A new approach to palynostratigraphy of the middle–late Famennian Gafo Formation, southern sector of the Pulo do Lobo Domain, SW Iberia (Portugal and Spain)

Márcia Mendes¹, Zélia Pereira¹, Z. Pereira, Nuno Vaz²,³, Alejandro Diez-Montes⁴, João X. Matos⁵, Luis Albardeiro⁵, Paulo Fernandes⁶, Raul Jorge⁷ and David Chew⁸

¹Laboratório Nacional de Energia e Geologia (LNEG), Rua da Amieira, Ap. 1089, 4466-901 São Mamede de Infesta, Portugal; ²Departamento de Geologia, Escola de Ciências da Vida e do Ambiente, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal; ³Centro de Geociências de Universidade de Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal; ⁴Instituto Geológico y Minero de España, Plaza de la Constitución, 1, 37001-Salamanca, Spain; ⁵Laboratório Nacional de Energia e Geologia (LNEG), Bairro do Val d’Oca, Ap. 14, 7601-909 Ajustrel, Portugal; ⁶Centre for Marine and Environmental Research, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal; ⁷Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edifício C6, Piso 4, 1749-016, Lisboa, Portugal, and ⁸Department of Geology, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland

Abstract

New palynological results from the Gafo Formation (southern sector of the Pulo do Lobo Domain, South Portuguese Zone) are integrated with recently studied sections and drillholes from the Portuguese and Spanish sectors. A total of 44 samples were studied, 27 of which were positive for palynomorph taxonomy. This research revealed well preserved palynological assemblages, including 73 spor species allocated to 28 genera, four acritarch genera, three psinophyte algae genera plus common chitinozoan remains. Some additional forms were retained under open nomenclature. From this, the first complete age determination for the Gafo Formation in Portugal and Spain was achieved, indicating a middle Famennian (Grandispora gracilis–Grandispora famenensis, GF Biozone) to a late Famennian (Grandispora echinata, VH Biozone) age. A greywacke sample from the same Gafo Formation was dated by U–Pb zircon geochronology and a maximum depositional age of 369 ± 2.5 Ma was obtained. A correlation between these palynological and U–Pb zircon data and the palynoflora assemblages of previous authors was made, as well as with the ages of felsic volcanic rocks found intercalated in the Gafo Formation, confirming the complex stratigraphy of Pulo do Lobo Domain. The results are consistent with stratigraphic mapping and structural interpretations, allowing a middle–late Famennian age (GF and VH Biozone) to be assigned to the Gafo Formation sedimentary rocks. This work has also contributed to a reinterpretation of Gafo Formation depositional facies correlatives (e.g. the Santa Barbara Group in Spain) as being the same lithological unit.

1. Introduction

The Pulo do Lobo Domain (PLD) antiform structure has been considered an accretionary terrane located between the Variscan Ossa-Morena Zone (OMZ) and the South Portuguese Zone (SPZ) collisional belt (Oliveira, 1990; Oliveira et al., 2019; Quesada et al., 2019; Fig. 1).

Four main domains are identified in the SPZ, namely: the PLD, Iberian Pyrite Belt (IPB), Baixo Alentejo Flysch Group (BAFG) and the SW Portuguese Sector (Oliveira, 1990; Oliveira et al., 2019). This research focuses on the PLD anticlinal structure (Fig. 1), particularly the southern sector, which comprises clastic formations including the Atalaia and Gafo formations. The Gafo Formation is characterized by flysch facies in turbiditic sedimentary rocks. While its petrographic and paleogeographic setting is known, the definition of stratigraphic units for field mapping, the lateral correlation of the facies and depositional age all remain contentious.

This paper discusses the Late Devonian miospore assemblages of the Gafo Formation, southern PLD, comprising palynostratigraphic analysis from drillhole and outcrop samples collected in both the Portuguese and Spanish sectors of the PLD (see location in Fig. 1 and online Supplementary Material, available at http://journals.cambridge.org/geo).

The Gafo Formation was previously studied by PA Lake (unpubl. Ph.D. thesis, University of Southampton, 1991), Rodríguez González (1999) and Pereira et al. (2006a, b, 2008), who attributed a Givetian – early Famennian age, late Frasnian – late Famennian age and early Frasnian
age, respectively (Figs 2, 3). An attempt is made to integrate and correlate these data with new biostratigraphic records based on spores and chitinozoans in order to achieve an accurate age of the Gafo Formation, as well as an understanding of the microfloral assemblages of the PLD and the SPZ, thus confirming an affinity with the Avalonian Terrane (Oliveira et al. 1979; Loboziak & Streel 1981; Korn 1997; Clayton et al. 2002; Higgs et al. 2013). Newly obtained U–Pb detrital zircon data are also included and discussed.

This research was a co-sponsored geological mapping project supported by the Portuguese (LNEG) and Spanish (IGME) geological surveys of the South Portuguese Zone, 1:200 000 scale (GEO_PFI Project), including the Pulo do Lobo and Iberian Pyrite Belt domains. Based on this project, recent palynostratigraphy studies were developed to constrain the sedimentary sequence of the southern PLD, particularly the Gafo Formation, and to test correlations with the Santa Bárbara Unit, as defined in the Spanish sector.

2. Geological setting

The PLD E–W-trending complex antiform structure crops out both in Portugal and Spain, in a sigmoidal shape bound to the north by the OMZ (the Beja-Acebuches Ophiolite Complex in particular) and the south by the IPB, and is part of the SPZ (Fig. 1). The domain is divided into a northern sector, represented by the Ferreira–Ficalho Group (including the Ribeira de Limas, Santa Iria and Horta da Torre formations; Fig. 2) and the southern limb, characterized by the Chança Group (including Atalaia and Gafo formations; Fig. 2), the latter being the focus of this work.
In the core of this domain, the Pulo do Lobo Formation (Late Devonian, middle Frasnian in age; Pereira et al. 2006a, b, 2018, 2019) crops out and is well exposed in the Guadiana and Chança river sections, including strongly deformed chloritic and sericitic phyllites and quartzites with minor intercalations of felsic volcanic rocks (Pfefferkorn, 1968; Oliveira, 1990).

In the PDL northern sector, three formations are recognized in the Ferreira–Ficalho Group, including the Ribeira de Limas, Santa Iria and Horta da Torre formations (Fig. 2; Carvalho et al. 1976; Oliveira et al. 1986; Giese et al. 1988; Oliveira, 1990; CP Eden, unpubl. Ph.D. thesis, University of Southampton, 1991; Silva, 1998). In Spain, the northern sector of the PLD includes, from bottom to top: the Peramora Mélange, the Ribeira de Limas Formation (Late Famennian age), Santa Iria Formation and Horta da Torre Formation (both late Famennian age) (Pereira et al. 2018), and the Alájar Mélange (Fig. 2). In the northern part of the PLD, the stratigraphy and age of the formations are described in detailed in Pereira et al. (2018, 2019) and Oliveira et al. (2019).

