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PII: S0016-6995(17)30155-9
DOI: https://doi.org/doi:10.1016/j.geobios.2018.07.001
Reference: GEOBIO 832

To appear in: *Geobios*

Received date: 18-10-2017
Accepted date: 3-7-2018

Please cite this article as: Machado, G., Vavrdová, M., Fonseca, M., Fonseca, P.E., Rocha, F.,Stratigraphy and Palynology of the Pennsylvanian continental Buçaco Basin (NW Iberia), *Geobios* (2018), https://doi.org/10.1016/j.geobios.2018.07.001

Stratigraphy and Palynology of the Pennsylvanian continental Buçaco Basin (NW Iberia) ✡

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✡ Corresponding editor: Borja Cascales-Miñana.

Abstract

The Buçaco Basin is a Pennsylvanian continental basin located along an important NNW-SSE strike structure (Porto-Tomar-Ferreira do Alentejo shear zone) that separates the Ossa-Morena and Central Iberian Zones of the Iberian Variscan Fold Belt in central western Portugal. The shear zone controlled the sedimentation in the basin and probably its post-sedimentary evolution. Sedimentation is initially alluvial with characteristic red sandstones, breccias and conglomerates. A gradual change to a fluvial (and probably lacustrine) type of sedimentation is observed with finning-upward cycles of gravel conglomerates, sandstones and organic-rich mudstones with occasional coal seams. Three representative sections were sampled for palynology and seventeen samples yielded sporomorphs with moderate to poor preservation. The palynological content from the alluvial sediments shows low diversity and poorly preserved assemblages dominated by *Triquitrites* spp., *Densosporites* spp., *Laevigatosporites* spp., and other taxa associated with siliciclastic environments or rheophytic mires. The fluvial and lacustrine sediments show a dramatic increase in diversity with an abundant, typical peatland microflora including sporomorphs such as *Endosporites* spp., *Lycospora* spp. and *Monoletes* spp., but also marginal peat and siliciclastic substrate taxa such as *Densosporites* spp., *Latensina*/*Cordaitina* spp., and *Florinites* spp. Other common taxa are *Cheiledonites* spp., *Crassispora* spp., *Dictyotriletes*-like miospores (mostly fragments), *Potonieisporites* spp., and *Wilsonites* spp. The presence and considerable abundance of *Potonieisporites novicus* and *Cheiledonites* cf. *major* is indicative of the middle to upper *Potonieisporites novicus-bhardwajii–Cheiledonites major* (NBM) miospore biozone of Western Europe, corresponding to the late Stephanian (early Gzhelian).

Keywords:
Gzhelian
Sporomorph
Biostratigraphy
Paleoecology
Continental sedimentation
Ossa-Morena Zone
Central Iberian Zone

1. Introduction

The Buçaco Basin crops out in several scattered areas for nearly 30 km along a N-S trend Northeast of Coimbra (western central Portugal). Its width is highly variable due to the irregular contact (paleotopographic and tectonic) with neighbouring formations – maximum width is *ca*. 2 km. To the south it pinches out and locally the western and eastern edges are limited by faults associated with the Porto-Tomar-Ferreira do Alentejo shear zone (PTSZ;

Fig. 1). Cenozoic sediments cover the basin to the north, which is only visible along relatively deep valleys that cut the Cenozoic cover. Its western edge is very frequently limited by faults that put it in direct contact with the Albergaria-a-Velha and Arada units of the Ossa-Morena Zone (Chaminé et al., 2003; Machado et al., 2011) or with the Upper Triassic sediments (Adloff et al., 1974; Palain, 1976; Palain et al., 1977) of the Lusitanian Basin (Fig. 1(b)). The contact of the basin's rocks with the Upper Triassic sediments is seldom exposed. When observable, it is faulted or materialized by a high-angle angular unconformity. The eastern edge is defined by faults in the southernmost sector, but for the major part the basin, the basal unit (Algeriz Fm.; see below) rests unconformably over the units of the Central Iberian Zone (CIZ): Cambrian-Precambrian slates and Ordovician-Silurian metasedimentary rocks (Ribeiro, 1853; Courbouliex, 1972, 1974; Domingos et al., 1983; Flores et al., 2010; Fig. 1).

