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Review paper

The significance of reworked palynomorphs (middle Cambrian to Tournaisian) in the Visean Toca da Moura Complex (South Portugal). Implications for the geodynamic evolution of Ossa Morena Zone

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ABSTRACT

The 404.5 m deep SDJ1 borehole is located in the Jongeis mining sector of the Santa Susana Basin (SSB), and has been palynostratigraphically studied. The SSB is a Carboniferous coal-bearing basin developed along the suture contact between the Ossa Morena Zone (OMZ) and the South Portuguese Zone (SPZ).

The recovered palynologic assemblages are assigned to the NM Miospore Biozone of mid Visean age, with the lowermost 6.8 m of the borehole yielding an in situ miospore assemblage assigned to the SL Miospore Biozone of mid Moscovian age. All of the studied samples contained more than 90% of reworked palynomorphs ranging in age from the middle Cambrian to the early Tournaisian (0–397.7 m depth), with the first 6.8 m (397.7–404.5 m depth) yielding reworked palynomorphs from the middle Cambrian to the mid Moscovian. This particular palynologic signature provides further evidence for the interpretation of the reworked palynomorphs in the Toca da Moura Complex (TMC) and its importance in the geodynamic evolution of the OMZ, regarding the probable provenance areas of the reworked palynomorphs within the OMZ and SPZ. Six reworked sub-assemblages were discriminated: i. middle to (?)upper Cambrian; ii. Lower to Middle Ordovician; iii. middle to upper Silurian; iv. Lower Devonian; v. Upper Devonian and vi. lower Carboniferous.

From the study of the palynomorph assemblages (both in situ and reworked) recovered from the SDJ1 borehole samples, new inferences are made regarding the recognition of the subsurface extension of the Toca da Moura Complex and its structural relationship to the Pennsylvanian continental coal-bearing SSB. These new data, together with the palynologic study of a control sample (STS15) from the Jongeis old coal mine, housed in the LNEG Geological Museum, in Lisbon, makes possible new interpretations concerning the evolution of the SSB.

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1. Introduction

The Ossa Morena Zone (OMZ) is one of the most important paleogeographic domains of the Iberian Massif. It has been divided in several sectors according to its distinctive stratigraphy and structure (Oliveira et al., 1991). The study area is located in the Beja Massif (BM) sector of the Santa Susana region (Fig. 1). The BM is a magmatic suite that crops out in the southwestern region of the Portuguese part of the OMZ (Oliveira et al., 1991, 2006, 2013). Besides gabbros, diorites and granitoides, this suite includes two volcano-sedimentary complexes, the Mid to Late Devonian Odivelas Complex (Oliveira et al., 1991), and the upper Tournaisian to Visean Toca da Moura Complex (TMC) (Oliveira et al., 2006; Pereira et al., 2006; Oliveira et al., 2013).

The Toca da Moura Complex is exposed in scattered outcrops near the contact between the OMZ and the South Portuguese Zone (SPZ) (Fig. 1). In its northwestern exposure, it is unconformably overlain by the Pennsylvanian continental coal-bearing sediments of the Santa Susana Formation (SSF) (Wagner and Sousa, 1983; Gonçalves and Carvalhosa, 1984). The Toca da Moura Complex succession has been interpreted as the remnant of an extensional marine sedimentary basin that developed in intra-volcanic arc settings related to the collision of the OMZ with the SPZ (Oliveira et al., 1991; Araújo et al., 2006).

Reworked palynomorphs from Toca da Moura Complex outcrops were initially identified by Pereira et al. (2006). The present study provides further evidence of palynomorph reworking in the Toca da Moura Complex and sheds some light on the interpretation of the OMZ geodynamic evolution, specifically regarding the probable provenance of the reworked assemblages from OMZ and SPZ stratigraphic units. Samples for this study came from the SDJ1 borehole (Fig. 2) that allowed recognition of the Toca da Moura Complex to a depth of 397.7 m and the Santa Susana Formation in the first 6.8 m of the borehole.

2. Geological background

Devonian and Carboniferous rocks crop out along a north northwest–south southeast oriented narrow strip from Santa Susana to Alfundão, parallel to the contact between the OMZ and SPZ and also in the Cabrela Basin (Fig. 1). These rocks belong to the coeval Toca da Moura and Cabrela Volcano-Sedimentary Complexes of Late Devonian to Mississippian age and to the Pennsylvanian age Santa Susana Formation (Oliveira et al., 1991, 2006; Pereira et al., 2006; Oliveira et al., 2013). The Toca da Moura and Cabrela Complexes share many lithological similarities but only the former is discussed herein.