2.a. The Chança Group

Focusing on the southern sector of the PLD structure, the Chança Group comprises, from base to top, the Atalaia and the Gafo formations, defining a clastic succession (Pfefferkorn, 1968; Oliveira, 1990; Silva, 1989, 1998; Silva et al. 1990). In Spain, the northern sector of the PLD includes, from bottom to top: the Peramora Mélange, the Ribeira de Limas Formation (Frasnian age), Santa Iria Formation and Horta da Torre Formation (both late Famennian age) (Pereira et al. 2018), and the Alájar Mélange (Fig. 2). In the northern part of the PLD, the stratigraphy and age of the formations are described in detailed in Pereira et al. (2018, 2019) and Oliveira et al. (2019).
Fig. 3. (Colour online) Zonal scheme and ranges of stratigraphically relevant taxa recovered in this study. Palynoflora age correlation is integrated with previous studies in the Gafo Formation PA Lake (unpubl. Ph.D. thesis, University of Southampton, 1991; Rodríguez González, 1999; Pereira et al. 2006a, b, 2008). The zonal scheme follows Loboziak & Streel (1981, 1989), Streel et al. (1987), Higgs et al. (2000, 2013) and Pereira et al. (2008). R – reworked taxon.
3. Previous palynostratigraphic and geochronological studies of the Gafo Formation

The first reference to miospores in the Gafo Formation in PLD was provided by PA Lake (unpubl. Ph.D. thesis, University of Southampton, 1991), who recorded the presence of dispersed and poorly preserved assemblage of miospores. In three samples located in the vicinity of Paymogo, the author considered a late Givetian – early Famennian age for the Gafo Formation (Fig. 3). Rodríguez González (1999) and Matas et al. (2015) have also dated the Gafo Formation and Santa Bárbara Unit (included in the Santa Bárbara Group), and also obtained long-ranging ages, spanning middle Frasnian – (?early Frasnian to Late Devonian (PA Lake, unpubl. Ph.D. thesis, University of Southampton, 1991) and middle Frasnian – BM Biozone (Pereira et al. 2006a, b, 2008) based on palynostratigraphy (Fig. 3).

The Gafo Formation shows three main episodes of tectonic deformation and associated cleavages (Silva et al. 2013). The second-phase deformations exhibit an E–W-aligned trend in Spain, a WNW–ESE to NW–SE-aligned trend in Portugal, and tectonic vergence to the south or SSW. The structural thickness may reach 500 m (Oliveira et al. 2019). Metamorphism is low greenschist facies (Pereira et al. 2006a, b). In Spain, the stratigraphic equivalent unit of the Gafo Formation is the Santa Bárbara Group, which includes: (1) in the northern sector, the Gafo Formation itself, including greywackes and interbedded shale successions with minor tuffite intercalations, intruded by felsic and mafic veins (Quesada et al. 2019) of late Frasnian age (Late Devonian; Rodríguez González, 1999), and (2) in the south, the Santa Bárbara Unit, comprising an interbedded shale succession with siltite lamination, intruded by felsic veins of late Famennian (Late Devonian) to probably earliest Tournaisian age (early Carboniferous; Rodríguez González, 1999; Matas et al. 2015; Fig. 3). The units show identical lithological characteristics, but are tectonically divided by the Santa Bárbara Thrust Fault (Matas et al. 2015; Diez-Montes et al. 2020a).

4. Materials and methods

4.1. Gafo Formation palynology and U–Pb zircon geochronology

A total of 44 samples (20 outcrop samples and 24 drill core samples) collected from the Gafo Formation sediments were subjected to standard palynological laboratory procedures to extract and concentrate the palynomorphs (Wood et al. 1996). Oxidation of the palynomorphs was carried out using Schultze solution. Oxidation time varied according to the degree of carbonization, ranging from 30 min to 2 hours, and resulted in 27 productive samples for palynology studies (19 outcrop samples and 8 drill core samples), yielding moderate to well-preserved palynomorphs. A sample list with geographic coordinates is provided in the online Supplementary Table S1 (available at http://journals.cambridge.org/geo). The selected productive residues were mounted on slides and examined with a Nikon Eclipse Ci transmitted light microscope. All samples, residues and microscope slides are stored at the Portuguese Geological Survey (LNEG). The standard western Europe miospore biozonal scheme was followed (Loboziak & Streefland 1981, 1989; Streefland et al. 1987; Pereira et al. 2008; Higgs et al. 2000, 2013). The studies of Clayton et al. (2000) and Loboziak (2000) were used to correlate the palynoflora with Saudi Arabia assemblages.

The palynomorph assemblages recovered from the drillholes and outcrop samples are presented in Figures 3, 4. Important stratigraphic taxa are illustrated in Figures 5–8. A list of all taxa recovered or mentioned in this work is also available in the online Supplementary Material.

A representative sample from Gafo Formation greywacke unit (PL 18) was collected for U–Pb zircon geochronology (see Fig. 1 for location). Zircon grains were separated from whole-rock samples using standard crushing and mineral separation techniques.
Fig. 4. Palynomorph assemblages recovered in the Gafo Formation sedimentary rocks sampled in Portugal and Spain. Points indicate the presence of the specified taxon within the palynoflora; blanks indicate absence. R – reworked taxon.
The handpicked zircons were mounted in resin and ground and polished to half-thickness. Zircon U–Pb isotopic data were generated at the Department of Geology, Trinity College Dublin, Ireland. A Photon Machines Analyte Excite 193 nm ArF excimer laser-ablation system with a HelEx 2-volume ablation cell, coupled to an Agilent 7900 mass spectrometer, was used for the analyses. Line scans on NIST612 standard glass were used to tune the instruments by obtaining a Th/U ratio close to unity and low oxide production rates (i.e. ThO⁺/Th⁺ typically < 0.15%). A circular laser spot of 24 μm was used, with a repetition...
rate of 13 Hz. Helium carrier gas was fed into the laser cell at c. 0.4 L/min and was mixed with an aerosol of c. 0.6 L/min Ar make-up gas and 11 mL/min N₂. During each analysis, eight isotopes (⁹⁰Zr, ²⁰²Hg, ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³⁳Th and ²³⁸U) were measured. Each analysis comprised 21.5 s of ablation (280 shots) and 9 s of washout time. The latter portions of the washout time were used for baseline measurements. The reduction of the raw U–Th–Pb isotopic data was undertaken using the freeware IOLITE package (Paton et al. 2011), with the VizualAge data reduction scheme (Petrus & Kamber, 2012). Conventional sample-standard bracketing was applied to account for both downhole fractionation and long-term drift in isotopic or elemental ratios by normalizing all ratios to those of the U–Th–Pb reference materials. The primary U–Pb calibration standard was the 91500 zircon.

