper VSC sequence was identified in all the studied drill holes (Figs 2, 3). The Graça Fm. shows a miospore assemblage assigned to the early Visean TS? Biozone (drill hole CA1104: samples from 540.3 m to 511.1 m), and the Grandaços Fm. yielded a miospore assemblage assigned to NM Biozone (*Raistrickia nigra*) of mid-late Visean age (drill hole CA1: sample 186.40 m; drill hole CA1104: sample 453.3 m). The Godinho, Borra de Vinho and Brancanes VSC formations did not provide any palynological content in this sector. The Mértola Fm. occurs above the Upper VSC in the NE sector of the Algaré section. The flysch sediments show an assemblage that includes *Raistrickia nigra*, assigning them to the NM Biozone of mid-late Visean age (drill hole CA1105: samples from 171.50 m to 28.75 m; Fig. 3).

Overall, the geological setting seen in the NE sector of Algaré is also present in the CA1105 section (Figs. 1, 3). In the final portion of this hole, shales and thin bedded quartzites of the PQG (sample 1083.6 m) are late Famennian in age based on the key taxa *Apiculiretusispora verrucosa* and *Grandispora echinata*, typical from the VH Miospore Biozone. The PQG is followed by the Lower VSC, with the Corvo Fm. represented at the base of the sequence, namely by grey shales and associated pumice volcanic breccia and felsic volcanic rocks. The breccia provided a geochronological age of 373.7 ± 8.2 Ma compatible with the basal part of the Neves–Corvo mine (Pereira et al., 2021). An allochthonous PQG block is present (no palynostratigraphic record), followed by the Lower VSC Neves Fm. black shales (Fig. 3). Several samples from these sediments provided a palynostratigraphic age assigned to the LN Biozone (samples 876.5 m to 861.0 m), and its upper portion is characterized by a monospecific prasinophycean dominant assemblage, with the other palynomorph groups occurring very rarely and poorly preserved. This setting is similar in the two studied geological sections (Fig. 2: drill hole CA1104, 628.5 m and 628.8 m samples; Fig. 3: drill hole CA1105, samples from 757.90 m to 784.40 m).

In summary, the Algaré sector is characterized by a complex tectonic setting, with several repetitions, mostly consisting of a parautochthonous package of tectonic thrust sheets affecting the PQ Fm. and the Lower VSC units (Fig. 2). This structural framework can be correlated with the Neves–Corvo mine horizon (Matos et al., 2020b; Pereira et al., 2021).

The Algaré complex tectonic setting dominated by intense stacking could represent a significant horizontal movement to the WSW. Seismic reflectors and drill hole data (Lundin

Mining database) support the kilometric extension of low angle fault planes conditioned by a strong vergence to the SW (Matos et al., 2020b; Dias et al., 2021; Marques et al., 2021, 2022). A regional decollement structure cannot be excluded. Above this plane the Upper VSC sequence and the Mértola Fm. are present, showing a normal stratigraphic position (see NE portion of Fig. 2 section). The favorable correlation between the Algaré and Neves–Corvo mine sectors is important. In both sectors the Neves Fm. hanging wall is represented by the major Neves–Corvo thrust zone (Pereira et al., 2021), locally with exotic discontinuous flysch sediment blocks of the Mértola Fm. (Oliveira et al., 2013).

5. Palynostratigraphic results and discussion

The stratigraphic palynology data obtained in all the studied drill holes of the Guedelhinha–Lançadoiras–Algaré section provide a better understanding of the complexity of the Neves–Corvo mine WNW region. Below, new palynological data are presented and supported by main bioevents, while biozones and relevant taxa are described and discussed in detail, based on the Western Europe Miospore Zonation correlation (Clayton et al., 1977; Streel et al., 1987; Higgs et al., 1988; Pereira, 1999; Maziane et al., 1999; Pereira et al., 2008; Higgs et al., 2013; Fig. 7). Acritarchs and prasinophycean algae are common and well represented in the studied samples, although miospores are the dominant palynomorph group in most samples. A total of 52 miospore species (39 miospore genera), 8 acritarch species (9 genera) and 10 prasinophycean alga species (6 genera) have been identified.

5.1. Frasnian age

In Western Europe, the appearance of the characteristic miospore taxa bearing tabulate sculpture, such as *Verrucosisporites bulliferus*, characterizes an early to mid Frasnian bioevent (Richardson and McGregor, 1986; Streel et al., 1987; Loboziak and Streel, 1989; Loboziak et al., 2005; Streel et al., 2021). The *V. bulliferus* arises for the first time at the base of the Biozone BJ (*Verrucosisporites bulliferus–Cirratriradites jekhowskyi*) and remains abundant until the following BM Biozone, where *Lophozonotriletes media* first occurs (Richardson and McGregor, 1986; Streel et al., 1987; Loboziak and Streel, 1989).

Applying these characteristics to the lowermost PQG sediments studied in this section (drill hole NY19), a probable BM? Miospore Biozone of mid Frasnian age is recognized based on the co-occurrence of *Verrucosisporites* cf. *bulliferus* and *Lophozonotriletes* cf. *media*, together with *Aneurospora greggsii*, *A. goensis*, *Apiculiretusispora* sp., *Ancyrospora* sp., *Camarozonotriletes* sp., *Chelinospora* cf. *timanica*, *Chelinospora* sp., *Cristatisporites* cf. *deliquescens*, *Cymbosporites magnificus*, *Dibolisporites* sp., *Emphanisporites rotatus*, *Geminospora lemurata*, *G. punctata*, *Geminospora* sp., *Retusotriletes rugulatus*, *R. triangulatus*, *Retusotriletes* sp., *Verruciretusispora loboziakii*, *Verrucosisporites premnus*, *V. scurrus*, and *Verrucosisporites* sp. (Fig. 3; Table S2, Appendix A).

These data lead to a direct correlation with the ages previously achieved by Mendes et al. (2018a, 2018b, 2020) in the Lombador and Corvo/Semblana sectors (Neves–Corvo mine area). The authors recognize and confirm that the lowest part of the PQG assumes ages between mid Givetian (TA Miospore Biozone, *C. triangulates–A. ancyrea*) to mid Frasnian age (BM Miospore Biozone, *V. bulliferus–L. media*, and IV Miospore Biozone, *R. bricei* and *Diducites* cf. *poljessicus*) (Figs. 7, 8).

5.2. Famennian age

In Western Europe, the Frasnian/Famennian boundary is characterized by palynofloras dominated by small-sized miospores. From this leve, up to late Famennian, miospore assemblages include various small-sized and common spinose species assigned to the genus *Grandispora* (Higgs et al., 2000; Loboziak et al., 2005). The successive first occurrences of the species *Grandispora gracilis, G. famenensis*, *G. cornuta, G. echinata* and *G. acuta*, mark important bioevents that differentiates the bases of most of the Famennian miospore zone subdivisions (Higgs et al., 2000, 2013; Fig. 3).

The early to mid Famennian interval has not been documented in the Neves–Corvo mine region, since a major hiatus is proposed for this time interval (Mendes et al., 2018a, 2018b, 2020; this study). This important event is also recognized in other IPB sectors, such as in Lousal-Caveira (Pereira et al., 2008; Matos et al., 2014; Oliveira et al., 2013a, 2103b, 2019), in Pulo do Lobo Domain (South Portuguese Zone; Pereira et al., 2008; Oliveira et al., 2019; Mendes et al., 2022), or even in other foreign basins like in North Africa (Libya; Massa and Moreau-Benoit, 1976). In the Lousal-Caveira and Rosário–Neves–Corvo structures, similar Famennian age setting occurs in the PQG and VSC sequences (Pereira et al., 2008, 2021; Matos et al., 2014).

The late Famennian records in Western Europe are characterized by the VCo (*Diducites versabilis–Grandispora cornuta*) and VH (*Apiculiretusispora verrucosa–Vallatisporites hystricosus*) Miospore Biozones. The VCo Biozone is defined by the first occurrence of *Grandispora cornuta*, *Retusotriletes phillipsi* and *Rugospora flexuosa* (Maziane et al., 1999; Clendening et al., 1980). It is also characterized by the presence of *Diducites versabilis* and *Retispora macroreticulata* (Maziane et al., 1999; Higgs et al., 2000; 2013). The VH Biozone is characterized by the first appearance of *Apiculiretusispora verrucosa* and *Vallatisporites hystricosus*. Other taxa appearing in the VH Biozone include *Endoculeospora gradzinskii*, *Spelaeotriletes crenulatus* and *Grandispora echinata*. The first occurrence of *G. echinata* marks another important bioevent, having been recognized as occurring immediately before the first inception of *Retispora lepidophyta* (late Famennian age; Maziane et al., 1999; Higgs et al., 2000, 2013), and previously considered local key species in the South Portuguese Zone (Pereira et al., 2008).

The acritarch zonation of late Famennian age, is calibrated by the miospore zonation and includes, from bottom to top, the following acritarch zones: *Gorgonisphaeridium ohioense* and *Gorgonisphaeridium winslowiae–Exilisphaeridium simplex* (Maziane and Vanguestaine, 1997; Maziane et al, 1999; Streel et al., 1988; Fig. 7).

In the studied section, the late Famennian VCo Biozone is not recognized. Nevertheless, the VH Miospore Biozone is recovered in upper PQG sediments and comprises a moderately preserved assemblage including the miospore guide species *Apiculiretusispora* cf. *verrucosa* and *Grandispora echinata*, together with *Ancyrospora* sp., *Apiculiretusispora* sp., *Cirratriradites* sp., *Cristatisporites* sp., *C. triangulatus*, *Densosporites* sp., *Emphanisporites annulatus*, *Geminospora lemurata*, *Punctatisporites* sp., *Retusotriletes* sp., *R. triangulatus*, *Rugospora flexuosa,* and *Verruciretusispora loboziakii.* Prasinophytes and acritarchs are quite common and include the taxa *Maranhites* spp., *Cymatiosphaera* spp., *Dupliciradiatum* spp., *Duvernaysphaera* spp., and *Gorgonisphaeridium* spp.

In the IPB, the late Famennian palynoflora was extensively recorded (Pereira et al., 2008, 2014, 2021; Mendes et al., 2018a, 2018b, 2020), as well as in other South Portuguese Zone domains such as in the Pulo do Lobo (Pereira et al., 2008, 2018; Mendes et al., 2022). Similar assemblages have been recorded in southern Euramerica basins (Maziane et al., 1999; Loboziak et al., 2005; Higgs et al., 2000, 2013; Streel, 1986; Streel et al., 2000) and in north Gondwana (North Africa; Boumendjel et al., 1988; Streel et al., 1988).

5.3. Latest Famennian age (Strunian)

The latest Famennian age includes the informal substage Strunian that ranges from ~363 to 358.9 Ma (Streel, 2009; Streel et al., 2006; Higgs et al., 1988; Higgs et al., 2013). For easier reading, we will use from now on Strunian instead of latest Famennian Strunian age. The base is correlated with the first occurrence of the guide conodont fauna from the *Late expansa Zone* (Streel, 2005), the base of the foraminifera zone *Quasiendothyra kobeitusana* and, for the first occurrence of a characteristic microflora*, Retispora lepidophyta*. This singular and cosmopolitan taxon is characterized by a narrow stratigraphic range and a strong morphological variation (Streel, 1966; Owens and Streel, 1967; Higgs et al., 1988; Streel and Loboziak, 1996; Maziane et al., 2002). In Western Europe, the Strunian interval includes three well characterized biozones, namely from bottom to top: LL *(Knoxisporites literatus*), LE (*Indotriradites explanatus*), and LN (*Verrucosisporites nitidus*) (Clayton et al., 1977; Higgs et al., 1988). The extinction of *R. lepidophyta* is near-synchronous with the Devonian Carboniferous Boundary (DCB) (Higgs and Streel, 1993; Aretz et al., 2021).