The general structure of the Buçaco Basin has been presented by Domingos et al. (1983) and described in more details by Gama-Pereira et al. (2008) and Flores et al. (2010). The basin forms a highly asymmetrical syncline with a long eastern flank and an overturned to vertical short western flank (Domingos et al., 1983; Wagner and Sousa, 1983; Flores et al., 2010; Fig. 1). Based on the current outcrop pattern, field structural evidences and the relation with the PTSZ, Gama-Pereira et al. (2008) and Flores et al. (2010) interpret this as a pull-apart basin with a subsiding western block. In their model the pulses of the PTSZ control the major sedimentary phases of the basin as the Eastern block was uplifted and eroded, acting as a sediment source area. Gomes et al. (2007) suggested that a similar setting is recorded in Cenozoic sediments along this area.

According to sedimentological and paleobotanical criteria, Wagner et al. (1983) defined three formations for the Buçaco Basin. This definition is the one used in most of the subsequent studies. The sedimentary fill is alluvial for the basal *ca*. 200 m, with characteristic red breccias, conglomerates and sandstones. This basal unit constitutes the Algeriz Fm. (Wagner et al., 1983) and grades to the overlying unit with progressively more common interbedded grey shales. The 50 to 100 m above are dominated by coaly mudstones and thin coal seams of the Vale da Mó Fm. (Wagner et al., 1983). This unit provided most of the paleobotanical finds to date. The remaining *ca*. 500 m above are essentially fluviatile (and probable lacustrine) in nature, with monotonous fining-upward cycles of gravel conglomerates, sandstones, and organic-rich mudstones with occasional coal seams. This upper unit constitutes the Monsarros Fm. (Wagner et al., 1983; Fig. 2). The sedimentology and the prevailing sedimentary environments of the basin were addressed in a conference paper by Dinis and Reis (2007) and later developed in Dinis et al. (2012) who concluded that lacustrine sedimentation was a common feature, both vertically and laterally, and not restricted to the coaly shale-siltstone dominated Vale da Mó Fm.

In this work we present the first vertical and lateral comprehensive palynological results from the Buçaco Basin. We discuss the age and paleoecological significance of these findings and how they relate to the sedimentary evolution of the basin. The sedimentological and lithostratigraphic results will be presented in a subsequent work.

2. Previous works and stratigraphy of the basin

The first published work about the Buçaco Basin dates back to the 1800's when Carlos Ribeiro (Ribeiro, 1853) identified Carboniferous rocks in this area, based on unpublished reports by Charles J. F. Bunbury. He correctly identified and distinguished the several units that crop out in this area and described the geometrical relations between them.

The first palaebotanical studies were conducted by Bernardino Gomes and Wenceslau de Lima (Gomes, 1865; Lima, 1888/1892, 1894). Lima considered the assemblages to be comparable to the ones from Rotliegend in Germany and Autun in France (then lower Permian), although he mentioned in his correspondence with Zeiller (Teixeira, 1941b) that other taxa would correspond to the "houiller supérieur" (Pennsylvanian). Lima also considered that there were no significant differences between the assemblages found in different stratigraphic levels (Lima, 1888/1892), although these different levels were not identified. Florin (1940) considered the assemblage to be typically Permian due to the presence, among others, of *Lebachia laxifolia*. Later on, Teixeira (1941a, 1941b, 1944, 1945, 1947, 1949) built on the idea that the assemblages could be late Stephanian C or early Autunian. Courbouliex (1974) in his stratigraphical study of the basin reported two new palaeobotanical localities which, according to P. Corsin's identifications and interpretation, would be Stephanian C in age and concluded that sedimentation in the basin lasted from the Stephanian C to the Autunian. The most recent palaeobotanical works by Wagner and Sousa (1983) and Wagner et al. (1983) are based on the collections available in several Portuguese museums, previously published works, and collection of new specimens. They concluded that all the assemblages (including the ones referenced by Courbouliex, 1974) can be placed in the late Stephanian C–early Autunian interval and that no taxon had a range restricted to either of these stages. Last, Gomes et al. (2005) published on the palynology of the basin, describing a poorly preserved sporomorph assemblage containing *Potonieisporites novicus* from the Santa Cristina area (probably Vale da Mó Fm.) which the authors considered to be in accordance with the paleobotanical record.