Fig. 6. (Colour online) Important taxa from the studied drillholes and outcrops. All specimens are housed in the collections of the Portuguese Geological Survey (LNEG). 1, Ancyrospora sp.; CH0601 drillhole, slide 1_112, MC 958/266; 2, Ancyrospora sp.; H-318 sample, slide 1_54, MC 1135/458; 3, Geminaspore lemurotata (Balme) emend. Playford, 1983; H-339 sample, slide 1_111, MC 1037/230; 4, Geminaspore lemurotata (Balme) emend. Playford, 1983; CH0601 drillhole, 121.1 m sample, slide 1_75, MC 1113/414; 5, Geminaspore lemurotata (Balme) emend. Playford, 1983; CH0601 drillhole, 121.1 m sample, slide 1_49, MC 1065/430; 6, Grandispora echinata Hacquebard, 1957; H-339 sample, slide 1_105, MC 1050/237; 7, Grandispora echinata Hacquebard, 1957; H-339 sample, slide 1_88, MC 970/312; 8, Grandispora gracilis Streel in Becker et al. 1974; H-318 sample, slide 1_36, MC 1060/481; 9, Grandispora gracilis Streel in Becker et al. 1974; H-318 sample, slide 1_113, MC 1020/328; 10, Grandispora famenensis (Naumova) Streel, 1974 var. minuta Higgs et al. 2000; H-337 sample, slide 1_163, MC 1032/268; 11, Grandispora famenensis (Naumova) Streel, 1974 var. famenensis Higgs et al. 2000; CH0602 drillhole, 121.1 m sample, slide T1_2, MC 999/473; 12, Grandispora famenensis (Naumova) Streel, 1974 var. minuta Higgs et al. 2000; H-337 sample, slide 1_92, MC 1108/369.
(206Pb/238U age of 1065.4 ± 0.6 Ma; Wiedenbeck et al. 1995) and the secondary standard was WRS 1348 zircon (206Pb/238U age of 526.26 ± 0.70; Pointon et al. 2012). The secondary standard yielded a concordia age of = 530.2 ± 1.8 Ma (n = 25). Probability Density and Kernel Density Estimator plots were made using the Density Plotter spreadsheet (Vermeesch, 2012). The International Chronostratigraphic Chart ICS-v2021/07 (www.stratigraphy.org) was followed. Detailed information is provided in online Supplementary Table S2 (available at http://journals.cambridge.org/geo).

4.b. Gafo Formation drillholes

In this study two AGC Company exploration drillholes were sampled (Figs 1, 9). These holes were drilled at the IPB Chança massive sulphide deposit in 2006 by AGC Minas de Portugal.
The CH0601 hole (inclination 70°, azimuth 194°) is in the WNW sector of the Chança Volcano-Sedimentary Complex (VSC) anticline. CH0601 intersects the Gafo Formation sediments (shales, silts and greywackes) from the surface to a depth of 227.9 m, and is in thrust contact with the VSC felsic volcanic rocks from 227.9 m to the full depth of the drillhole (512.6 m). The CH0602 hole (inclination 60°, azimuth 180°) was drilled in the northern sector of the Chança mine, and intersects the same facies of Gafo Formation sediments between the surface and a depth of 191.2 m. Only VSC felsic volcanic rocks are found from 191.2 m to

Fig. 8. (Colour online) Important taxa from the studied drillholes and outcrops. All specimens are housed in the collections of the Portuguese Geological Survey (LNEG). 1, (?) Angochitina sp.; H-314 sample, slide 1_38; 2, Angochitina sp.; H-337 sample, slide 1_43; 3, Angochitina sp.; H-325 sample, slide 1_327; 4, Angochitina sp.; H-318 sample, slide 1_78; 5, Lagenochitina sp.; H-318 sample, slide 1_26; 6, Lagenochitinidae; H-318 sample, slide 1_19; 7, (?)/Lagenochitina sp.; H-318 sample, slide 1_89; 8, (?)Lagenochitina sp.; H-321 sample, slide 1_6; 9, Chitinozoan neck, with prosome preserved; H-339 sample, slide 21_37; 10, Chitinozoan neck, with prosome preserved; H-314 sample, slide 1_35.
the full depth of the drillhole (650 m). In both drillholes, minor mafic and felsic dykes occur in the Gafo Formation, and stockwork mineralization was intersected in the VSC felsic rocks (rhyolites and rhyodacites). Seven palynomorph-bearing samples were recovered from the CH0601 drillhole (from 37.5 m to 218.0 m) and one from the CH0602 drillhole (121.1 m). Figure 9 shows the WNW Chança section based on the CH0601 drillhole data and surface mapping.

4.c. Gafo formation outcrop sections

4.c.1. Chança River section

This first group of samples (H-145/H-26, H-142/H-27, AD-H-147/AD-H-148 and AD-H-150) are located in the Chança River section (Fig. 1). South of Vuelta Falsa mine, samples H-145/H-26 and H-142/H-27 were collected from outcrops defined by an alternation of greywackes and black slate. Samples H-147 and H-148 were collected from a thick layer of black slate. North of Vuelta Falsa mine, sample H-150 was collected from a section of black slate, with scarce layers of quartzites and quartz wackes.

4.c.2. South Paymogo section

Samples H-137/H-138, H-314, H-318, H-321, H-325, H-336, H-337, H-378 (c. 318 m) and H-405 (c. 337 m) were collected from the South Paymogo section.

Samples H-137 and H-138 were collected to the SE of Paymogo, on the road to Puebla de Guzmán (Fig. 1). An alternation of quartz wackes and slate forms the outcrop, a brownish colour with greenish tones. Some thin levels of impure quartzites can also be observed. Samples H-336 and H-337 (= H-405) were collected to the SE of Paymogo, on the route to Los Peros. The outcrops are formed by a succession of quartz wackes, lithic arenites and slate. Samples H-314, H-318 (= H-378) and H-321 were collected in the Albahacar creek. The outcrops are formed by a succession of quartz wackes, quartzite and black slate. Sample H-325 was taken from the riverbed of the Corte creek. The outcrop is formed by an alternation of black slate, greywackes, quartz wackes and occasional quartzite beds.

4.c.3. Paymogo SE sector

Sample H-339 was collected SE of Paymogo, on the Rivera Aguas de Miel. This outcrop is an alternation of black slate, lithic arenites, greywackes and quartz wackes.

4.c.4. Santa Bárbara section

Samples H-398, H-390 and H-395, collected from the Santa Bárbara section, are all negatives. Sample H-390 was collected east of Santa Bárbara de Casa from a horizon of slate with an intense schistosity. Sample H-395 was collected from an outcrop consisting of greenish slate, sandstones and quartzites along the road from Cabezas Rubias to El Mustio. Sample H-398 was collected north of Santa Bárbara de Casa, on the road that leads to El Mustio. The outcrop comprises slate and sandstones. S-C-type textures are observed throughout the outcrop, which show thrust movement towards the south.
4.5. South of Gil Márquez Unit section
Sample H-420 was collected south of Gil Márquez, in the Rivera de Olvarga. A succession of slate and sandstones forms this outcrop, which is very close contact with the Pulo de Lobo thrust.