The Strunian age key-acritarchs can also be used to calibrate with the miospore zonation (Fig. 7). The *Umbellasphaeridium saharicum* is a well-known Strunian acritarch (Jardiné et al., 1974; Wood, 1984; Díaz-Martínez et al., 1999; Vavrdova and Isaacson, 1999; Wicander et al., 2011); its occurrence defines an endemic phytoplankton bio-province restricted to Western Gondwana and Euramerica (including Portugal) and North Africa (Vavrdova and Isaacson, 1999; Clayton et al., 2002; Shen et al, 2018). *U. saharicum* commonly occurs associated with other acritarchs such as *Duvernaysphaera radiata*, *Horologinella quadrispina*, *U. deflandrei* and *Stellinium micropolygonale.*

The Devonian-Carboniferous Boundary (DBC) is also marked by the phytoplankton blackout, underlined by a drastic reduction of the phytoplankton diversity (Riegel, 2008). During this catastrophic event, loss of the Late Devonian *U. saharicum* bioprovince is recorded (Vavrdova and Isaacson, 1999), although some acritarch genus manage to survive (e.g., *Gorgonisphaeridium*, *Veryhachium* and *Micrhystridium*; Sarjeant and Stancliffe, 1994; Servais et al., 2007).

Focusing on the latest Famennian (Strunian) of the Neves–Corvo mine region, the LL and LE Biozones were not recognized so far besides the large sampling and dating programs. The LL Miospore Biozone was only recognized in the Nascedios Fm. (Pomarão anticline, IPB; Oliveira et al., 2006; Pereira et al., 2008; Albardeiro et al., 2020).

Regarding the LN Biozone recognized in the Neves Fm., a relatively diverse miospore and phytoplankton (acritarchs and prasinophycean algae) assemblage is recorded. The Neves Fm. provides a moderately preserved assemblage consisting of the key taxa *Retispora lepidophyta* and rare *Verrucosisporites nitidus* that confirms the LN Biozone of latest Famennian (Strunian) age. The following taxa complete the assemblage: *Aneurospora greggsii*, *Auroraspora macra*, *Ancyrospora andevalensis*, *Calamospora* sp., *Convolutispora* sp., *Cymbosporites magnificus*, *Densosporites spitsberguensis*, *Densosporites* sp., *Dibolisporites* sp., *Dictyotriletes fimbriatus*, *Dictyotriletes* sp., *Discernisporites micromanifestus*, *Discernisporites* sp., *Emphanisporites annulatus*, *E. rotatus*, *Epigruspora regularis*, *Geminospora lemurata*, *G. spongiata*, *Grandispora cornuta*, *G. echinata*, *Knoxisporites* sp., *Leiotriletes* sp., *Punctatisporites* sp., *Pustulatisporites dolbi*, *Pustulatisporites* sp., *Raistrickia* sp., *Retusotriletes incohatus*, *R. planus*, *R. triangulatus*, *Rugospora explicata*, *R. flexuosa*, *Teichertospora iberica*, *Tumulispora concentricus*, *T.* cf. *triangulatus*, *T.* cf. *malevkensis*, *Vallatisporites pusillites*, *V. verrucos*us, and *Verrucosisporites* sp. (Fig. 3).

The assemblage also includes common acritarchs assigned to the *U. saharicum* phytoplankton bio-province, including *Chomotriletes* sp., *Craterisphaeridium sprucegrovence*, *Dictyotriletes* spp., *Dupliciradiatum crassum*, *Gorgonisphaeridium plerispinosum*, *G. ohioense*, *Gorgonisphaeridium* spp., *Palacantus* sp., *Umbellasphaeridium deflandrei*, *U. saharicum*, *Veryhachium downiei*, and *Winwaloeusia repagulata*, as well as abundant prasinophytes algae such as *Leiosphaeridia* sp., *Cymatiosphaera* sp., *Duvernaysphaera radiata*, *D. tessella*, *Duvernaysphaera* spp., *Maranhites brasiliensis*, *M. mosesii*, *M. multioculos*, *M. perplexus*, *M.* cf. *gallicus*, and *Pterospermella euriptio*. Rare chitinozoans and scolecodonts also occur.

The miospore *Retispora lepidophyta* is consistently recognized as occurring in the latest Famennian (Strunian) sediments from the Neves Fm. (Oliveira et al., 2004, 2013, 2019; Pereira et al., 2008, 2014, 2021, this work; Mendes et al., 2017). The base of the LN Miospore Biozone, defined by the occurrence of *Retispora lepidophyta* together with the first occurrence of the sparce and rare occurrence of key taxon *Verrucosisporites nitidus*, together with other important species such as *Densosporites spitsberguensis*, *Lophozonotriletes malevkensis*, and *Vallatisporites verrucosus* (Higgs et al., 1988; Fig. 3). The scarcity of *V. nitidus* could be related to ecological factors (presence or absence of the parent plant) and/or to the distance from the source. The *V. nitidus* miospore is generally of small dimensions and occurs more abundantly in proximal settings (as recovered in the Tercenas Fm., Southwest Portugal; Pereira, 1999).

The Late Devonian predominance of prasinophycean algae such as *Maranhites* spp. in the upper part of the Neves Fm. may reflect the beginning of the DCB crisis, since this opportunistic proliferation occurs in a highly stressed environment (Tyson, 1995, 1997; Batten, 1996). Other evidence of this crisis, as for instance common spore tetrads with malformations sculpture and pigmented walls, were not documented in this region.

5.4. Early Visean age

In Western Europe, the early Visean is characterized by Pu-and TS Miospore Biozone assemblages. The base of the Pu Biozone (Neves et al., 1972) is defined by the first occurrence of the genus *Lycospora*, that includes *Lycospora pusilla* (Owens et al., 1977; Clayton et al., 1977). The TS Biozone (Clayton, 1985; Higgs et al., 1988) is defined by the first occurrence of the *Knoxisporites triradiatus,* and *K. stephanephorus zonal* species. The recognition of the Pu and TS Biozones within the Neves–Corvo sequence is limited to the Graça Fm. (base of the Upper VSC sequence). The Pu assemblage Biozone is based on the occurrence of *Lycospora pusilla* in association with *Calamospora* sp., *Convolutispora* sp., *Convolutispora cerebra*, *Densosporites annulatus*, *Densosporites* sp., *Retusotriletes* sp., and *Vallatisporites* sp.

Although in this work the TS Biozone is poorly documented, previous studies (Pereira et al., 2008, 2014, 2021) have detailed this biozone in the Graça Fm. shales, defined by the presence of the key species *Knoxisporites triradiatus* and *K. stephanephorus*. Other present taxa include *Anapiculatisporites* sp., *Convolutispora nigrata*, *Densosporites rarispinosus*, *Diatomozonotriletes rarus*, *Dictyotriletes propius*, *Hymenozonotriletes caperatus*, *Knoxisporites hederatus*, *K. rhulandii*, *Microreticulatisporites concavus*, *Proprisporites* sp., *Spelaeotriletes pretiosus*, *S. arenaceus*, *Vallatisporites pusillites*, *V. hystricosus*, and *V. galearis*.

The early Visean is also recognized in other sectors of the Portuguese IPB, namely in the Aljustrel mine (Matos et al., 2010; Pereira et al., 2008, 2014), Albernôa and Serra Branca regions (Pereira et al., 2008). In all these localities the Pu Biozone was identified based on *Lycospora pusilla.*

5.5. Mid-late Visean age

In Western Europe the mid-late Visean is characterized by the TC, NM, and VF Miospore Biozones (Clayton et al., 1977; Pereira et al., 2007). The base of the TC Biozone is marked by the presence of the genus *Schulzospora* together with the first occurrence of *Chaetosphaerites pollenisimilis*, *Waltzispora planiangulata*, *Verrucosisporites baccatus*, *Crassispora aculeata*, and *Perotriletes tesselatus.* The following NM Biozone includes the key taxon *Raistrickia nigra* in close association with *Densosporites* cf. *velatus*, *Murospora parthenopia*, *Monilospora mutabilis*, and *Kraeuselisporites echinatus* (Clayton et al., 1977). The VF Biozone is established for the Western Europe, consisting of the first occurrence of *Tripartites venustus*, *T. nonguerickei*, *Triquitrites trivalvis*, *Rotaspora fracta*, *R. knoxi*, *Savitrisporites nux*, *Crassispora maculosa*, *Spencerisporites radiatus*, and *Grandispora spinosa.*

In the Neves–Corvo mine region, the TC Biozone is absent, probably due to the pervasive tectonic setting (Pereira et al., 2008, 2021; Oliveira et al., 2013). Nevertheless, the NM Biozone is recognized in all the Upper VSC units (Graça, Grandaços and Godinho formations) as well as in the turbidites of the Mértola Fm. (Pereira et al., 2008, 2014, 2021).

In this study, the NM Biozone was only determined in the Grandaços and Mértola (MT1 Mb.) formations, based on the presence of *Raistrickia nigra* together with *Auroraspora macra*, *Convolutispora* sp., *Densosporites* sp., *Endosporites* sp., *Knoxisporites* sp., *Kraeuselisporites* sp., *Punctatisporites* sp., *Raistrickia* spp., *Tumulispora* sp., and *Verrucosisporites* sp. A distinctive feature of the Mértola Fm. is the characteristic turbiditic facies reflected in the palynology assemblages, e.g., by the great abundance and dominance of phytoclasts.

Regarding the Mértola Fm. (MT2 Mb.), a VF? was noted based on the local key species *Savitrisporites* cf. *nux* associated with rare *Leiotriletes* sp., *Lophotriletes* sp., *Microreticulatisporites*? sp., *Pustulatisporites* sp., and *Raistrickia nigra.* Opaque phytoclasts remain dominant in this assemblage.

5.6. New biostratigraphic results in the context of the Neves–Corvo mine region and the Iberian Pyrite Belt

Despite the complex geological setting of the Guedelhinha–Lançadoiras–Algaré section, the PQG and VSC units share the same lithological composition and ages as those of the Neves–Corvo mine region. In the studied section, the sulphide mineralization occurs at the Algaré mine and in the CA1104 drill hole (Fig. 2) represented by stockworks hosted in the VSC Neves Fm. black shales and in felsic volcanic rocks. At the Algaré mine, stockwork veins occur also in PQG sediments of late Famennian age (Fig. 2). The presence of stockwork-style mineralization hosted in PQG sediments is common across the Neves–Corvo mine (e.g., Lombador deposit).

Fig. 8 illustrates a schematic chronostratigraphic chart where all the lithostratigraphic units are included together with their corresponding palynological data. Straightforward correlation and updating of the stratigraphy and volcanism of the Neves–Corvo mine region is established.