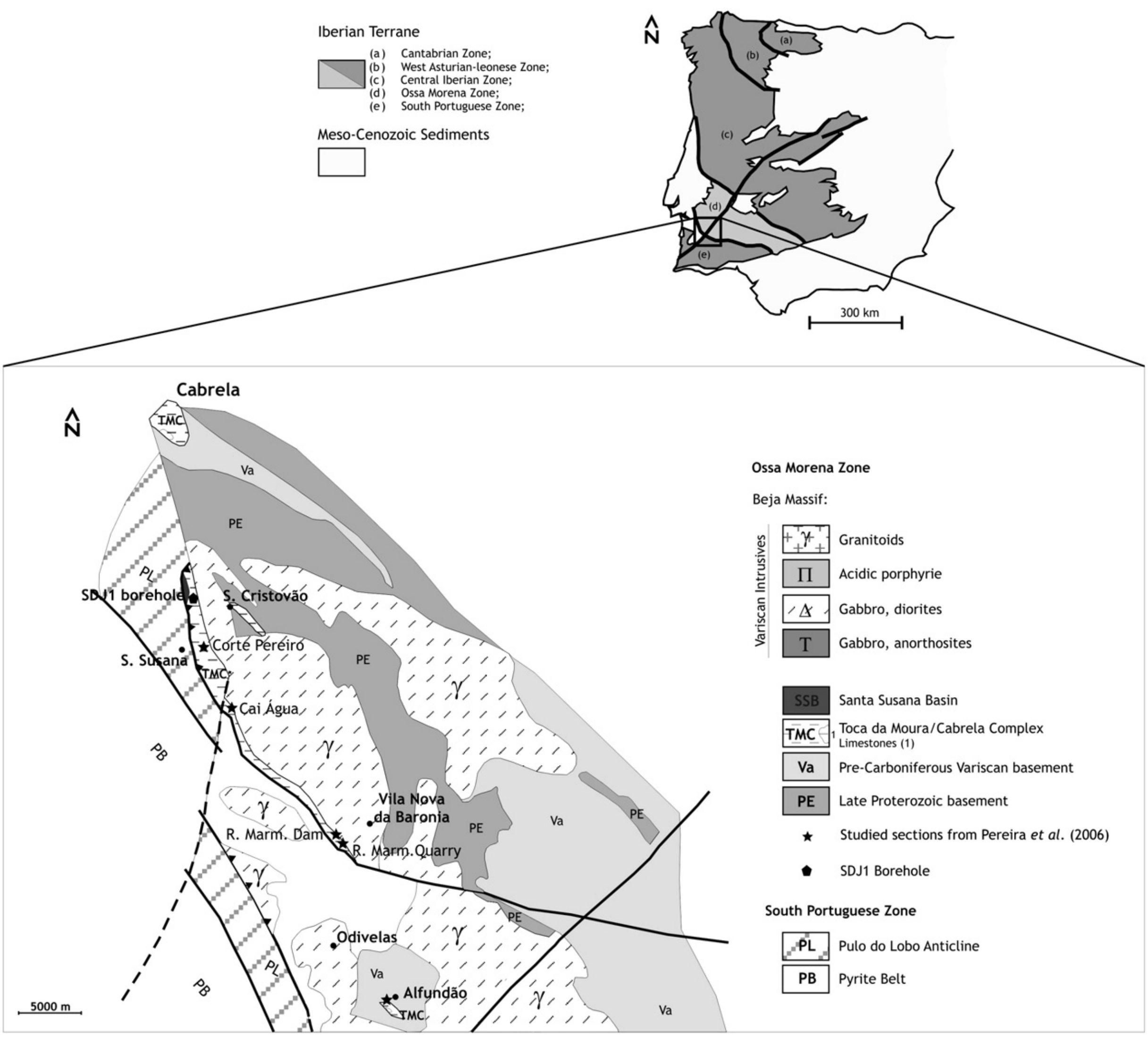

Fig. 1. Simplified geologic map of the southwestern border of the Ossa Morena Zone (OMZ) and South Portuguese Zone (SPZ), with the location of the studied borehole SDJ1 and Santa Susana region.
Adapted from Pereira et al. (2006).