3. Material and methods

The sections available are relatively continuous E-W road cuts connecting the main villages of the area: the Vale da Mó-Vale de Boi road (Northern part; VMO section); Parada-Algeriz-Monsarros road (central area; ALG section), and around Santa Cristina (Southern part; CRI section) (Figs. 1, 2). Additional sections are available in the Gralheira area, especially around the Gralheira reservoir (GRA section) and at Salgueiral (SAL section). The ALG section is the most complete and the one used by most authors to describe the basin. Road cuts are typically *ca*. 3 m high, except for some conglomeratic levels that can reach more than 10 m. Strata dip from 20 to *ca*. 60º to the West, which seriously limits the observation of lateral facies variations. Other sections are available in ~N-S roads but these have limited stratigraphic extents. The current structure of the basin and the available sections result in the construction of lithological columns that go not only from basal to upper strata, but also from proximal to distal facies as the observer moves away from the sediment source area.

Several sections were described and sampled for palynology, including (Figs. 1, 2):

- the ALG section (all formations well exposed);
- the CRI (southern) section (parts of the Monsarros Fm. exposed);
- the VMO section (Algeriz Fm. badly exposed, but very fresh road cuts for the Monsarros Fm.);
- the GRA section (Algeriz Fm. well exposed);
- the SAL section (part of the Algeriz Fm. and a small part of the Vale da Mó and Monsarros formations).

Samples collected for palynology were preferably taken from grey or dark grey shaley siltstones or shales. These occur at the top of fining-upward cycles, frequently just below thin coal seams that occasionally topped the cycles. A total of 29 samples were processed in the Micropaleontology and Chemostratigraphy lab of the Czech Geological Survey, Prague, using standard procedures (HCl + HF maceration) and sieved at 15 μm and 53 μm. Several slides were produced from both fractions. Residues were observed unoxidized and with mild oxidation using [4%] NaOCl (low concentrated bleach). Observation and documentation were performed using an OLYMPUS BX-40 microscope and OLYMPUS DP20 camera.

4. Results

All collected samples provided a good amount of organic residue, but only sixteen provided identifiable sporomorphs (Figs. 2-6). All assemblages were dominated by phytoclasts. Most of them showed some degree of corrosion, which probably originated from weathering and sparse Fe-oxide mineralization observed at the outcrop and possibly from sedimentary transport and early diagenesis (?bacterial decay). Twelve samples from the ALG section provided identifiable sporomorphs, including nine samples from the Vale da Mó and Monsarros formations. Four of them contained relatively common, moderately to poorly preserved sporomorphs, and two contained very abundant, moderately preserved sporomorphs. Three samples from the Monsarros Fm. of the VMO section and one from the CRI section provided rare and very poorly preserved sporomorphs. Over 60 taxa were identified in total, although many were left in open nomenclature (Fig. 6; Appendix A). This limitation was particularly evident for grains attributable to the genera *Potonieisporites, Florinites,* and *Monoletes* (Figs. 3-6).

Rare reworked acritarchs with obvious higher thermal maturation (dark grey and black colors) were recorded in all units. These include *Cymatiosphaera* spp., *Gorgonisphaeridium* spp., and *Michrystridium* spp. (Figs. 5, 6).

Samples from the Algeriz Fm. only showed rare and poorly preserved sporomorphs, although with increasing diversity and better preservation towards the top. The basal sample (Alg2.2) provided only rare specimens of *Densosporites* spp. and ?*Triquitrites* spp., while the upper samples (Alg2.4 and 2.7) contained, among other taxa, *Cheiledonites* spp., *Laevigatosporites* spp., *Torispora* spp., *Thymospora* spp., and more rare *Vittatina* sp. and *Verrucosisporites* spp. (Figs. 3-6).

The samples providing diversified assemblages are restricted to the Vale da Mó and Monsarros formations and were dominated by *Potonieisporites* spp., *Florinites* spp., *Monoletes* spp., and *Laevigatosporites* spp. Other common genera are *Cheiledonites* spp., *Densosporites* spp. (decreasing abundance towards the top), *Crassispora* spp., *Dictyotriletes*-like miospores (mostly fragments), *Lycospora* spp. (slight decrease towards the top), *Thymospora* spp., *Verrucosisporites* spp., and *Wilsonites* spp. (Figs. 3-6). The presence of *Potonieisporites novicus* and *Cheiledonites* cf. *major* along with the considerable abundance of the two genera are noteworthy, as discussed below. Other relevant genera such as *Spinosporites, Thymospora* and *Triquitrites* have fairly constant frequencies throughout the sequence. Rare to frequent *Vittatina* spp. and *Disaccites* spp. are also present throughout the sequence.