5.7. Stratigraphic hiatuses

The following stratigraphic hiatuses are rvidenced based in palynostratigraphic studies (Oliveira et al., 2013a, 2013b; Mendes et al., 2020; Pereira et al., 2021).

~10 myr hiatus (mid Frasnian to mid Famennian) separating the lowermost PQG sequence (mid Givetian to mid Frasnian age) from the uppermost PQG sequence (late Famennian age to Strunian age; Fig. 7). The lowermost PQG (mid Givetian to mid Frasnian age) has a prominent expression in the Algaré sequence, where the shales and siltites with rare quartzites are possibly related to high sedimentation ratios in a deep-water marine basin environment. This parautochthonous lowermost PQG overthrusts the uppermost PQG as shown in Fig. 2 (NY19 drill hole). The upper PQG sequence of dark shales and siltites with common quartzites was certainly deposited in a more proximal setting, late Famennian to Strunian in age. At this stage, the basin demonstrates some instability related to the beginning of Lower VSC deposition, contemporaneous of the upper PQG sequence (Diez-Montes et al., 2020; Mendes et al., 2021). This hiatus can be traced across the IPB (Lousal and Caveira mines, Neves–Corvo mine, in Portugal and Gerena-El Garrobo sections in Spain (Pereira et al., 2008, 2014, 2021; Matos et al., 2014; Oliveira et al., 2019; Mendes et al., 2020; González et al., 2002, 2004, 2005; Diez-Montes et al., 2020) and could represent a non-deposition period or alternatively an erosive event related to the complex tectonic regime (Oliveira et al., 2013a, 2013b, 2019; Silva et al., 2013; Matos et al., 2014; Martin-Izard et al., 2016; Diez-Montes et al., 2020). Another hypothesis could be related to the Frasnian-Famennian massive extinction (Kellwasser event) which occurred ca. 372 Ma. The cause of this extinction is unclear and includes changes in sea level and ocean anoxia (Streel et al., 2000). More studies are needed and new proxies (e.g., geochemical and sedimentological data) could be investigated to better constrain the environmental interpretation.

~ 1 myr hiatus covering the Late Devonian LL and LE Miospore Biozones (within the Lower CVS sequence; Fig. 7), possibly corresponding to a non-deposition period conditioned by the intense felsic volcanism observed during this time (U/Pb geochronology data: Albardeiro et al., 2017, 2020). This small hiatus is also observed in Lousal, Caveira, and Montinho mines (Pereira et al., 2008; Matos et al., 2011, 2014) and in Aznalcóllar and Tharsis mines in Spain (González et al., 2002).

~ 9 myr hiatus covering the early Carboniferous (Tournaisian, VI, HD, BP and part of PC Miospore Biozones; Fig. 7), corresponding to a sedimentary hiatus that separates the Lower and Upper VSC, between the Neves and Graça formations, respectively. This hiatus is consistent with previous studies in the Neves–Corvo mine region (Oliveira et al., 2004, 2013b), being also recognized across the IPB. An explanation for this hiatus has already been pointed out, namely a regional submarine erosion of uplifted basin blocks following the extensional tectonism that affected the entire IPB (Oliveira, 1990; Oliveira et al., 2004, 2013a; Silva et al., 2013). This interpretation is based on the occurrence of reworked Tournaisian miospore assemblages both in the Upper VSC units and in the Mértola Fm. This hiatus could also reflect the biotic disturbances recognized worldwide in the post Devonian-Carboniferous extinction event. Despite Tournaisian age sediments are absent in the IPB, microflora of this age has been found in the Southwest Portugal sector (Bordalete Fm.; Pereira et al., 2008). In this sector, tectonic and volcanic environments are more stable, allowing the flora recovery and preservation.

6. Conclusions

New detailed palynological data from the recently studied Guedelhinha–Lançadoiras–Algaré sector allowed establishing a direct correlation with the stratigraphic model previously defined for the Neves–Corvo mine region, improving the understanding of the complex structural setting and refining the geological knowledge of this important mine region. The main results from this research are as follows:

- The Guedelhinha–Lançadoiras–Algaré sector shows a stratigraphic sequence similar to the one previously defined for the Neves–Corvo mine region, whose biostratigraphic ages range from Middle Devonian (Givetian) to early Carboniferous (late Visean);
- At Cerro do Algaré mine, the allochthonous PQG sediments were dated from the late Strunian age (Miospores Biozone LN);

- The late Strunian age (Miospore Biozone LN) is confirmed to be a key stage of sulphide mineralization across the IPB., in close association to black shales and coeval rhyolites (359.6 ± 1.6 Ma; Albardeiro, 2020);
- The upper part of the Neves Formation is characterized by an abundant/dominant monospecific prasinophycean assemblage which could be related to the major extinction event and environmental changes documented around the Devonian-Carboniferous Boundary;
- Stratigraphic hiatus in the palynological record were highlighted and confirmed, occurring : (*i*) during the mid Frasnian to mid Famennian (ca. 10 myr), separating the lower PQG sediments (Mid-Late Devonian) from the upper PQG sediments (Late Devonian); (*ii*) during the early and mid Strunian (ca. 1 myr), separating the Corvo and Neves formations; and (*iii*) during the early-mid Tournaisian (ca. 9 myr), dividing the Lower and Upper VSC sequences and reflecting submarine erosion across the basin and/or tectonic events.

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Appendix A. Supplementary information

Supplementary information (including Tables S1-S3) associated with this article can be found, in the online version, at:

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Figure captions

Fig. 1. Geological map of the Neves–Corvo mine region with massive sulphide deposit location (surface projection). The Graça and Corvo formations are only recognized in drill holes. Geological cross-section is presented in Fig. 2. Geology adapted from Oliveira et al. (2016), Lundin Mining (2017) and Matos et al. (2020).

Fig. 2. Guedelhinha–Lançadoiras–Algaré geological section, located NW of the Neves–Corvo mine. Surface mapping correlation from the Almodóvar 1/50.000 geological map (Oliveira et al., 2016). Exploration drill holes performed by Somincor/Lundin Mining.

Fig. 3. North Algaré CA1105 drill hole section.

Fig. 4. A, B. *Savitrisporites nux* (Butterworth et Williams) Smith et Butterworth, 1967. **C.** *Microreticulatisporites* sp. **D.** *Raistrickia nigra* Love, 1960. **E.** *Knoxisporites stephanephorus* Love, 1960. **F.** *Knoxisporites* cf. *hederatus* (Ishchencko) Playford, 1962. **G.** *Lycospora pusilla* (Ibrahim) Schopf, Wilson et Bentall, 1944. **H, I.** *Verrucosisporites nitidus* (Naumova) Playford, 1964. **J-L.** *Retispora lepidophyta* (Kedo) Playford, 1976. See Table S3 (Appendix A) for details. Scale bar: 10 µm.

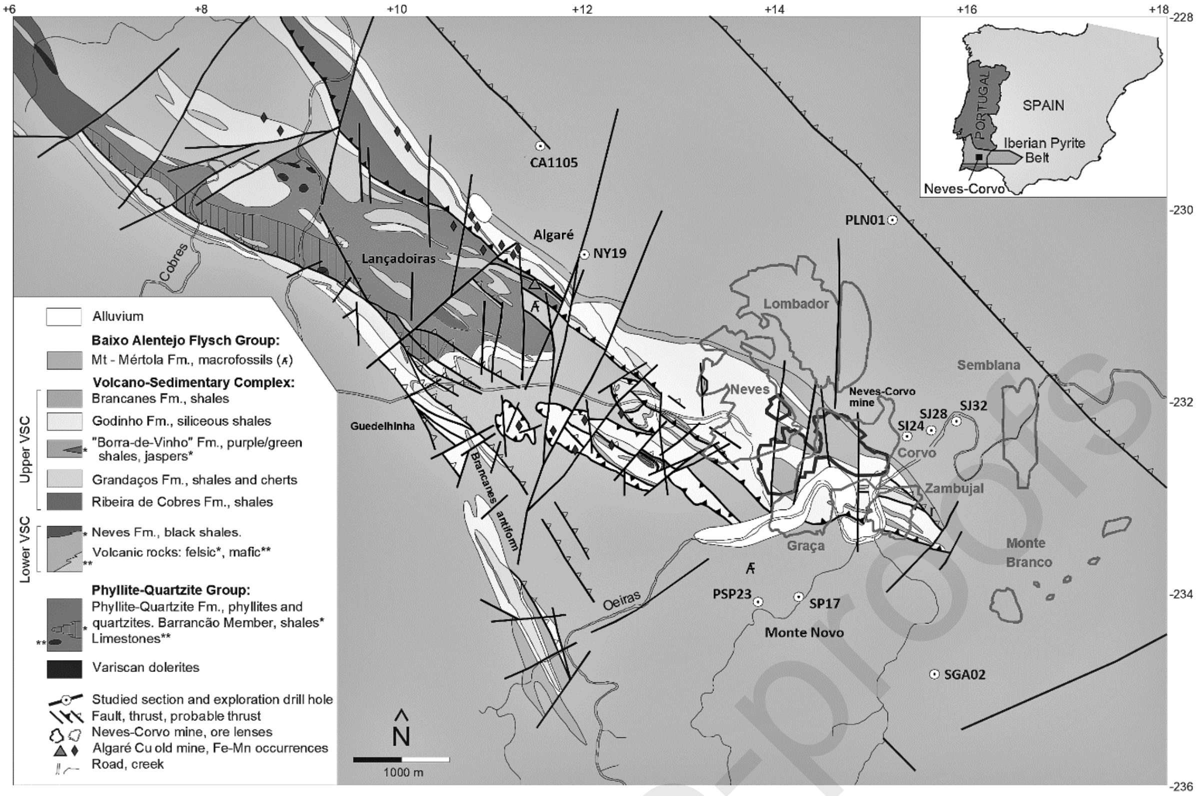
Fig. 5. A, B. *Vallatisporites pusillites* (Kedo) Dolby et Neves, 1970. **C.** *Densosporites annulatus* (Loose) Smith et Butterworth, 1967. **D.** *Auroraspora macra* Sullivan, 1968. **E.** cf. *Diducites* sp. **F.** *Grandispora cornuta* Higgs, 1974. **G.** *Grandispora echinata* Hacquebard emend. Utting, 1987. **H.** *Rugospora flexuosa* González, Playford et Moreno, 2005. **I.** *Rugospora explicata* González, Playford et Moreno, 2005. **J.** *Chelinospora* sp. **K.** *Emphanisporites rotatus* McGregor emend. McGregor, 1973. **L, M.** *Verrucosisporites bulliferus* Richardson et McGregor, 1986. See Table S3 (Appendix A) for details. Scale bar: 10 µm.

Fig. 6. A. *Maranhites mosesii* (Sommer) Brito, 1967. **B, C.** *Maranhites perplexus* Wicander et Playford, 1985. **D, E.** *Maranhites multioculus* González, Playford et Moreno, 2005. **F.** *Maranhites* sp. **G.** *Chomotriletes vedugensis* Naumova, 1953. **H.** *Duvernaysphaera radiata* Brito, 1967. **I.** *Duvernaysphaera radiata* Brito, 1967. **J.** *Palacantus* sp. **K.** *Winwaloeusia repagulata* González, Playford et Moreno, 2005. **L.** *Umbellasphaeridium saharicum* Jardiné, Combaz, Magloire, Peninguel et Vachey, 1972. **M.** *Umbellasphaeridium* cf. *saharicum* Jardiné, Combaz, Magloire, Peninguel et Vachey, 1972. **N.** *Gorgonisphaeridium ohioense* (Winslow) Wicander, 1974. See Table S3 (Appendix A) for details. Scale bar: 10 µm.