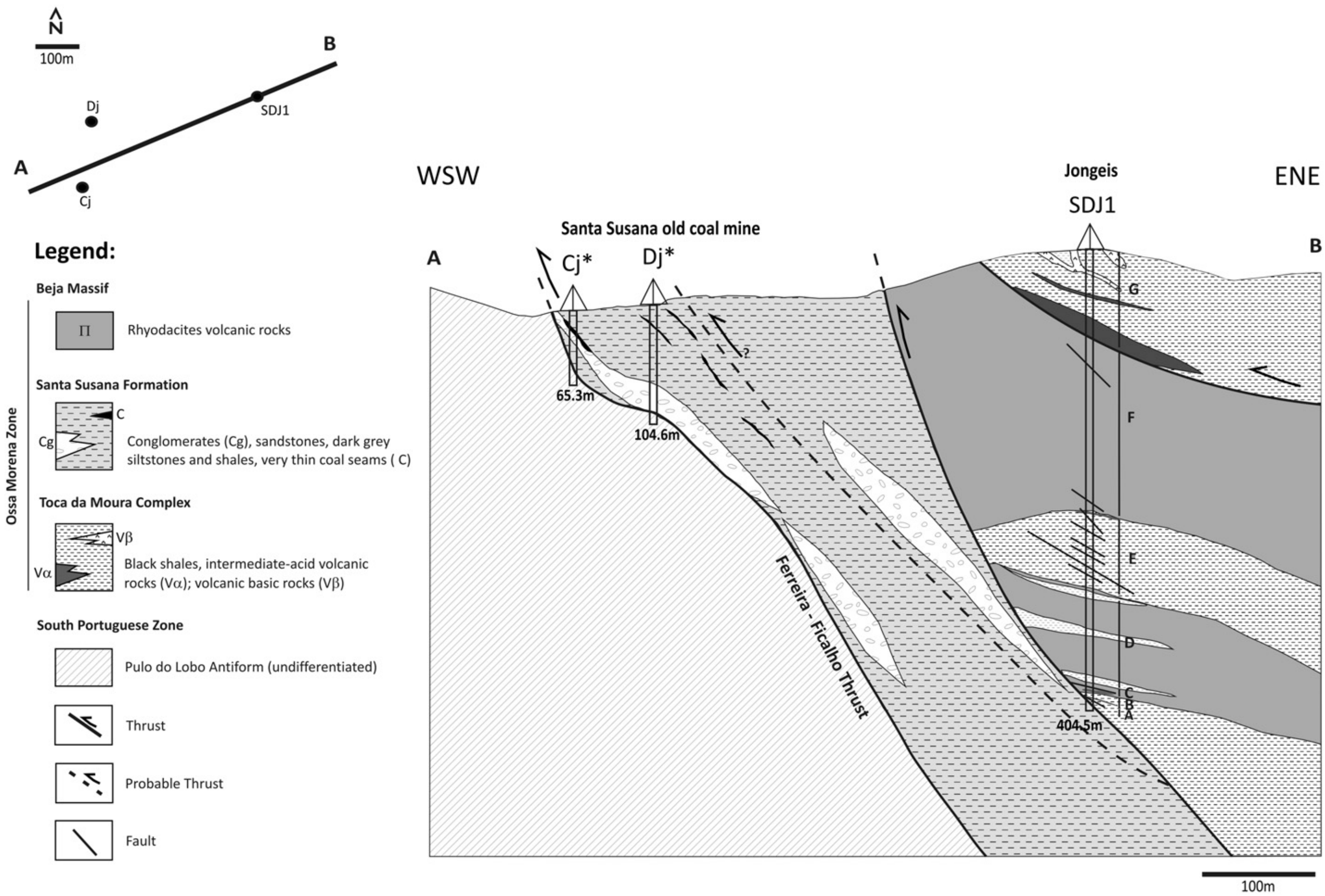

Fig. 2. Interpretative geological profile of the TMC and SSB in the Jongeis/Santa Susana region, with the boreholes Cj*, Dj* (projected) and SDJ1. A to G — lithological studied intervals described in the text for the SDJ1 borehole. The structural interpretation is based on the new data obtained in this study and in the description of Andrade et al. (1955), Domingos et al. (1983) and Oliveira and Matos (1991).