5. Gafo Formation palynology results
The Gafo Formation palynoflora comprises a diverse and abundant set of 73 spore types (including 28 different genera), five acritarch types, five prasinophyte specimens and some chitinozoans and graptolite remains, enabling the identification of three different assemblages. The poor preservation of some specimens did not allow specific identification; these specimens were left as open nomenclature (Figs 3, 4). These assemblages are characterized by the first occurrence (FO) of key taxa and the relative abundance of prominent taxa. The palynomorph assemblages and biozones identified are described in stratigraphic order in the following sections.

5.a. Latest Givetian – (?)early Frasnian assemblage
The Gafo Formation was sampled in three outcrop sections in the southernmost Spanish sector, exposed along the Chança River (southern section) (Fig. 1). The shales yielded a poorly preserved assemblage of miospores assigned a Late Devonian age, probably of latest Givetian – (?)early Frasnian.

The assemblage includes Ancepsporas greggisi, Apiculiretusisporas sp., Cristatisporites Cristatisporites cf. insulisatus, Cristatisporites Cristatisporites sp., Geminosporares lemurata, Grandisporares sp., Punctatisporites sp., Retusotriletes triangulatus, Retusotriletes sp., Verruciretusispora dubia, Verrucosissporas cf. bulliferus, Verrucosissporas premnus, Verrucosissporas scurrus and Verrucosissporas sp. Despite its poor general preservation, the assemblage includes long-ranging species that include taxa first occurring in the Eifelian Stage, such as Verrucospores ancyrea and early Givetian species, such as Cristatisporites Cristatisporites triangularis. The assemblages seem incomplete, but the presence of Cristatisporites Cristatisporites cf. insulisatus, Lophozonotriletes sp. and Verrucosissporas cf. bulliferus indicates a Late Devonian age (?)early Frasnian. Marine palynomorphs were relatively rare, including Leiosphaeridias sp., Maranhites mosesii and Maranhites sp.

5.b. Middle Famennian assemblage
The Gafo Formation was sampled in two drillholes, CH0601 (of the 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 1 was positive) at Chança mine sector in Portugal, and a road section (Fig. 1). The shales yielded an abundant and well preserved palynoflora comprising a diverse and abundant assemblage of miospores assigned to the GF Biozone of middle Famennian (Fig. 1). The shales yielded an abundant and well preserved palynoflora, 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 7 were positive) at Chança mine sector in Portugal, and a road section (Fig. 1). The shales yielded an abundant and well preserved palynoflora, 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 7 were positive) at Chança mine sector in Portugal, and a road section (Fig. 1).

5.5. Middle Famennian assemblage
The Gafo Formation was sampled in two drillholes, CH0601 (of the 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 1 was positive) at Chança mine sector in Portugal, and a road section (Fig. 1). The shales yielded an abundant and well preserved palynoflora, 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 7 were positive) at Chança mine sector in Portugal, and a road section (Fig. 1). The shales yielded an abundant and well preserved palynoflora, 12 studied samples, 7 were positive) and CH0602 (of the 12 studied samples, 7 were positive) at Chança mine sector in Portugal, and a road section (Fig. 1).

5.c. Late Famennian assemblage
Preliminary data obtained in two samples, one collected from the easternmost region of the Gafo Formation in the Santa Bárbara East section (sample H-339) and the other from south of Gil Márquez (sample H-420) (see Fig. 1), present a palynomorph assemblage assigned to the VH Miospore Biozone of late Famennian age based on first occurrence of the regional key species Grandispora echinata (Fig. 3). Assemblages are also dominated by Apiculiretusispora sp., Cristicavatispora dispersa, Grandispora cf. echinata Grandispora sp., Retusotriletes philippsii, Rugospora cupulata and Rugospora flexuosa. Other common miospore species are Ancepsporas greggisi, Ancyrospores cf. implicata, Ancyrospores sp., Convolutisporas sp., Diducites sp., Emphanisporas sp., Geminospores lemurata, Grandispora cf. megaronis, Grandispora sp., Punctatisporas sp., Retusotriletes sp., Retusotriletes prematus, Lophozonotriletes sp., Verruciretusispora dubia, Verrucosissporas lobatii, Verrucosissporas sp., bulliferus, Verrucosissporas prematus, Verrucosissporas scurrus and Verrucosissporas sp.

Rare acritarchs and prasinophytes of the taxa Delitososporas sp., Dupliciradiatum sp., Gorgonisphaeridium sp., Veryhachium downiei, Veryhachium trigispinum, Leiosphaeridium sp., Dictyotidium sp., Maranhites mosesii, Maranhites perplexus and Maranhites sp. were found. All samples contain common Grandispora sp. tetradrs.

The identified species Camarozonotriletes sp., Dictyotrides sp. cf. emiensis and Retusotriletes cf. maculatus of Early Devonian age, and Grandispora cf. megafornis, Grandispora cf. protea and Grandispora protea of Middle Devonian age, are interpreted as reworked miospores. Chitinozoans and scolocodont fragment remains are very common in the samples studied in the Spanish sector sections (Fig. 7).

6. Gafo Formation chitinozoan results
Eight samples were studied for chitinozoans, four of which were productive (H-314, H-318, H-321 and H-378). It was possible to recognize some chitinozoans from the observations made, but the preparations mostly included other groups, namely prasinophytes algae and spores. Most of the chitinozoan specimens observed show evidence of transport, as most of them are broken, incomplete and worn on their surface.
Focusing on the Spanish outcrop samples, the chitinozoan taxa recovered in palynology samples of middle–late Famennian age were carefully documented. Two main subfamilies were identified – Lagerochitinae and Anchochitinae (Paris & Verniers, 2005) – with the recognized species Lagerochitina sp. and Anchochitina sp. (Fig. 8) assigned a Middle–Late Devonian age. Some additional forms or fragments of low preservation are retained under open nomenclature.

7. U–Pb age results

Sampled PL 18 greywacke (north of the VSC Chança structure, Fig. 1) yielded 149 zircon grains, 119 of which are concordant and comprising Palaeozoic (33%), Neoproterozoic (34%), Mesoproterozoic (11%), Palaeoproterozoic (19%) and Archean (3%) grains. Within the Palaeozoic population, the largest population is of Devonian (28%), particularly Late Devonian (22%) and Middle Devonian (9%) age; there were also single zircons of Early Devonian (1%) and Carboniferous (348 Ma) (1%) age, interpreted as representing minor lead loss (Fig. 10). Based on probability distribution and kernel density estimator plots, a major Late Devonian peak at c. 374 Ma was identified. Within this Late Devonian peak, 10 grains occur in the 371.4–367.3 Ma age range (early Famennian) and 16 zircon ages within the 381.9–373.6 Ma time range (Frasnian). The remaining Devonian-aged grains comprise four of Givetian (385.3–382.8 Ma), two of Etfelian (393–388 Ma) and one of Emsian (401.4 Ma) age. A single Silurian grain has an age of 426.1 Ma. These Devonian grains are associated with the Early Variscan evolution of the Iberian Pyrite Belt.