Fig. 7. Biozonal scheme, miospore and acritarch events (based on first occurrence of one or more well-known taxa), and range chart of selected species.

Fig. 8. Schematic representation of the overall current knowledge concerning the stratigraphy and volcanism of the Guedelhinha, Lançadoiras and Algaré stockwork in the general context of the Neves–Corvo mine region (Rosário–Neves–Corvo Antiform). The Devonian-Carboniferous Boundary (DCB) is at 358.9 ± 0.4 Ma according to the International Chronostratigraphic Chart 2022/02. Baixo Alentejo Flysch Group: MT, Mértola Formation (MT1, MT2 and MT3 members). Volcano-Sedimentary Complex: r, Brancanes Formation; g, Godinho Formation; bv, Borra de vinho Formation; s, Grandaços Formation; RC, Ribeira Cobres Formation; Va, felsic volcanic rocks; Vb, mafic volcanic rocks; MS, massive sulphides; ST, stockwork; n, Neves Formation; Co, Corvo Formation; d, dolerites; J, jaspers; PQ, Phyllite Quartzite Formation; Ba, Barrancão Member; ca, limestones.

- Devonian-Carboniferous sedimentation and paleoenvironments along the Iberian Pyrite Belt are analysed
- Several stratigraphic hiatuses are identified and confirmed in the Neves-Corvo region
- Palynostratigraphy is an important tool to define the age of the black shales hosting the mineralization
- IPB bioevents related to the major extinction event and environment changes are documented in the Devonian-Carboniferous Boundary
- Improvement of the stratigraphy of the IPB and geological knowledge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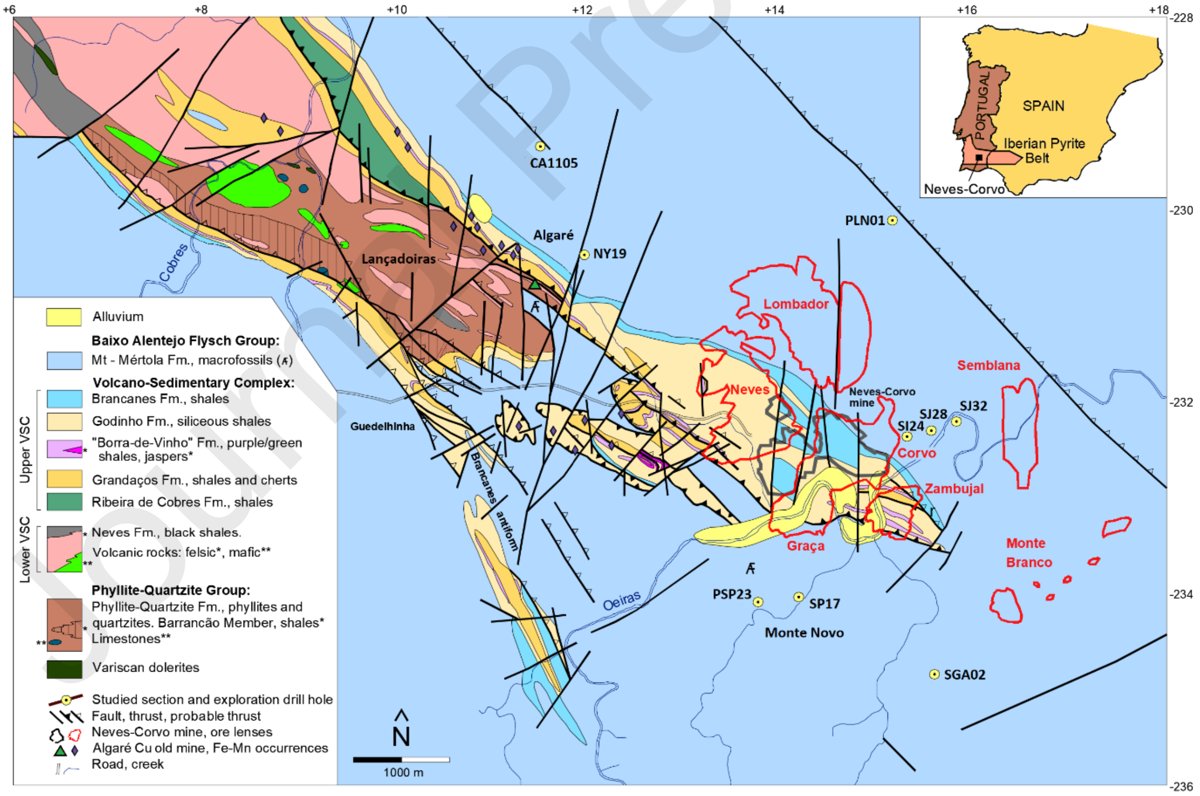
SPAIN
PORTUGAL
Iberian Pyrite Belt
Neves-Corvo
CA1105
Algaré
NY19
Lançadoiras
Cobres
PLN01
Lombador
Semblana
Neves
Neves-Corvo mine
SJ28
SJ32
SJ24
Corvo
Zambujal
Guedelhinha
Brancanes antiform
Graça
Monte Branco
PSP23
SP17
Oeiras
Monte Novo
SGA02
N
1000 m
Alluvium
Baixo Alentejo Flysch Group:
Mt - Mértola Fm., macrofossils
Volcano-Sedimentary Complex:
Brancanes Fm., shales
Godinho Fm., siliceous shales
"Borra-de-Vinho" Fm., purple/green shales, jaspers*
Grandaços Fm., shales and cherts
Ribeira de Cobres Fm., shales
Upper VSC
Lower VSC
Neves Fm., black shales.
Volcanic rocks: felsic*, mafic**
Phyllite-Quartzite Group:
Phyllite-Quartzite Fm., phyllites and quartzites. Barrancão Member, shales* Limestones**
Variscan dolerites
Studied section and exploration drill hole
Fault, thrust, probable thrust
Neves-Corvo mine, ore lenses
Algaré Cu old mine, Fe-Mn occurrences
Road, creek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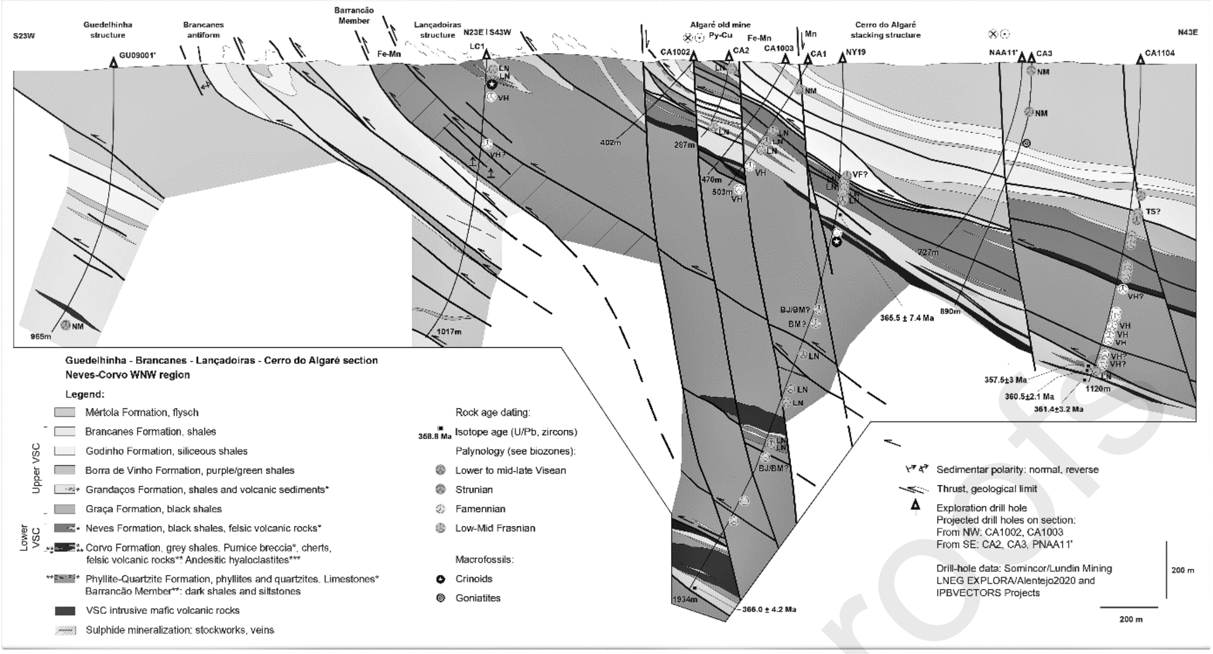
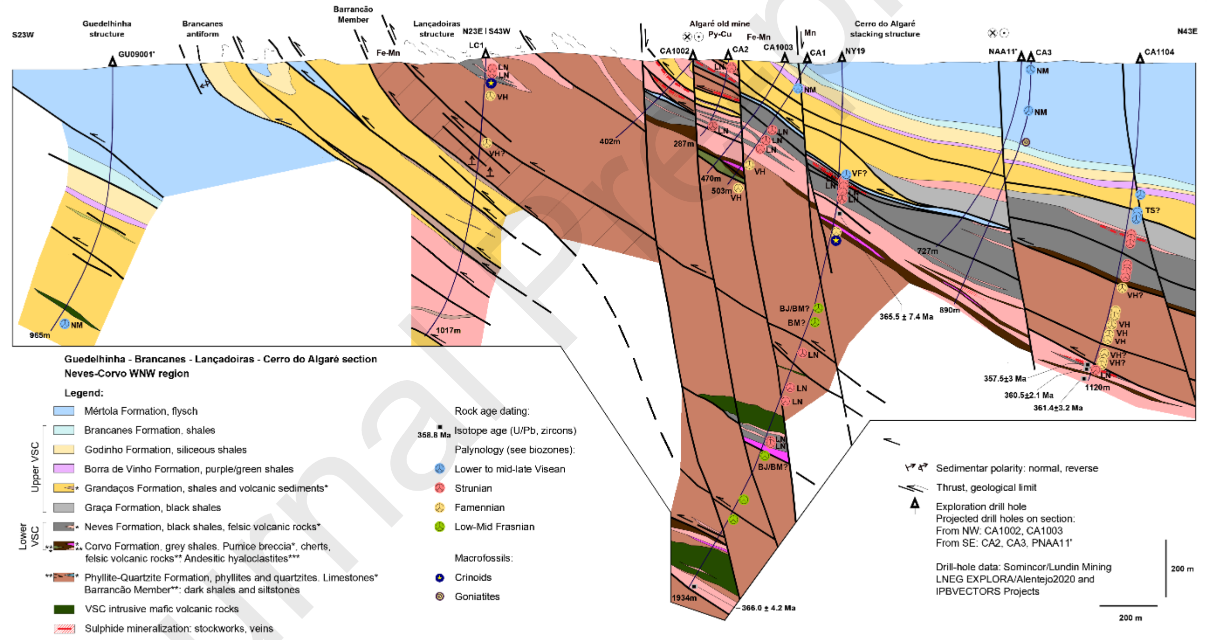
SPAIN
PORTUGAL
Iberian Pyrite Belt
Neves-Corvo
CA1105
Algaré
NY19
Lançadoiras
Cobres
PLN01
Lombador
Semblana
Neves
Neves-Corvo mine
SJ28
SJ32
SJ24
Corvo
Zambujal
Guedelhinha
Brancanes antiform
Graça
Monte Branco
PSP23
SP17
Oeiras
Monte Novo
SGA02
N
1000 m
Alluvium
Baixo Alentejo Flysch Group:
Mt - Mértola Fm., macrofossils
Volcano-Sedimentary Complex:
Brancanes Fm., shales
Godinho Fm., siliceous shales
"Borra-de-Vinho" Fm., purple/green shales, jaspers*
Grandaços Fm., shales and cherts
Ribeira de Cobres Fm., shales
Upper VSC
Lower VSC
Neves Fm., black shales.
Volcanic rocks: felsic*, mafic**
Phyllite-Quartzite Group:
Phyllite-Quartzite Fm., phyllites and quartzites. Barrancão Member, shales* Limestones**
Variscan dolerites
Studied section and exploration drill hole
Fault, thrust, probable thrust
Neves-Corvo mine, ore lenses
Algaré Cu old mine, Fe-Mn occurrences
Road, creek