5. Discussion

The sporomorph assemblages from the Algeriz Fm. show a low diversity characterized by a mix of taxa whose parent plants are typical of rheotrophic mires (e.g., *Densosporites* spp. Smith, 1962; Bek et al., 2015) and also plants associated, but not restricted to clastic substrates such as *Laevigatosporites* spp. (DiMichele and Phillips, 1994; Libertín et al., 2009) such as flood plains (Fig. 6). The presence of other taxa such as *Convolutispora* spp., *Torispora* spp., *Thymospora* spp., and *Verrucosisporites* spp. towards the top of the unit are indicative of a macroflora tolerant to periodic flooding (DiMichele and Phillips, 1994), but that can also occur in coals. This is generally consistent with the sedimentological data (first grey measures to the top of the Algeriz Fm.). The rare presence of *Vittatina* spp. is indicative of an upland flora contributing to the assemblages.

The Vale da Mó Fm. assemblages show a marked change with the first appearance and abundance of *Endosporites* spp., *Lycospora* spp., and *Monoletes* spp., all of which indicative of peat development (Fig. 6). Vegetation was probably dominated by arborescent and sub-arborescent lycopsids of the *Polysporia* type and arborescent medullosaleans, near the water-logged areas (DiMichele and Phillips, 1994; Shaver et al., 2006; Dimitrova, 2008; Opluštil et al., 2009; Bek et al., 2008; Bek, 2017), but surrounded by different macroflora in marginal peat or rheotrophic mire (indicated by *Densosporites* spp.) and siliciclastic substrates as indicated by common *Latensina*/*Cordaitina* spp. and *Florinites* spp., among others (DiMichele and Phillips, 1994; Libertín et al., 2009). This is consistent with the dominant grey mudstones and thin coal seams of this unit. Wagner et al. (1983) report the dominance of hygrophilous plant remains, but with the presence of mesophilous and xerophilous elements in this unit, in accordance with the palynological record.

The Monsarros Fm. assemblages show significant variability in terms of sporomorph diversity, either very low (≤ 8 taxa) or quite high (close to or above 40 taxa; Fig. 6). The low diversity assemblages are dominated by *Laevigatosporites* spp. and *Florinites* spp., usually associated with siliciclastic or exposed peat substrates (DiMichele and Phillips, 1994; Libertín et al., 2009; Bek and Dimitrova, 2014). The high diversity assemblages are associated with peat development (similar to the Vale da Mó Fm.), although they do not seem to be directly associated with coal-bearing intervals. The fluviatile nature of this unit is consistent with the low diversity assemblages, possibly during time intervals and/or areas where peatland did not develop significantly. Overall the palynological results coupled with the sedimentological data point to time and space-restricted lacustrine settings in the Monsarros Fm., possibly linked to abandoned meanders/oxbow lakes within a fluviatile-dominated system. The Northern part of the basin, as observed in the VMO section, between *ca*. 300 to 350 m and *ca*. 400 to 450 m (Fig. 2), may be an exception to this general scheme, where lacustrine settings may have prevailed for longer periods. The occurrence of rare but rather consistent reworked acritarchs is explained by the presence of earlier Paleozoic metasediments in the sediment source area to the East, in the Central Iberian Zone (Fig. 1).

The palynological results indicate that the sediments of the Buçaco Basin most likely range from the middle to upper NBM sporomorph biozone of Clayton et al. (1977), corresponding to the late Stephanian (late Stephanian C–Stephanian D in older literature, e.g., Clayton et al., 1977; Stephanian C in more recent literature). The presence of *Potonieisporites novicus* and *Cheiledonites* cf. *major* along with the considerable abundance of the two genera is indicative of this biozone. The decrease of the frequency of *Densosporites* spp. and the disappearance of *Crassispora konsakei* (and all *Crassispora* spp.) to the top of the sequence are further indications of this biozone. These differences in abundance are consistent with what Clayton et al. (1977) describe for the NBM biozone, although the influence of local paleoecological bias cannot be ruled out.

Considering the new division of the Carboniferous system (Heckle and Clayton, 2006) the age is probably early Gzhelian. However, the work by Opluštil et al. (2016) would suggest that Stephanian C actually corresponds to the late Gzhelian. The definitive correlation of the global and west European divisions of the late Pennsylvanian has not been achieved. Thus some uncertainty remains regarding the ascription of Buçaco Basin's sediments to a globally-defined stage or part of a stage.