Within the Neoproterozoic-aged population, the Ediacaran period is dominant (631.8–541.2 Ma with a central peak at c. 617 Ma and a secondary peak at c. 579 Ma) with 26% of all grains, followed by Cryogenian (8%) and Tonian (2%) ages. The Palaeoproterozoic group ages range from 2175.6–2051.1 Ma to 2042.4–1842.2 Ma with 11 and 10 grains, respectively. Minor peaks were defined at c. 1977, 2035 and 2121 Ma.

A Concordia age was obtained using the youngest five (out of 10) late Famennian grains with favourable statistics, yielding an age of 369.1 ± 2.5 Ma (mean squared weighted deviation and probability of concordance of 0.019 and 0.89, respectively). This age is proposed as the maximum depositional age for the greywackes of the Gafo Formation.

8. Discussion

8.a. Miospores

This study was undertaken on a regional basis, based on both exploration drillholes and reference geological sections of the turbiditic sequences of the Gafo Formation in the Portuguese and Spanish PLD southern sector (Fig. 1). The miospore content was qualitatively considered, first and last occurrences were established, and common distinctive taxa presented (Figs 3, 4).

The Gafo Formation samples cropping out in the south Chança River section yielded an assemblage from a (?)-latest Givetian – early Frasnian age based on the occurrence of Verrucosisporites cf. bulliferus. The palynoassemblage is complemented by frequent Cristatisporites Cristatisporites triangularis and Anycyospora ancyrea, and by the most frequent Frasnian taxa, Cristatisporites Cristatisporites cf. insutatus and Lophozonotriletes sp. Since the association is uncertain, it is not possible to constrain the age considering the poorly preserved and long-ranging palynomorphs. Nevertheless, these preliminary age constraints have redefined the Gafo Formation as a greywacke and interbedded shale unit, previously interpreted as Culm facies in the Spanish literature and assigned to the BAFG and an early Carboniferous age (typically Visean; Matas et al. 2015).

The Gafo Formation data sampled in drillholes (Portugal) and several outcrops (Spain) show a very consistent GF Miospore Biozone, assigned a middle Famennian age. The microflora observed contain similar miospore taxa as recorded by Steel (2009) and Higgs et al. (2013), specifically Grandispora gracilis, Grandispora famenensis and Grandispora cf. microseta. According to Higgs et al. (2013), the GF Miospore Biozone can be characterized by the first occurrence of Grandispora famenensis and of Grandispora microseta, which appear in the middle of the GF Biozone. Common occurrences of Grandispora gracilis are also observed in this biozone, suggesting a middle GF Miospore Biozone of middle Famennian age.

In Spain, the Santa Bárbara Group crops out in the south Paynogo road section, where the Gafo Formation (to the north) and the Santa Bárbara Unit (to the south) are separated by the Santa Bárbara Fault (Fig. 1). The Santa Bárbara Unit has yielded a middle Famennian age (GF Biozone) based on palynomorphs for the first time. The same palynomorph assemblage is recognized in the Gafo Formation, both in Portuguese and Spanish outcrops and drillholes, allowing lithological and age correlation (Figs 2, 3).

The Santa Bárbara Unit in Spain and the Gafo Formation are therefore reinterpreted in the present work as representing the same unit (Figs 2, 4; Diez-Montes et al. 2020a).

A late Famennian palynomorph assemblage (VH Miospore Biozone) was also identified in the easternmost part of the Spanish sector, indicating a probable younger age for the Gafo Formation in the SPZ region, suggesting a probable sedimentary progradation from the west to the east sector. Nevertheless, more detailed palynostratigraphic studies are needed to confirm this hypothesis. A similar age and palynoassemblage are found in the Represa and Phyllite-Quartzite Formations of the IPB Phyllite-Quartzite Group (Cunha & Oliveira, 1989; Pereira et al. 2008, 2014, 2021; Oliveira et al. 2013).

8.b. Reworked miospores

The common presence of Early–Middle Devonian cosmopolitan taxa in the samples, such as Camarazoanotriletes sp., Dictyotriletes cf. ensissis and Retusotriletes cf. maculatus (Early Devonian), Grandispora cf. megiformis, Grandispora cf. protea and Grandispora protea (Middle Devonian; Lobozia & Melo, 2002) are interpreted as reworked.

In the PLD northern sector, common Early Devonian reworked spore assemblages were reported by Pereira et al. (2018) within the Pulo do Lobo and Ribeira de Limas formations (sections located ESE of Serpa). Reworking is also confirmed by the presence of graptolite fragments.

When we consider the palynoassemblages described by PA Lake (unpubl. Ph.D. thesis, University of Southampton, 1991), Rodriguez González (1999), and Pereira et al. (2006a, b, 2008), the following conclusions can be drawn. Despite the complex tectonics, the small number of samples studied, the low biodiversity and the long-ranging species associated with the reworking processes, the age interval is broad and unclear, or else corresponds to the age of reworked miospores (Fig. 3).

However, examining the new data with the palynoassemblage described by Rodriguez González (1999) in Castillo de las
Guardas (Fig. 3), an age correlation can be made based on the abundance of miospores and chitinozoans remains; however, the age is not constrained as it is mainly based on long-ranging species taxa.

8.c. Chitinozoans

The occurrence of several fragments of *Lagenochitina* sp. and *Angochitina* sp. (Fig. 8) indicates a Middle and Late Devonian age. These taxa are common in assemblages showing erosion of the main processes. Chitinozoan biostratigraphic schemes for the Middle–Late Devonian are scarce for Europe and Iberia (Paris et al. 2000), and few previous studies have been undertaken (Askew & Russell, 2019).

In this research, the occurrence of moderately to well preserved chitinozoans can be helpful for stratigraphic correlations with other Devonian chitinozoan biozonal schemes (e.g. North Africa, Brazil, Argentina and Poland; Grahn et al. 2006), confirming a Middle–Late Devonian age.

In Santa Barbara unit (PLD), Rodríguez González (1999) identified chitinozoan assemblages that included reworked *Fungochitina pilosa*, a late Givetian – Frasian key species globally (Paris, 1996). Other uncertain fragments were interpreted as reworked, probably from close to the Middle–Late Devonian boundary (Rodríguez González, 1999). In this complex stratigraphic context, the occurrence of chitinozoan taxa in the assemblages studied, including reworked graptolite remains and reworked Early–Middle Devonian miospore taxa, reinforces the importance of reworking processes. This is highlighted by the first documented chitinozoan specimens in the IPB and PLD (Rodríguez González, 1999). However, more detailed studies are needed to improve knowledge of the chitinozoan assemblages and the importance of identified in situ and reworked taxa.

8.d. Comment on depositional environment

The palaeoecology of chitinozoans and scolecodonts indicates deposition in marine nearshore to offshore environments. However, moderate to good preservation of specimens of these fossil groups in the flysch sediments of the Gafo Formation suggests a short time gap from their reworking on the continental platform and transport in turbidity currents to deep-sea fans.