S23W
Guedelhinha structure
Brancanes antiform
Barrancão Member
Lançadoiras structure
N23E I S43W
Fe-Mn
LC1
GU09001'
Algaré old mine
Py-Cu
Fe-Mn
Mn
Cerro do Algaré stacking structure
N43E
CA1002
CA2
CA1003
CA1
NY19
NAA11'
CA3
CA1104
LN
VH
NM
VH?
402m
287m
470m
503m
VF?
TS?
227m
365.5 ± 7.4 Ma
890m
BJ/BM?
BM?
965m
1017m
357.5±3 Ma
1120m
360.5±2.1 Ma
361.4±3.2 Ma
1934m
366.0 ± 4.2 Ma
Guedelhinha - Brancanes - Lançadoiras - Cerro do Algaré section
Neves-Corvo WNW region
Legend:
Upper VSC
Lower VSC
Mértola Formation, flysch
Brancanes Formation, shales
Godinho Formation, siliceous shales
Borra de Vinho Formation, purple/green shales
Grandaços Formation, shales and volcanic sediments*
Graça Formation, black shales
Neves Formation, black shales, felsic volcanic rocks*
Corvo Formation, grey shales. Pumice breccia*, cherts, felsic volcanic rocks** Andesitic hyaloclastites***
Phyllite-Quartzite Formation, phyllites and quartzites. Limestones* Barrancão Member**: dark shales and siltstones
VSC intrusive mafic volcanic rocks
Sulphide mineralization: stockworks, veins
Rock age dating:
368.8 Ma
Isotope age (U/Pb, zircons)
Palynology (see biozones):
Lower to mid-late Visean
Strunian
Famennian
Low-Mid Frasnian
Macrofossils:
Crinoids
Goniatites
Sedimentar polarity: normal, reverse
Thrust, geological limit
Exploration drill hole
Projected drill holes on section:
From NW: CA1002, CA1003
From SE: CA2, CA3, PNAA11'
Drill-hole data: Somincor/Lundin Mining
LNEG EXPLORA/Alentejo2020 and
IPBVECTORS Projects
200 m
200 m