6. Conclusions

The palynological record of the Buçaco Basin is in general agreement with the sedimentological and paleobotanical data, with poorly diversified assemblages in the basal, alluvial part of the basin infill, increasing dramatically in diversity in the fluviatile-lacustrine upper part, with the development of peatland in some areas and stratigraphic intervals of the basin. Reworked palynomorphs are consistent with a sediment source area that included earlier Paleozoic metasediments, currently locate to the East of the basin. The age determination based on sporomorph biostratigraphy – early Gzhelian – is in general agreement with the paleobotanical age determinations, although there is no evidence of

"Autunian" (*sensu* lowermost Permian) strata being present in the basin, as it was previously suggested by paleobotanical studies.

Acknowledgements

We thank Geoff Clayton (Trinity College Dublin) for clarifying some aspects of sporomorph biostratigraphy, Luís Gama Pereira (Coimbra University) and Hélder Chaminé (Instituto Superior de Engenharia do Porto) for helpful discussions on the geology of this area, and Pedro Dinis (Coimbra University) for discussions on the sedimentology of the basin. Fundação para a Ciência e a Tecnologia (Portugal) is acknowledged for the funding through grant no. SFRH/BD/23787/2005. The work was partially supported by project UID/GEO/04035/2013 (FCT and COMPETE). We thank the three anonymous reviewers that greatly contributed to the final version of this work.

Appendix A. Alphabetical list of the reported taxa, with taxonomic notes

Ahrensisporites sp.

Apiculatisporis sp.

Cheiledonites aff. *major* Doubinger, 1957

Cheiledonites gigantea (Alpern) Doubinger, 1968

Cheiledonites potoniei Doubinger, 1957

Cheiledonites sp.

Cirratriradites cf. *saturni*

Cirratriradites sp.

aff. *Columinisporites* sp.

Convolutispora sp.

Cordaitina spp.

Cordaitina uralensis (Luber) Dibner, 1971

Crassispora kosankei (Potonié et Kremp) Bharadwaj, 1957

Crassispora spp.

aff. *Cycadopites* sp.

Densosporites spp.

Dictyotriletes sp.

Disaccites sp.

Endosporites spp.

Florinites bederi Pittau et al., 2008

Florinites sp. A

Description: Oval to ellipsoidal pollen, 80 to 140 µm long and 50 to 80 µm wide. The saccus is often folded, changing the overall shape and dimensions of the sporomorph. Corpus minute, less than 20 µm in maximum dimension, usually centered, well defined and darker than saccus. Trilete mark not discernible. Saccus laevigate with (internal?) irregular and incomplete reticulate pattern.

Remarks: *Florinites* sp. specimens with similar morphology and very small corpus have also been recorded from the Kasimovian Santa Susana Basin in SW Portugal (Machado et al., 2012).

Florinites spp.

aff. *Granulatisporites* sp.

Guthoerlisporites sp.

Illinites sp.

Laevigatosporites cf. *desmoinesensis* (Wilson et Coe) Schopf, Wilson et Bentall, 1944

Laevigatosporites medius Kosanke 1950

Laevigatosporites sp.

Latensina aff. *trileta* Alpern, 1958

Latosporites sp.

Leiotriletes spp.

Limistisporites spp.

Lueckisporites sp.

aff. *Lundbladispora gigantea* (Alpern) Doubinger, 1968

Lycospora spp.

Monoletes ellipsoides (Ibrahim) Potonié et Kremp, 1954

Monoletes spp.

Nuskoisporites sp.

Potonieisporites novicus Bharadwaj, 1954

Potonieisporites sp.

Potonieisporites sp. A

Description: Bilateral, monosaccate, monolete pollen grain. Oval to ellipsoidal amb, 130-150 µm × 50-100 µm maximum dimensions. Very large corpus occupying over ¾ of the grain with an incomplete crassitude (*ca*. 6 µm wide). Saccus often folded with a vermiculate to irregular and incomplete reticulate pattern. Monolete mark simple, extending from half to full width of the corpus.