From the discussion above, the Gafo Formation was deposited during middle–late Famennian time (c. 368–363 Ma), corresponding to the GF and VH palynomorph biozones.

The Gafo Formation sediments are intersected by felsic intrusive rocks (rhodacite, dacite and felsic porphyritic rocks), of age c. 346–356 Ma (e.g. Rosa et al. 2009; Solà et al. 2019; Diez Montes et al. 2020a), interpreted as feeder structures to volcanic activity closely related to IPB volcanism (Rosa et al. 2008; Diez-Montes et al. 2020a). A maximum depositional age of 369 ± 2.5 Ma was obtained in this study.
9. Conclusions

This study of the Gafo Formation from the southern sector of the Pulo do Lobo Domain allows the following conclusions to be made.

- The Gafo Formation yielded an abundant and diverse palynostratigraphic assemblage assigned to the GF Miospore Biozone of middle Famennian (Late Devonian) age, both in Portugal and in Spain. In the easternmost sector of the basin (Spain), a VH Miospore Biozone of late Famennian age was also attained.

- The palynological results obtained for the Gafo Formation, both in Portugal and Spain, are consistent and in agreement with the stratigraphic, structural and mapping interpretations.

- In Spain, these data show that the Santa Bárbara Unit corresponds to the same lithostratigraphic unit as the Gafo Formation (Fig. 1).

- In the south Chança River section, an assemblage probably of (? latest Givetian – early Frasnian (Late Devonian) age was recovered based on a poorly preserved assemblage. Further studies will be developed in this section to improve the accuracy of the age. However, this preliminary study allowed identification of a greywacke and interbedded shale unit previously interpreted as culm (BAFG; of Visean age) as being part of the Gafo Formation (Late Devonian age) (Fig. 1).

- The consistent occurrence of Lagenochitininae and Angochitininae chitinozoans indicates a Middle–Late Devonian age, consistent with the miospore age determination.

- Common grauplite fragments, poorly preserved chitinozoans fragments and the common occurrence of Early–Middle Devonian miospores represent strong evidence of reworking processes in the basin.

- A maximum U–Pb depositional age of 369 ± 2.5 Ma from detrital zircons was obtained for the Gafo Formation greywackes.

- This work highlights the importance of palynostratigraphy and detrital zircon geochronology for an integrated understanding of the depositional age and paleoenvironmental models, confirming the field-based interpretations of the complex stratigraphy of the southern sector of the Pulo do Lobo Domain.

Acknowledgements. This research received financial assistance from the European Regional Development Fund, EU/Interreg-VA/Portugal/ 0052_GEO_FPI_5_E Project. DC acknowledges support from a Science Foundation Ireland (grant no. 13/RG/2092_2). Special thanks are extended to Rosa Irene Sousa (National Laboratory of Energy and Geology, Portugal) for palynological laboratory and sample procedures and José Tomás Oliveira for the careful discussion of the Gafo Formation geological and structural setting. The editors and reviewers are gratefully acknowledged for valuable comments that helped to improve the paper.

Declaration of interests. None.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0016756822000346

References

Askel AJ and Russell E (2019) A new Middle Devonian chitinozoan assemblage from northern Iberia. Review of Palaeobotany and Palynology 268, 72–87.

Becker G, Bless MJM, Stree M and Thorez J (1974) Palynology and ostracode distribution in the Upper Devonian and basal Dinantian of Belgium and their dependence on sedimentary facies. Mededelingen Rijks Geologische Dienst: Nieuwe serie 25, 9–99.

Carvalho D, Correia M and Inverno C (1976) Contribuição para o conhecimento geológico do Grupo Ferreira-Ficalho suas relações com a Faixa Piritosa e o Grupo do Pulo do Lobo. Memórias e noticias, Museu Laboratório Mineralógico Faculdade Ciências 82, 145–69.

Clayton G, Owens B, Al-Hajri S and Filatoff J (2000) Latest Devonian and Early Carboniferous miospore assemblages from Saudi Arabia. In Stratigraphic Palynology of the Palaeozoic of Saudi Arabia (eds SA Al-Hajri and B Owens), pp. 146–53. GeoArabia, Special Publication no. 1.

Clayton G, Wicander R and Pereira Z (2002) Palynological evidence concerning the relative positions of northern Gondwana and southern Laurussia in latest Devonian and Mississippian times. Special Papers in Palaeontology 67, 45–56.

Clendening JA, Eames LE and Wood GD (1980) Retusotriletes philippisi n. sp., a Potential Upper Devonian guide palynomorph. Palynology 4, 15–21.

Cunha TA and Oliveira JT (1989) Upper Devonian palynosporomorphs from the represa and phylite–quartzite formations, Mina De Sao Domingos Region, southeast Portugal: tectonostratigraphic implications. Bulletin de la Société beigee de Géologie 98(3/4), 295–309.

Diez-Montes A, Matos JX, Dias R, Huerta Carmona JJ, Albardeiro L, Oliveira JT, Morais I, Fernandes P, Inverno C, Machado S, Ressurreição R, Pereira Z, Mendes M, Solá R, Salgueiro R, Matilla AS, Valdés MC, Gonçalves P, Santos S and López MT (2020a) Noticia Explicativa e Carta Geológica da Zona Sul Portugal, esc. 1:400,000. Laboratório Nacional de Energia e Geologia, Junta de Andalucía, 55 pp.

Diez-Montes A, Matos JX, Valverde-Vaquero P, Solá R, Albardeiro L, Salgueiro R and Morais I (2020b) Estudio isotópico de rocas ignea das Fajas Piríticas Ibéricas mediante la realización de edades U-Pb en círcones. Programa Interreg V-A España-Portugal 2014–2020: Observatorio transfronterizo para la valorización geo-económica de la Faja Pirítica Ibérica (0052_GEO_FPI_5_E). Instituto Geológico y Minero de España, Laboratorio Nacional de Energía e Geología.

Donaire T, Sáez R and Pascual E (2002) Bhylolitic globular peperites from the Aznalcollar mining district (Iberian Pyrite Belt, Spain): physical and chemical controls. Journal of Volcanology and Geothermal Research 114(1–2), 119–28.

Giese Y, Reitz E and Walter R (1998) Contributions to the stratigraphy of the Pulo do Lobo succession in Southwest Spain. Comunicaciones Servicios Geológicos de Portugal 74, 79–84.

Graham Y, Melo J and Lobozisk S (2006) Integrated Middle and Late Devonian miospore and chitinozoan zonation of the Parnaiba Basin, Brazil: an update. Revista Brasileira de Paleontologia 9, 283–94.

Hacquebard PA (1957) Plant spores in coalform from the Horton group (Mississippian) of Nova Scotia. Micropaleontology 3, 301–24.

Higgs KT, Avkhimovitch VI, Lobozisk S, Maziane-Serraj N, Stempnic-Salek M and Stree M (2000) Systematic study and stratigraphic correlation of the Grandispora complex in the Famennian of northwest and eastern Europe. Review of Palaeobotany and Palynology 112, 207–28.