S23W
Guedelhinha structure
Brancanes antiform
Barrancão Member
Lançadoiras structure
N23E I S43W
Fe-Mn
LC1
GU09001'
Algaré old mine
Py-Cu
Fe-Mn
Mn
Cerro do Algaré stacking structure
N43E
CA1002
CA2
CA1003
CA1
NY19
NAA11'
CA3
CA1104
LN
VH
NM
VH?
402m
287m
470m
503m
VF?
TS?
227m
365.5 ± 7.4 Ma
890m
BJ/BM?
BM?
965m
1017m
357.5±3 Ma
1120m
360.5±2.1 Ma
361.4±3.2 Ma
1934m
366.0 ± 4.2 Ma
Guedelhinha - Brancanes - Lançadoiras - Cerro do Algaré section
Neves-Corvo WNW region
Legend:
Upper VSC
Lower VSC
Mértola Formation, flysch
Brancanes Formation, shales
Godinho Formation, siliceous shales
Borra de Vinho Formation, purple/green shales
Grandaços Formation, shales and volcanic sediments*
Graça Formation, black shales
Neves Formation, black shales, felsic volcanic rocks*
Corvo Formation, grey shales. Pumice breccia*, cherts, felsic volcanic rocks** Andesitic hyaloclastites***
Phyllite-Quartzite Formation, phyllites and quartzites. Limestones* Barrancão Member**: dark shales and siltstones
VSC intrusive mafic volcanic rocks
Sulphide mineralization: stockworks, veins
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368.8 Ma
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Lower to mid-late Visean
Strunian
Famennian
Low-Mid Frasnian
Macrofossils:
Crinoids
Goniatites
Sedimentar polarity: normal, reverse
Thrust, geological limit
Exploration drill hole
Projected drill holes on section:
From NW: CA1002, CA1003
From SE: CA2, CA3, PNAA11'
Drill-hole data: Somincor/Lundin Mining
LNEG EXPLORA/Alentejo2020 and
IPBVECTORS Projects
200 m
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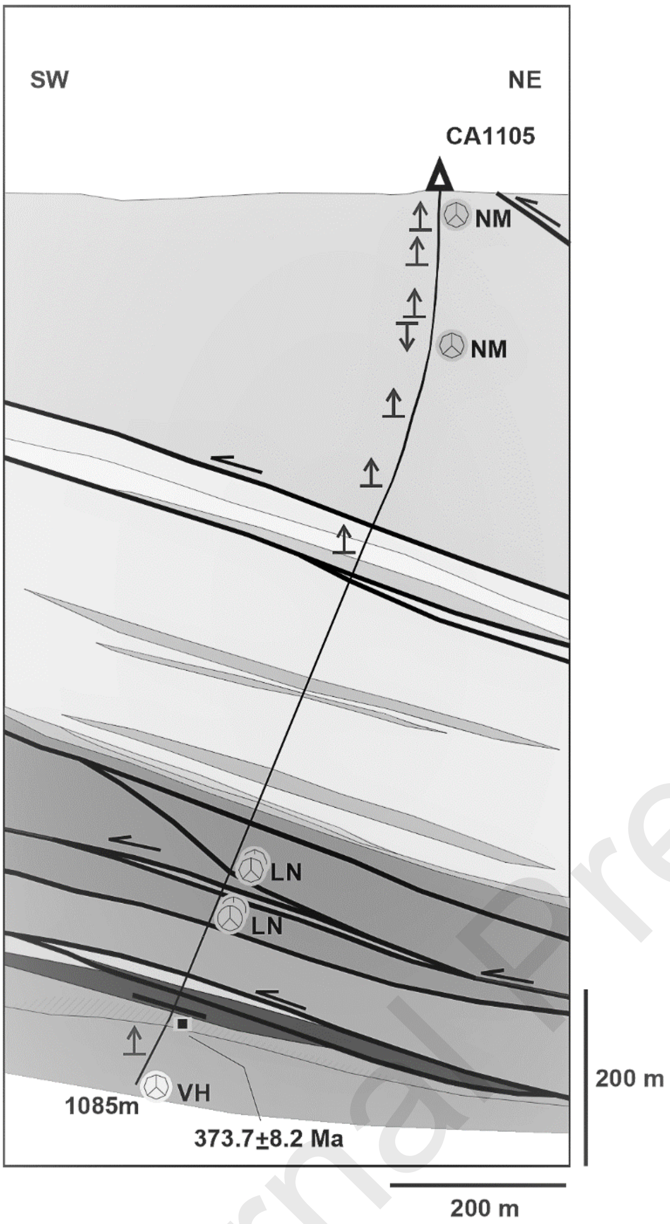
SW
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VH
1085m
373.7±8.2 Ma
200 m
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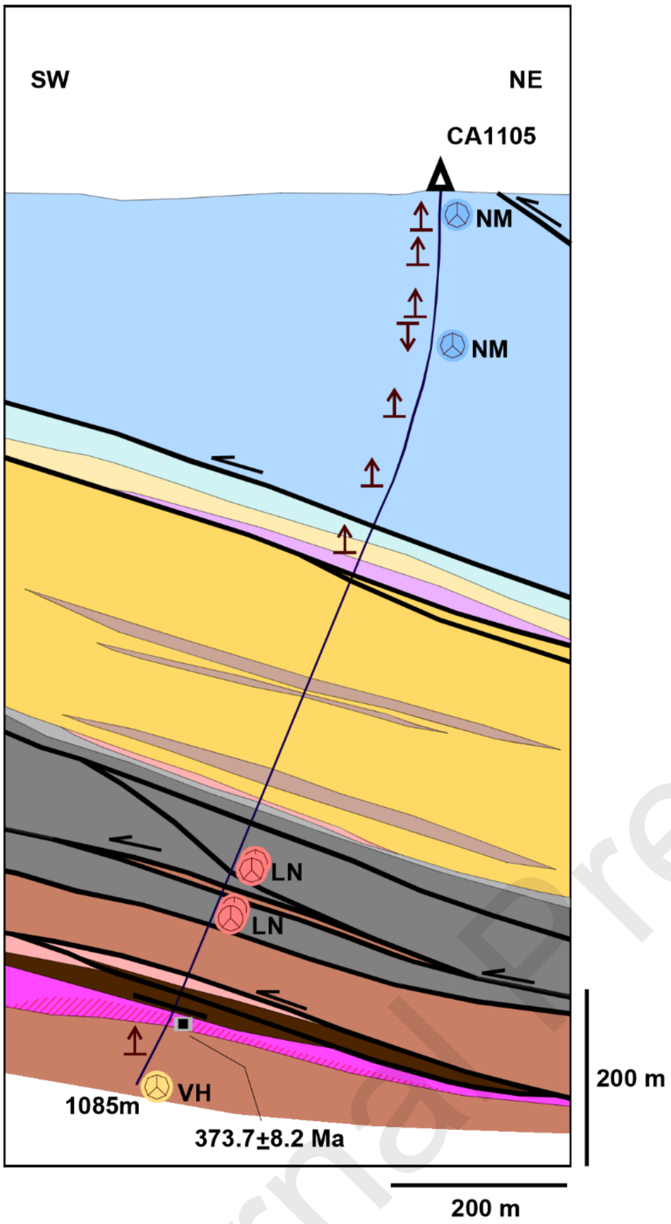
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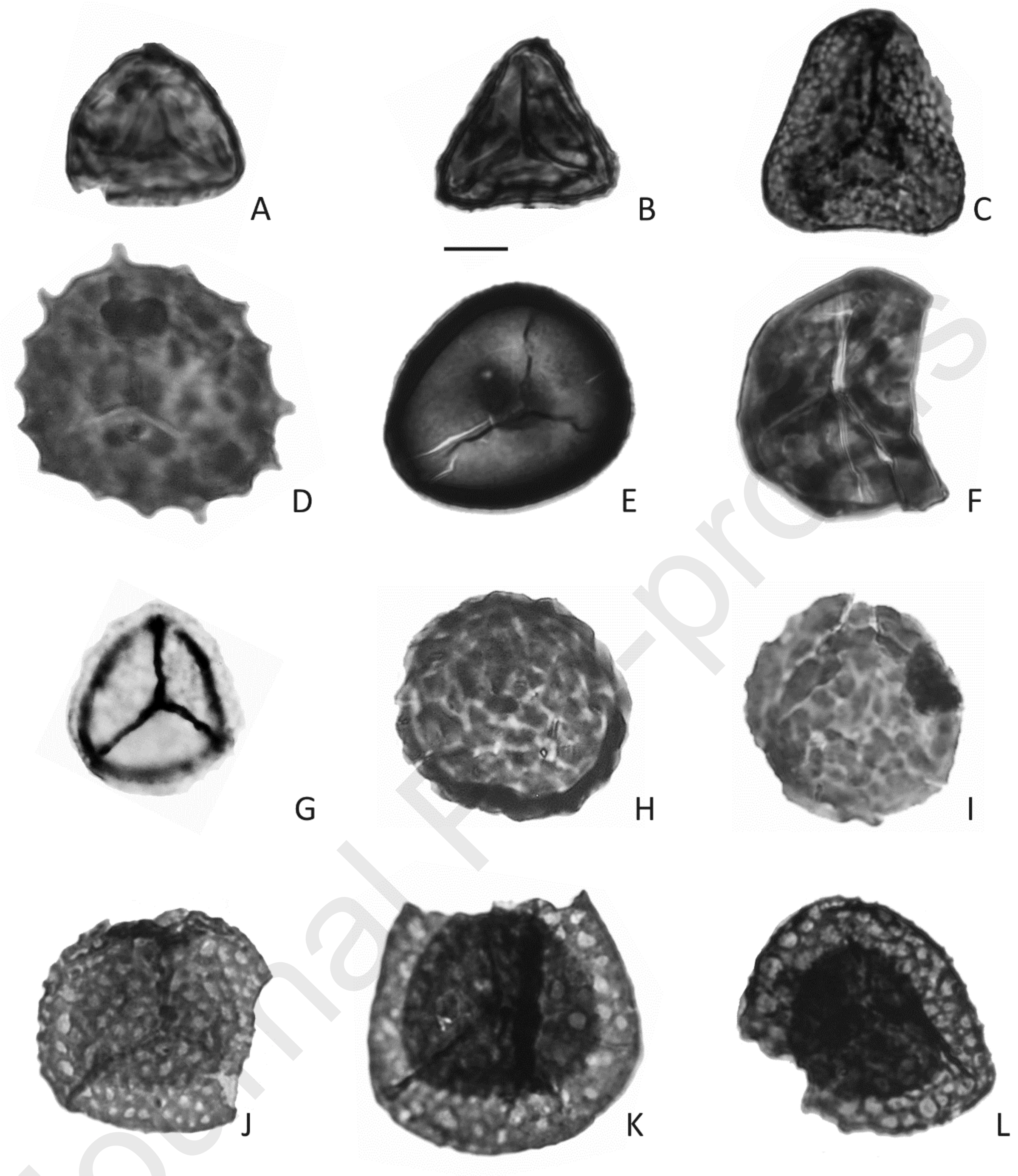
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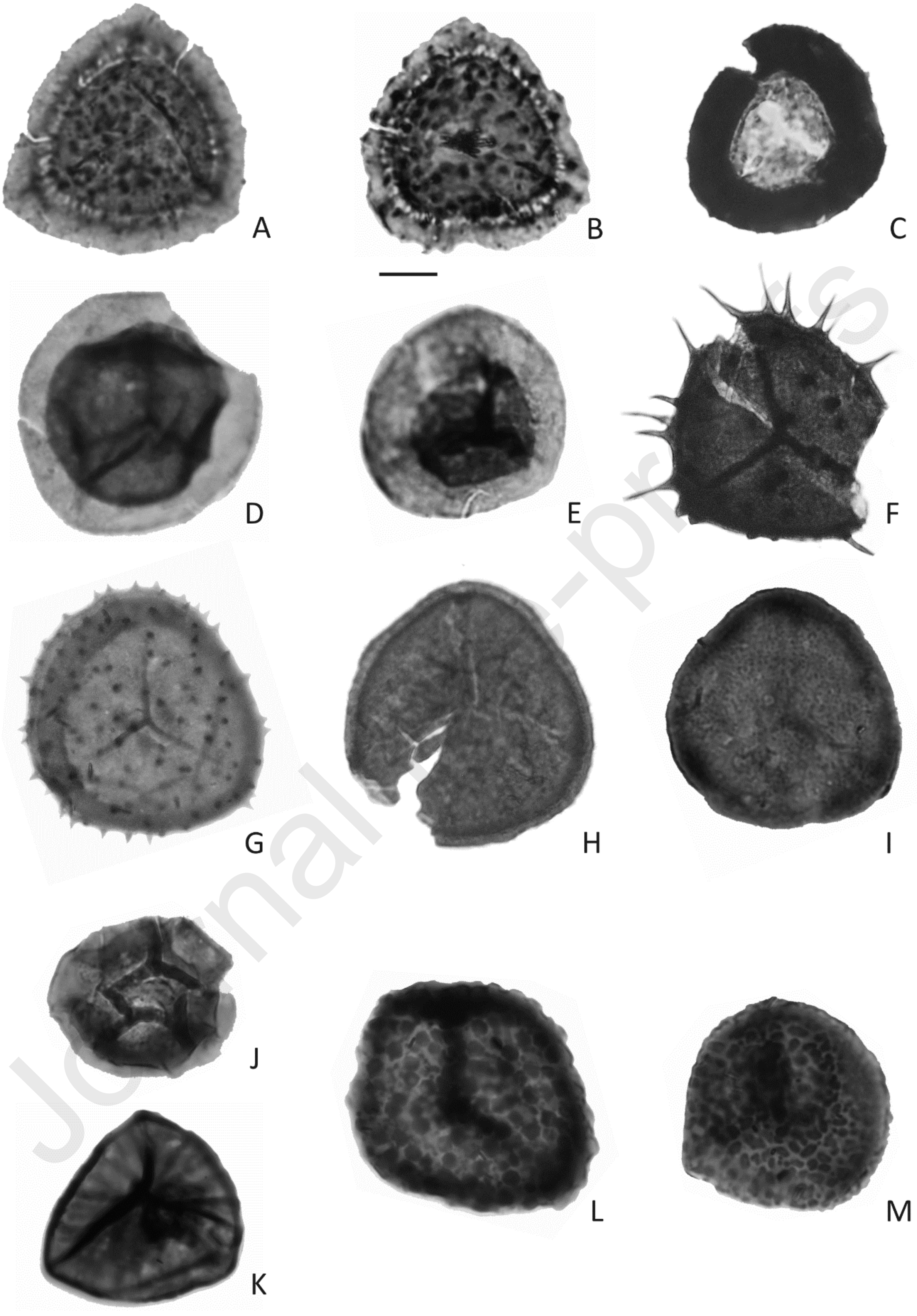
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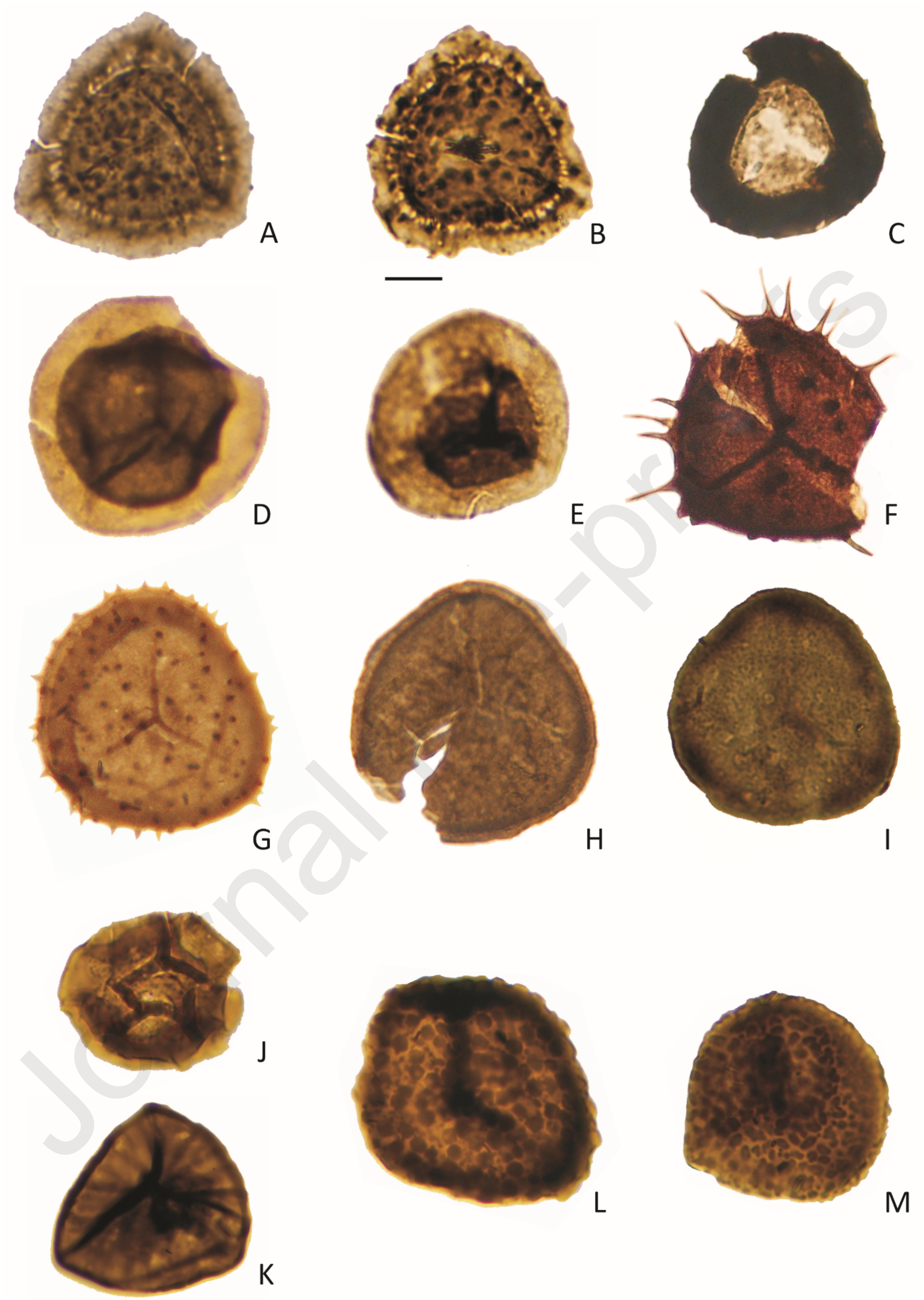
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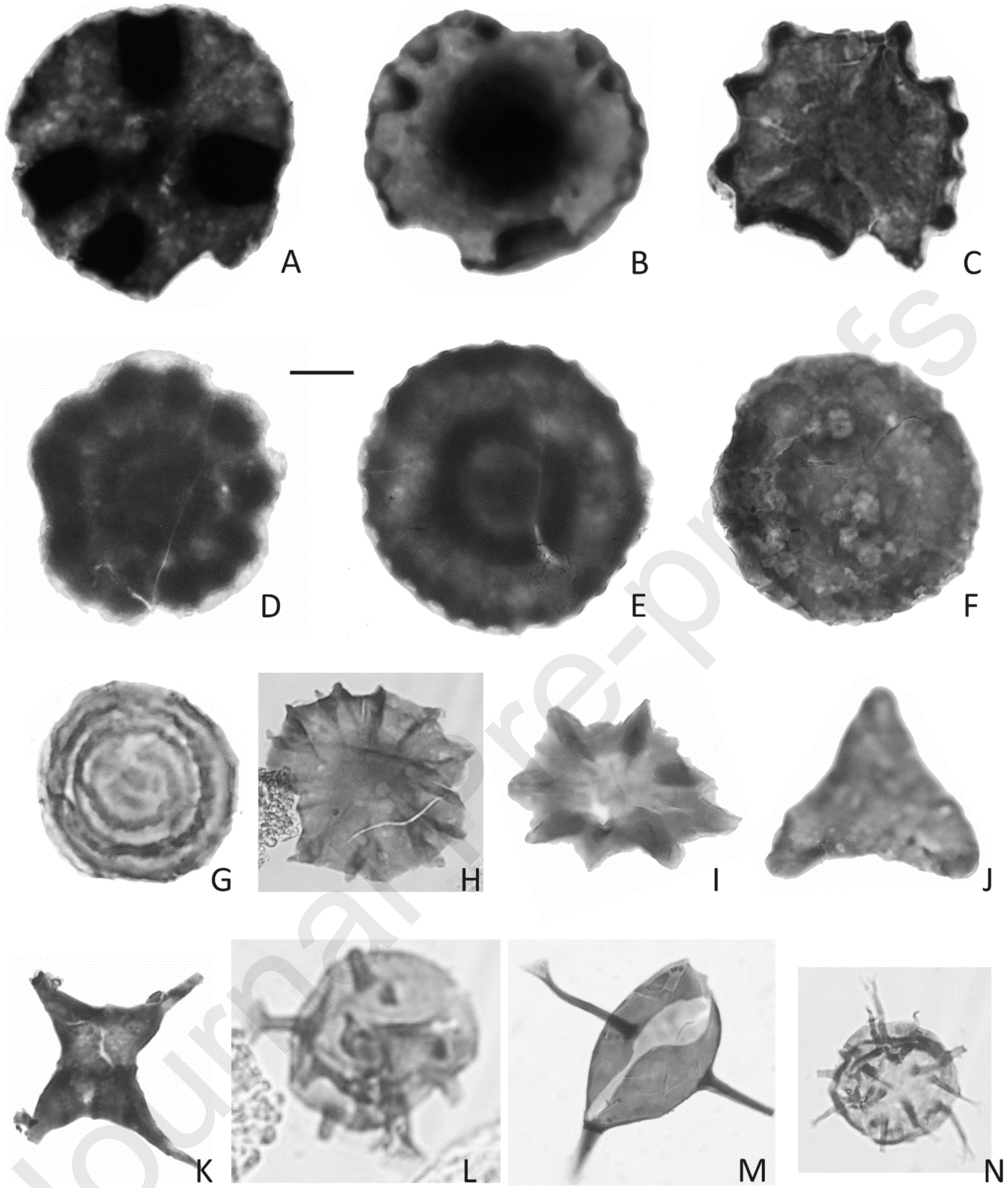
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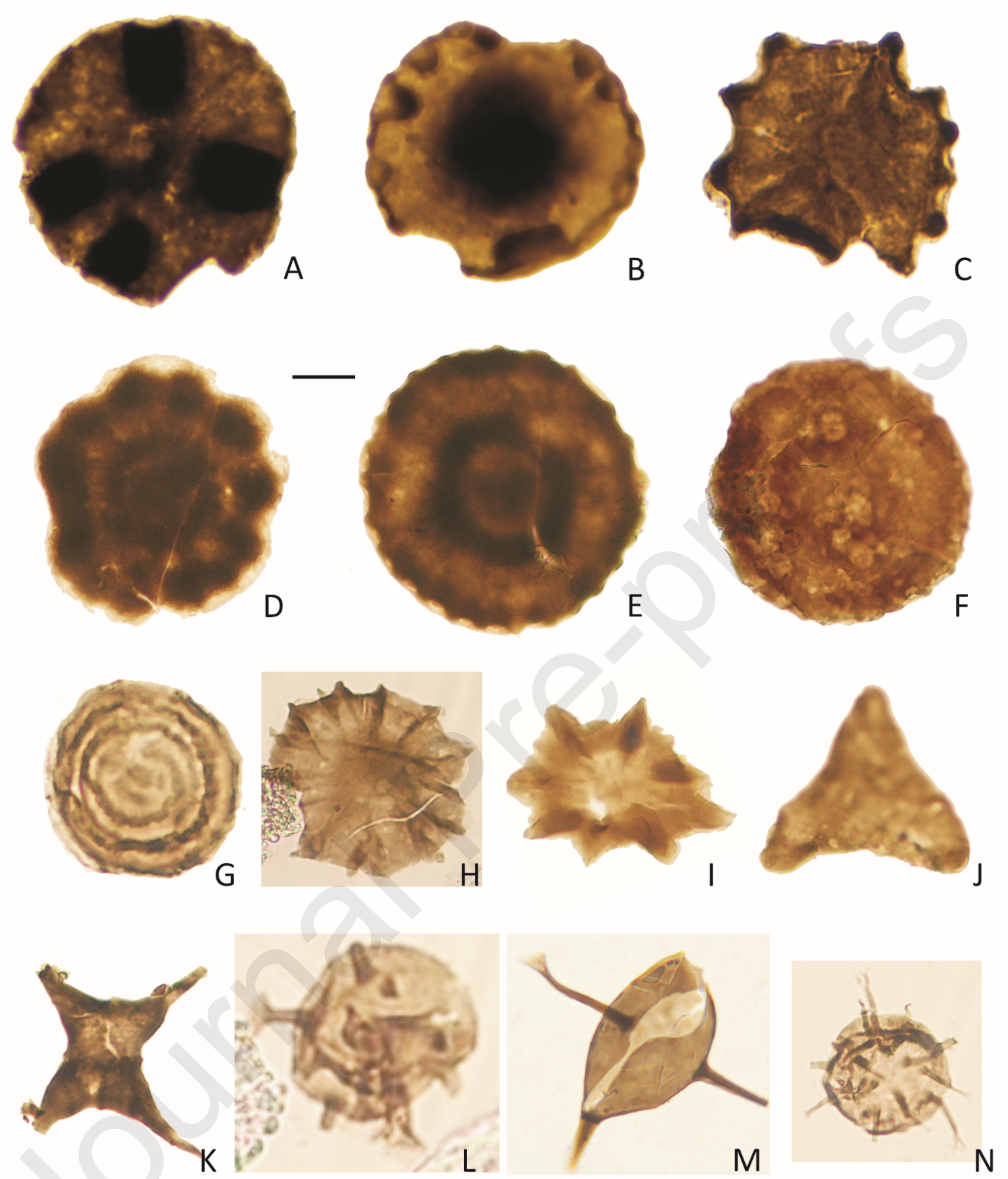
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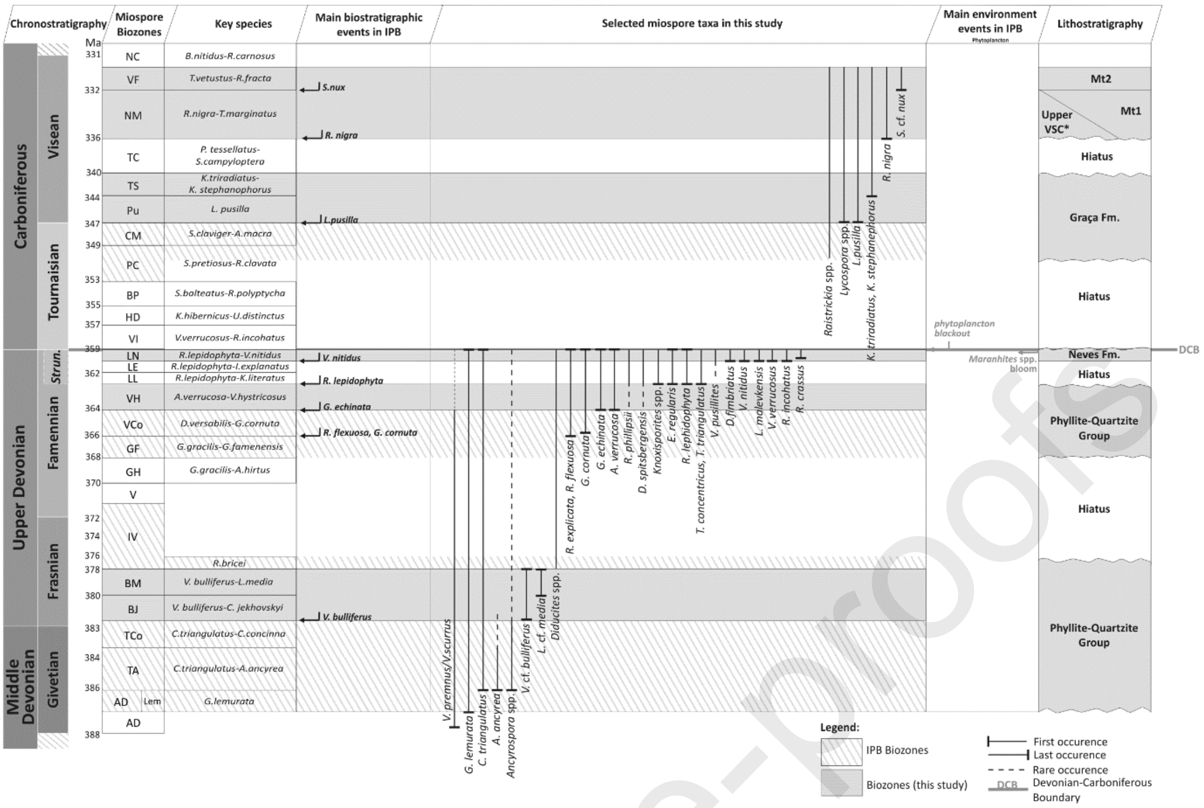
Chronostratigraphy
Miospore Biozones
Key species
Main biostratigraphic events in IPB
Selected miospore taxa in this study
Main environment events in IPB
Phytoplancton
Lithostratigraphy
Ma
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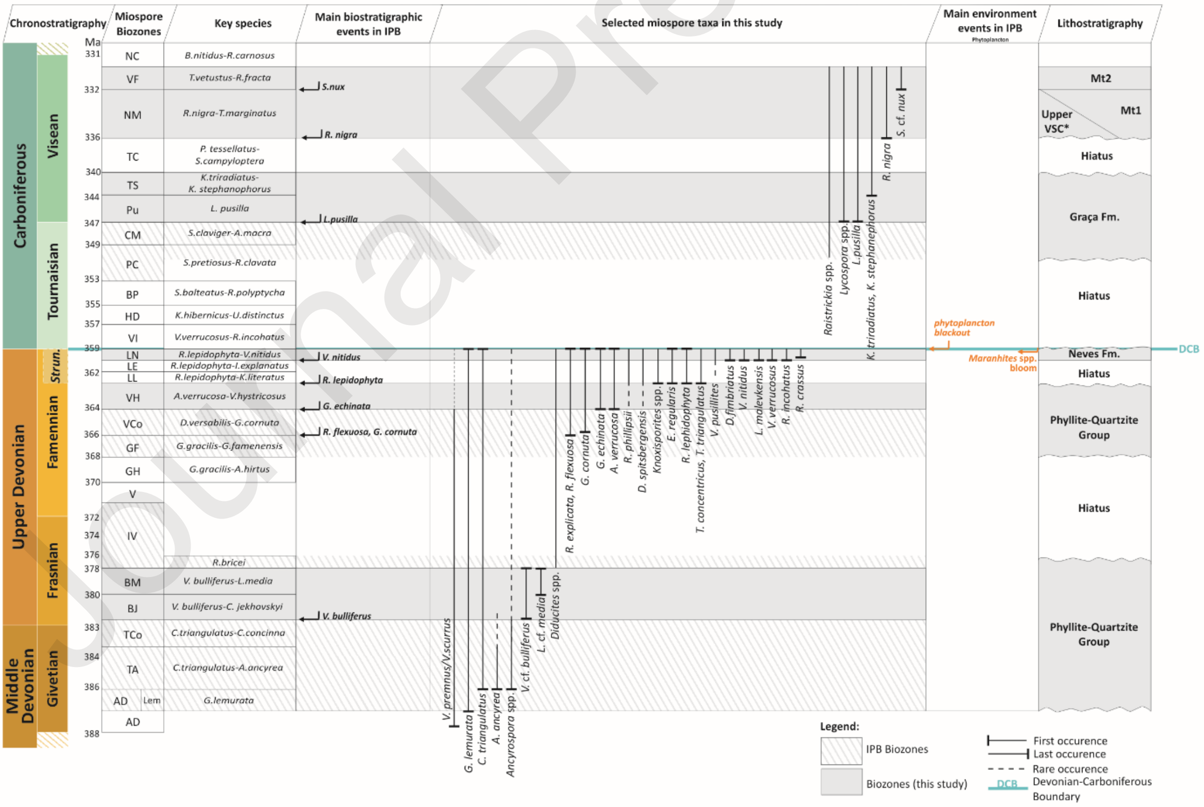
Carboniferous
Visean
Tournaisian
Upper Devonian
Strun.
Famennian
Frasnian
Middle Devonian
Givetian
NC
B.nitidus-R.carnosus
VF
T.vetustus-R.fracta
NM
R.nigra-T.marginatus
TC
P. tessellatus-S.campyloptera
TS
K.triradiatus-K. stephanophorus
Pu
L. pusilla
CM
S.claviger-A.macra
PC
S.pretiosus-R.clavata
BP
S.balteatus-R.polyptycha
HD
K.hibernicus-U.distinctus
VI
V.verrucosus-R.incohatus
LN
R.lepidophyta-V.nitidus
LE
R.lepidophyta-I.explanatus
LL
R.lepidophyta-K.literatus
VH
A.verrucosa-V.hystricosus
VCo
D.versabilis-G.cornuta
GF
G.gracilis-G.famenensis
GH
G.gracilis-A.hirtus
V
IV
R.bricei
BM
V. bulliferus-L.media
BJ
V. bulliferus-C. jekhovskyi
TCo
C.triangulatus-C.concinna
TA
C.triangulatus-A.ancyrea
AD
Lem
G.lemurata
AD
S.nux
R. nigra
L.pusilla
V. nitidus
R. lepidophyta
G. echinata
R. flexuosa, G. cornuta
V. bulliferus
S. cf. nux
R. nigra
Raistrickia spp.
Lycospora spp.
L.pusilla
K. triradiatus, K. stephanophorus
V. premnus/V.scurrus
G. lemurata
C. triangulatus
A. ancyrea
Ancyrospora spp.
V. cf. bulliferus
L. cf. media
Diducites spp.
R. explicata, R. flexuosa
G. cornuta
G. echinata
A. verrucosa
R. phillipsii
D. spitsbergensis
Knoxisporites spp.
E. regularis
R. lephidophyta
T. concentricus, T. triangulatus
V. pusillites
D.fimbriatus
V. nitidus
L. malevkensis
V. verrucosus
R. incohatus
R. crassus
phytoplancton blackout
Maranhites spp. bloom
DCB
Mt2
Mt1
Upper VSC*
Hiatus
Graça Fm.
Hiatus
Neves Fm.
Hiatus
Phyllite-Quartzite Group
Hiatus
Phyllite-Quartzite Group
Legend:
IPB Biozones
Biozones (this study)
First occurence
Last occurence
Rare occurence
DCB
Devonian-Carboniferous Boundary