Protohaploxypinus sp.
Punctatisporites sp.
Punctatosporites spp.
Spinosporites spinosus Alpern, 1958
Spinosporites spp.
Thymospora cf. *thiessenii* (Kosanke) Wilson et Venkatachala, 1963
Thymospora pseudothiessenii (Kosanke) Alpern et Doubinger, 1973
Torispora sp.
Triquitrites spp.
Verrucosisporites spp.
Vestispora sp.
Vittatina costabilis Wilson, 1962
Vittatina sp.
Waltzispora sp.
Wilsonites cf. *vesicatus* Kosanke, 1950
Wilsonites spp.

Reworked elements:
Cymatiosphaera spp.
Gorgonisphaeridium spp.
Michrystridium spp.

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Figure captions

Figure 1. Geological setting of the Buçaco Basin (adapted from Courbouliex, 1974, and Flores et al., 2010). **a**. Schematic sketch map of Iberian Pre-Mesozoic terranes. **b**. Geological map of the Buçaco Basin with location of the studied sections. CIZ: Central Iberian Zone.

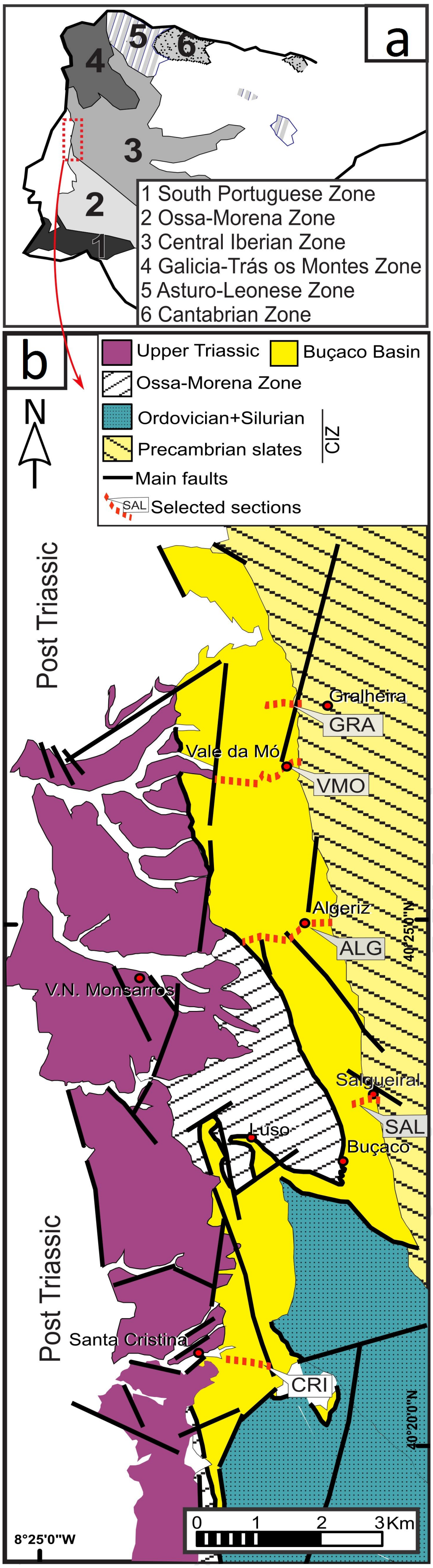
a
1
2
3
4
5
6
1 South Portuguese Zone
2 Ossa-Morena Zone
3 Central Iberian Zone
4 Galicia-Trás os Montes Zone
5 Asturo-Leonese Zone
6 Cantabrian Zone
b
N
Upper Triassic
Buçaco Basin
Ossa-Morena Zone
Ordovician+Silurian
Precambrian slates
CIZ
Main faults
SAL Selected sections
Post Triassic
Gralheira
GRA
Vale da Mó
VMO
Algeriz
ALG
40°25'0"N
V.N. Monsarros
Salgueiral
SAL
Luso
Buçaco
Post Triassic
Santa Cristina
CRI
40°20'0"N
8°25'0"W
0
1
2
3Km

Figure 2. Correlation of the logged sections in the Buçaco Basin, indicating the location of the productive palynological samples. See text and Fig. 1 for section references.