Higgs KT, Prestianni C, Stree M and Thorez J (2013) High resolution miospore stratigraphy of the Upper Famennian of eastern Belgium and correlation with the conodont zonation. Geológica Bélgica 16, 84–94.

Korn D (1997) The Paleozoic ammonoids of the South Portuguese Zone. Memórias do Instituto Geológico Mineiro Portugal 33, 1–131.

Lobozisk S (2000) Middle to Early Late Devonian miospore biostratigraphy of Saudi Arabia. In Stratigraphic Palynology of the Palaeozoic of Saudi Arabia (eds EA Al-Hajri and B Owens), pp. 146–53. GeoArabia, Special Publication no. 1.

Lobozisk S and Melo J (2002) Devonian miospore successions of Western Gondwana: update and correlation with Southern Euramerican miospore zones. Review of Palaeobotany and Palynology 121, 133–48.

Lobozisk S and Stree M (1981) Miospores in Givetian to Lower Frasnian sediments dated by conodonts from the Boulonnais, France. Review of Palaeobotany and Palynology 29, 285–99.

Lobozisk S and Stree M (1989) Middle–Upper Devonian Miospores from the Ghabadis Basin (Tunisia–Libya): Systematics and Stratigraphy. Review of Palaeobotany and Palynology 58, 173–96.
Mange MA and Maurer HFW (1992) Heavy Minerals in Colour. London: Chapman and Hall, 147 p.
Matas J, Martin Parra LM, Rubio Pascual FJ, Roldán FJ and Martín-Serrano Á (2015) Mapa Geológico y Memoria de la Hoja nº 75/74 (Sevilla-Puebla de Guzmán). Mapa Geológico de España E. 1:200.000. Madrid: Instituto Geológico y Minero de España, 179 p.
Matos JX, Pereira Z, Solá R, Represas P and Dias R (2018) A Região NW Da Zona Sul Portuguesa, un contributo dos programas regionais do LNEG de cartografia geológica e prospeção mineral. Vulcânica II, 51–52.
 McGregor DC (1973) Lower and Middle Devonian spores of eastern Gaspe, Canada. I. Systematics. Palaeocontinentale Abdriftung B Band 142(1–3), 1–77.
 McGregor DC and Camfield M (1982) Middle Devonian microspores from the Cape de Bray, Weatherall and Hecla Bay formations of northern Melville Island, Canadian Arctic. Geological Survey of Canada, Bulletin 348, 1–105.
 Moreau-Benoit A (1980) Les spores du Dévonien de Libye. Paris: Cahiers de Micropaléontologie, vol. 1, 3–53.
 Oliveira JT (1990) Stratigraphy and syn-sedimentary tectonism in the South Portuguese Zone. In: Pre-Mesozoc Geology of Iberia (eds RD Dallmeyer and E Martinez Garcia), pp. 334–47. New York: Springer-Verlag.
 Oliveira JT, Cunha TA, Streel M and Vanguestaine M (1986) Dating the Horta da Torre Formation, a new lithostratigraphic unit of the Ferreiras-Ficalho Group. South Portuguese Zone: geological consequences. Comunicações Serviços Geológicos de Portugal 72(1–2), 129–35, 363–68.
 Oliveira JT, Horn M and Paproth E (1979) Preliminary note on the stratigraphy of the Baixo Alentejo Flysch Group, Carboniferous of Portugal and on the palaeogeographic development compared to corresponding units in Northwest Germany. Comunicações Serviços Geológicos Portugal 65, 151–66.
 Oliveira JT, Quesada C, Pereira Z, Matos JX, Solá JX, Solá RA, Rosa D, Albardeiro L, Diez-Montes A, Morales I, Inverno C, Rosa C and Relvas JB (2019) South Portuguese Terrane: A Continental Affinity Exotic Unit. In The Geology of Iberia: A Geodynamic Approach. Volume 2: The Variscan Cycle (eds C Quesada and JT Oliveira), 34 p. New York: Springer.
 Oliveira JT, Relvas J, Pereira Z, Matos JX, Rosa C, Rosa D, Mumhá JM, Fernandes P, Jorge R and Pinto A (2013) Geologia da Zona Sul Portuguesa, com ênfase na estratigrafia e na vulcanologia física, geoquímica e mineralizações da Faixa Piritosa. In Geologia Pré-mesozóica de Portugal, Geologia de Portugal Vol. I (eds R Dias, A Araújo, P Terrinha and JC Kullberg), pp. 673–767. Amadora: Laboratório Nacional de Energia e Geologia.
 Oliveira JT, Relvas J, Pereira Z, Matos J, Rosa C, Rosa D, Mumhá JM, Jorge R and Pinto A (2006) O Complexo Vulcano-Sedimentar da Faixa Piritosa: estratigrafia, vulcanismo, mineralizações associadas e evolução tectono-estratigráfica no contexto da Zona Sul Portuguesa. In Geologia de Portugal no contexto da Ibéria (eds R Dias, A Araújo, P Terrinha and JC Kullberg), pp. 267–43. Évora: Universidade Évora.
 Oliveira TO (1982) Carta Geológica de Portugal, escala 1:200.000. Notícia Explicativa da Folha 8. Serviços Geológicos de Portugal.
 Paton C, Hellstrom J, Paul B, Woodhead J and Hergt J (2011) Iolite: Freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry 26, 2508–18.
 Paris F (1996) Chitinoozoan biostatigraphy and palaeoecology. In Palynology: Principles and Applications, Volume 2 (eds J Jansonius and DC McGregor), pp. 531–52. American Association of Stratigraphic Paleontologists Foundation.
 Paris F and Verniers J (2005) Chitinoozoa microfossils. In Encyclopaedia of Geologia (eds R Selye, I Plimer and R Cocks), pp. 428–440. Amsterdam: Elsevier.
 Paris F, Winchester-Seeto T, Boumendel K and Hrahn Y (2000) Toward a global biozonation of Devonian chitinozoans. Courier Forschungsinsitut Senckenberg 220, 39–55.
 Pereira MF, Gutierrez-Alonso G, Murphy JB, Drost K, Gama C and Silva JB (2017) Birth and demise of the Betic Ocean magmatic arc(s). Combined U-Pb and Hf isotope analyses in detrital zircon from SW Iberia siliciclastic strata. Lithos 278–281, 383–99.
 Pereira Z, Fernandes P, Matos JX, Oliveira JT and Jorge R (2018) Stratigraphy of the Northern Pulo do Lobo Domain, SW Iberia Variscides: a palynological contribution. Geobios 51, 491–506.
 Pereira Z, Fernandes P, Matos JX, Oliveira JT and Jorge R (2019) Reply to ‘Comment on Stratigraphy of the Northern Pulo do Lobo Domain, SW Iberia Variscides: a palynological contribution by Zélia Pereira et al. (2018)’. Geobios 51, 491–506.
 Pereira Z, Fernandes P and Oliveira JT (2006a) Palinoestratigraphy of the Dominio Pulo do Lobo, Zona Sul Portuguesa. VII Congresso Nacional de Geologia, Universidade Évora, pp. 649–52.
 Pereira Z, Fernandes P and Oliveira JT (2006b) Upper Devonian palynostratigraphy and organic matter maturation of the Pulo do Lobo Domain, South Portuguese Zone, Portugal. Comunicações Geológicas 93, 23–38.
 Pereira Z, Matos JX, Batista MJ, Sóla R, Salgueiro R, Oliveira D, Oliveira JT, Inverno C and Rosa C (2014) Caracterización geológica, estratigráfica e litogeoesquemática das unidades geológicas da zona do Algarve, Antiforma do Rosário e da mineralización de sulfuretos macicios da Semblanca. Rel. Proj. IPB Vectors, LNEG/Lundin Mining, 150 p.
 Pereira Z, Matos JX, Fernandes P and Oliveira JT (2008) Palynostratigraphy and systematic palynology of the Devonian and Carboniferous successions of the South Portuguese Zone Portugal. Memorias do Instituto Nacional de Engenharia, Tecnologia e Inovação 34, 1–176.
 Pereira Z, Matos JX, Solá AR, Batista MJ, Salgueiro R, Rosa C, Albardeiro L, Mendes M, Morais I, de Oliveira D, Pacheco N, Araújo V, Castelo Branco JM, Neto R, Lains Amalaral J, Inverno C, Oliveira JT (2021) Geology of the recently discovered massive and stockwork sulphide mineralization at Semblanca, Rosa Magra and Monte Branco, Neves–Corvo mine region, Iberian Pyrite Belt, Portugal. Geological Magazine 158, 1253–68.
 Petrus JA and Kamber BS (2012) VizualAge: a novel approach to laser ablation ICP-MS U-Pb geochronology data reduction. Geostandards and Geocatalytic Research 36, 247–70.
 Pfeifferkorn HW (1966) Geologie des Gebietes zwischen Serpa und Mértola (Baixo Alentejo, Portugal). PhD thesis. University of Münster, 143p. Published thesis.
 Playford G (1983) The Devonian microspore genus Geminispora Balme, 1962: a reappraisal based upon toptotypic G.lemurata (type species). Association of Australasian Palaeontologists, Memoir 1, 311–25.
 Pionton MA, Chew DM, Ovtcharova M, Sevastopulo GD and Crowley QG (2012) New high-precision U-Pb dates from western European Carboniferous tuffs: implications for time scale calibration, the periodicity of late Carboniferous cycles and stratigraphical correlation. Journal of the Geological Society 169, 713–21.
 Quesada C, Braid JA, Fernandes P, Ferreira P, Jorge RS, Matos JX, Murphy JB, Oliveira JT, Pedro J and Pereira Z (2019) SW Iberia Variscan Suture Zone: oceanic affinity units. In The Geology of Iberia: A Geodynamic Approach (eds C Quesada and JT Oliveira), pp. 131–71. New York: Springer.
 Rodríguez Gonzalez RM (1999) Informe palinológico. Project: Investigación geológica y cartografía básica en la Faja Piritica y áreas aledañas. Junta de Andalucía (JA) - Instituto Geológico y Minero de España (IGME). Report in 1:200 000 Sevilla-Puebla de Guzmán 75/74, Memoria do Mapa Geológico de España.
 Rosa CJP, McPhie J and Relvas JMR (2009) The felsic volcanic centres of Neves Corvo and Lousial massive sulphide deposits in the Iberian Pyrite Belt. In: Smart Science for Exploration and Mining (ed. P Williams), pp. 484–6. Townsville: Economic Geology Research Unit, James Cook University.
 Rosa DRN, Finch AA, Andersen T and Inverno C (2008) U-Pb geochronology of felsic volcanic rocks hosted in the Gafo Formation, South Portuguese Zone; the relationship with Iberian Pyrite Belt magmatism. Mineralogical Magazine 72, 1103–18.
 Silva JB (1989) Estrutura de uma geotransversal da Faixa Piritosa Vale do Guadiana, Estudo de tectónica pelicular em regime de deformação não coaxial. Tese Doutoramento Faculdade Ciencias Universidade Lisboa, 294 p.
 Silva JB (1998) Enquadramento Geodinâmico da Faixa Piritosa na Zona Sul Portuguesa. In: Livro Guia das Excursões, V Congresso Nacional de Geologia (eds JT Oliveira and RP Dias), pp. 79–89. Lisboa: IGM.
 Silva JB, Oliveira JT and Ribeiro A (1999) South Portuguese Zone. Structural outline. In Pre-Mesozoic Geology of Iberia (eds RD Dallmeyer and E Martinez Garcia), pp. 348–62. New York: Springer Verlag.
 Silva JB, Pereira MF and Chichorro M (2013) Estruturas das áreas internas da Zona Sul Portuguesa, no contexto do Orógeno Varisco. In: Geologia de Palynostratigraphy of the Gafo Formation, SW Iberia
Portugal Ibéria (eds R Dias, A Araújo, P Terrinha and JC Kullberg), pp. 767–86. Lisbon: Escolar Editora.