Chronostratigraphy
Miospore Biozones
Key species
Main biostratigraphic events in IPB
Selected miospore taxa in this study
Main environment events in IPB
Phytoplancton
Lithostratigraphy
Ma
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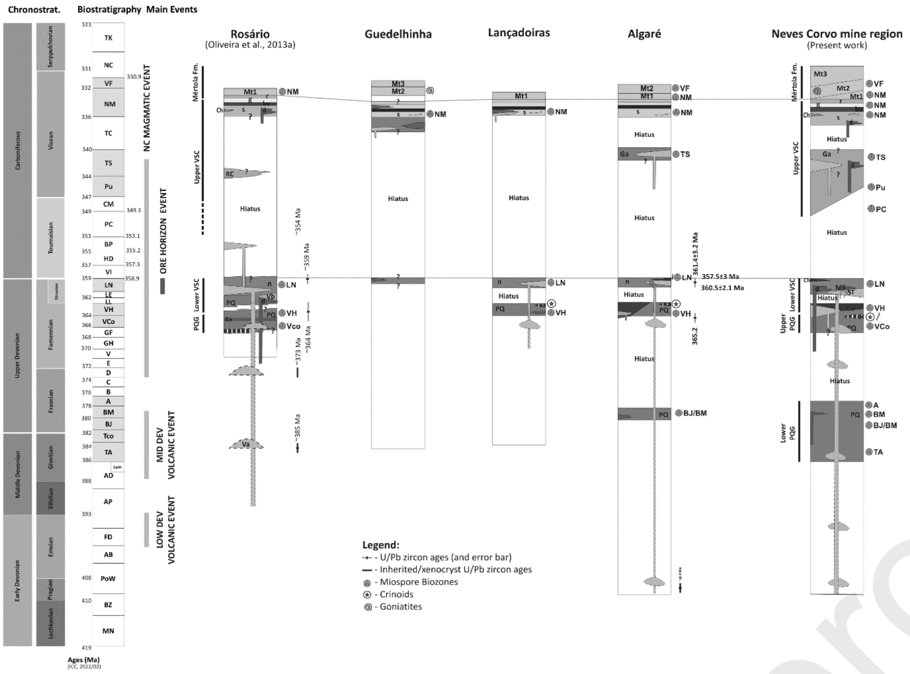
Carboniferous
Visean
Tournaisian
Upper Devonian
Strun.
Famennian
Frasnian
Middle Devonian
Givetian
NC
B.nitidus-R.carnosus
VF
T.vetustus-R.fracta
NM
R.nigra-T.marginatus
TC
P. tessellatus-S.campyloptera
TS
K.triradiatus-K. stephanophorus
Pu
L. pusilla
CM
S.claviger-A.macra
PC
S.pretiosus-R.clavata
BP
S.balteatus-R.polyptycha
HD
K.hibernicus-U.distinctus
VI
V.verrucosus-R.incohatus
LN
R.lepidophyta-V.nitidus
LE
R.lepidophyta-I.explanatus
LL
R.lepidophyta-K.literatus
VH
A.verrucosa-V.hystricosus
VCo
D.versabilis-G.cornuta
GF
G.gracilis-G.famenensis
GH
G.gracilis-A.hirtus
V
IV
R.bricei
BM
V. bulliferus-L.media
BJ
V. bulliferus-C. jekhovskyi
TCo
C.triangulatus-C.concinna
TA
C.triangulatus-A.ancyrea
AD
Lem
G.lemurata
AD
S.nux
R. nigra
L.pusilla
V. nitidus
R. lepidophyta
G. echinata
R. flexuosa, G. cornuta
V. bulliferus
S. cf. nux
R. nigra
Raistrickia spp.
Lycospora spp.
L.pusilla
K. triradiatus, K. stephanophorus
V. premnus/V.scurrus
G. lemurata
C. triangulatus
A. ancyrea
Ancyrospora spp.
V. cf. bulliferus
L. cf. media
Diducites spp.
R. explicata, R. flexuosa
G. cornuta
G. echinata
A. verrucosa
R. phillipsii
D. spitsbergensis
Knoxisporites spp.
E. regularis
R. lephidophyta
T. concentricus, T. triangulatus
V. pusillites
D.fimbriatus
V. nitidus
L. malevkensis
V. verrucosus
R. incohatus
R. crassus
phytoplancton blackout
Maranhites spp. bloom
DCB
Mt2
Mt1
Upper VSC*
Hiatus
Graça Fm.
Hiatus
Neves Fm.
Hiatus
Phyllite-Quartzite Group
Hiatus
Phyllite-Quartzite Group
Legend:
IPB Biozones
Biozones (this study)
First occurence
Last occurence
Rare occurence
DCB
Devonian-Carboniferous Boundary