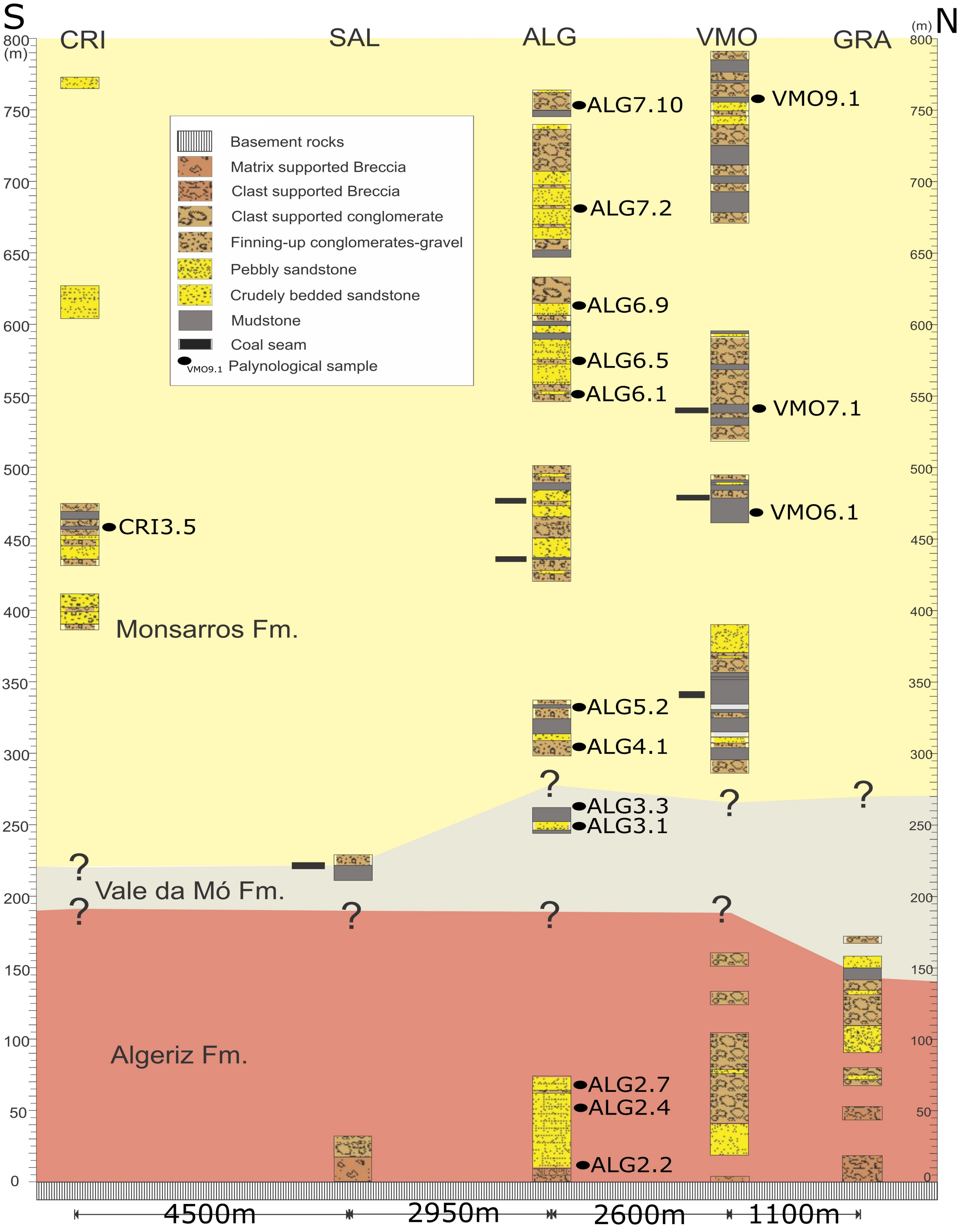

Figure 3. Sporomorphs of the Buçaco Basin. **a**. *Apiculatisporis* sp. **b**. *Cheiledonites* aff. *major* Doubinger, 1957. **c**. *Cheiledonites gigantea* (Alpern) Doubinger, 1968. **d**. *Cheiledonites potoniei* Doubinger, 1957. **e**. *Cirratriradites* cf. *saturni*. **f**. *Cirratriradites* sp. **g**. aff. *Columinisporites* sp. **h**. *Convolutispora* sp. **i**. *Cordaitina* sp. **j**. *Cordaitina uralensis* (Luber) Dibner, 1971. **k**. *Crassispora kosankei* (Potonié et Kremp) Bharadwaj, 1957. **l**. *Crassispora* sp. **m**. aff. *Cycadopites* sp. **n, o**. *Densosporites* spp. **p**. *Dictyotriletes* spp. **q**. *Disaccites* sp. **r**. *Endosporites* sp. **s**. *Florinites bederi* Pittau et al., 2008. **t**. *Florinites* sp. A. **u**. *Florinites* sp. Scale bar: 60 µm.