Sóla R, Albardeiro L, Salgueiro R, Morais I, Díez-Montes A and Matos JX (2019) Idades U-Pb em rochas vulcano-sedimentares da Zona Sul Portuguesa: resultados preliminares dos programas de cartografia regional do Projeto GEO-FPI. CIG. Congresso Ibérico de Geoquímica, Évora, 4 p.

Stockmans F and Willière Y (1962) Hystrichosphères du Dévonien belge (sondage de L’Asile d’aléniés à Tournai). Bulletin de la Société belge de géologie, de paléontologie et d’hydrologie 71, 41–77.

Streel M (1967) Associations de spores du Dévonien inférieur belge et leur signification stratigraphique. Annales de la Société géologique de Belgique 90, 11–53.

Streel M (1974) Similitudes des assemblages de spores d’Europe, d’Afrique du Nord et d’Amérique du Nord au Dévonien terminal. Sciences Géologiques Bulletin 27(1), 25–38.

Streel M (2009) Upper Devonian miospore and conodont zone correlation in Western Europe. In Devonian Change: Case Studies in Palaeogeography and Palaeocology (ed. P Königshof), pp. 163–76. Geological Society of London, Special Publication no. 314.

Streel M, Higgs K, Loboziak S, Riegel W and Steemans Ph (1987) Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardennes-Rhenish regions. Review of Palaeobotany and Palynology 50, 211–29.

Vermeesch P (2012) On the visualisation of detrital age distributions. Chemical Geology 312–3, 190–4.

Wiedenbeck M, Allé P, Corfu F, Griffin WL, Meier M, Oberli F, von Quadt A, Roddick JC and Spiegel W (1995) Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards Newsletter 19, 1–23.

Wood GD, Gabriel AM and Lawson JC (1996) Palynological techniques-processing and microscopy. In Palynology: Principles and Applications (eds J Jansonius and DC McGregor), 29–50. American Association of Stratigraphic Palynologists.