Chronostrat.
Biostratigraphy
Main Events
Carboniferous
Upper Devonian
Middle Devonian
Early Devonian
Serpukhovian
Visean
Tournaisian
Strunian
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
323
331
332
336
340
344
347
349
353
355
357
359
362
364
366
368
370
372
374
376
378
380
382
384
386
388
393
408
410
419
TK
NC
VF
NM
TC
TS
Pu
CM
PC
BP
HD
VI
LN
LE
LL
VH
VCo
GF
GH
V
E
D
C
B
A
BM
BJ
Tco
TA
Lem
AD
AP
FD
AB
PoW
BZ
MN
330.9
349.3
353.1
355.2
357.3
358.9
Ages (Ma)
(ICC, 2022/02)
NC MAGMATIC EVENT
ORE HORIZON EVENT
MID DEV VOLCANIC EVENT
LOW DEV VOLCANIC EVENT
Rosário
(Oliveira et al., 2013a)
Guedelhinha
Lançadoiras
Algaré
Neves Corvo mine region
(Present work)
Mértola Fm.
Upper VSC
Lower VSC
PQG
Upper PQG
Lower PQG
Mt1
Mt2
Mt3
g
r
bv
Ch
s
d
?
RC
Hiatus
n
Vb
PQ
Ba
Va
Ga
MS
ST
Co
NM
LN
VH
Vco
VF
TS
Pu
PC
VCo
A
BM
BJ/BM
TA
~354 Ma
~359 Ma
~364 Ma
~373 Ma
~385 Ma
361.4±3.2 Ma
357.5±3 Ma
360.5±2.1 Ma
365.2
Legend:
- U/Pb zircon ages (and error bar)
- Inherited/xenocryst U/Pb zircon ages
- Miospore Biozones
- Crinoids
- Goniatites