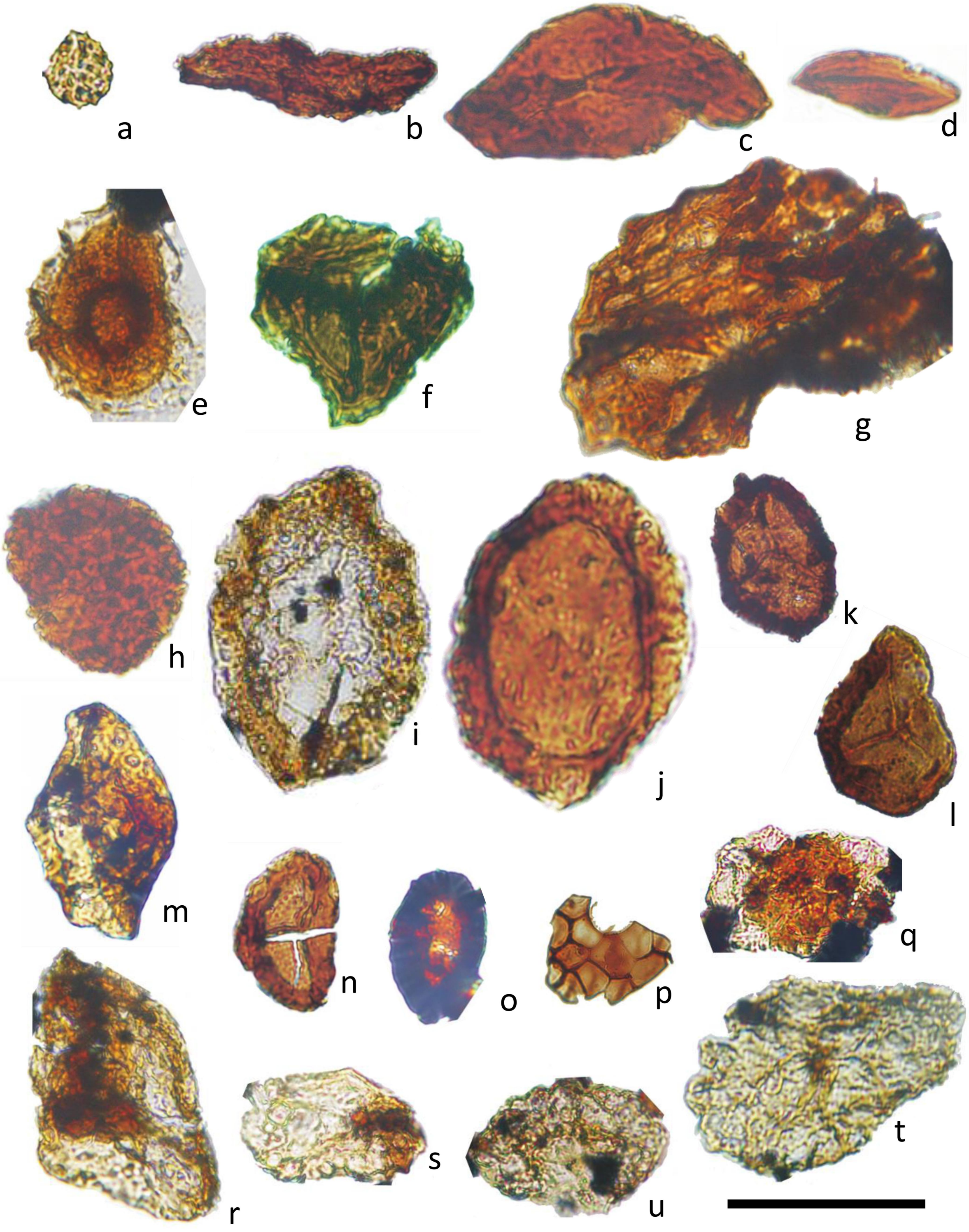

Figure 4. Sporomorphs of the Buçaco Basin. **a**. aff. *Granulatisporites* sp. **b**. *Guthoerlisporites* sp. **c**. *Illinites* sp. **d**. *Laevigatosporites* cf. *desmoinesensis* (Wilson et Coe) Schopf, Wilson et