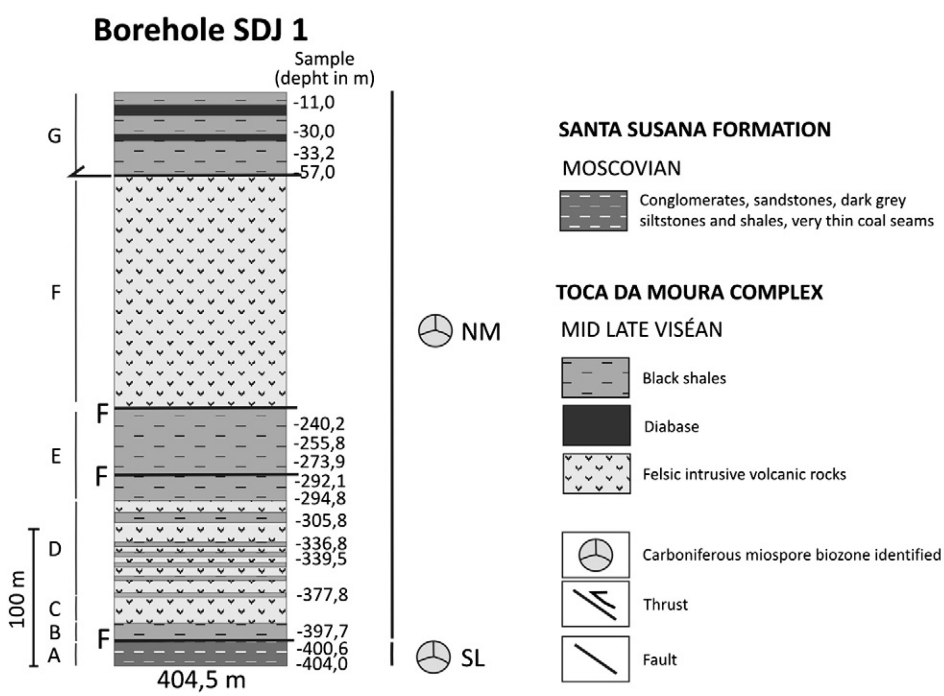

Fig. 3. Detailed log from SDJ1 borehole with the location of the studied lithologic intervals (A–G) and the 16 palyniferous samples and identified miospore biozones along the cut.

Plate I. Selected reworked palynomorphs from the middle to upper Cambrian of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC).

1. *Cymatiosphaera* cf. *C. ovillense* Cramer and Díez 1972, Santa Susana Formation, sample 43, slide 43_3, MC 1155-168.
2. *Retisphaeridium* cf. *R. dichamerum* Staplin, Jansonius and Pocock 1965, Toca da Moura Complex, sample 34, slide 34_3, MC 1153-164.
3. *Eliasum* sp., Toca da Moura Complex, sample 34, slide 34_3, MC 1298-42.
4. *Retisphaeridium* cf. *R. howelli* Martin in Martin and Dean 1983, Toca da Moura Complex, sample 27, slide 27_4, MC 1188-155.
5. *Cristallinium* cf. *C. cambriense* (Slavíková 1968) Vanguestaine 1978, Toca da Moura Complex, sample 34, slide 34_3, MC 1405-101.
6. *Timofeevia* cf. *T. phosphoritica* Vanguestaine 1978, Toca da Moura Complex, sample 34, slide 34_3, MC 1436-145.
7. *Vulcanisphaera* cf. *V. turbata* Martin in Martin and Dean 1981, Toca da Moura Complex, sample 32, slide 32_3, MC 1412-86.
8. *Acanthodiacrodium* cf. *A. estonicum* Timofeev 1966, Toca da Moura Complex, sample 34, slide 34_3, MC 1140-55.
9. *Impluviculus* cf. *I. multiangularis* (Umnova in Umnova and Fanderflit 1971) Volkova 1990, Toca da Moura Complex, sample 32, slide 32_3, MC 1219-19.
10. *Leiosphaeridia* sp., Toca da Moura Complex, sample 27, slide 27-4, MC 1471-142.

Plate II. Selected reworked palynomorphs from the Lower to the Middle Ordovician of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 6)

1 *Cymatiogalea* cf. *C. cristata* (Downie 1958) Rauscher 1973, Toca da Moura Complex, sample 27, slide 27_4, MC 1473-188.
2. *Vulcanisphaera* cf. *V. simplex* Jardiné, Combaz, Magloire, Peniguel and Vachey 1974, sample 43, Santa Susana Formation, slide 43_3, MC 1345-205.
3. *Veryhachium* cf. *V. lairdii* Deflandre 1946c *ex* Loeblich 1970, Toca da Moura Complex, sample 32, slide 32_3, MC 1389-108.
4. *Acanthodiacrodium* cf. *A. tadlense* Cramer and Díez 1977, Toca da Moura Complex, sample 34, slide 34_3, MC 1096-217.
5. *Coryphidium* sp., Santa Susana Formation, sample 43, slide 43_3, MC 1380-155.
6. *Striatotheca* sp., Santa Susana Formation, sample 43, slide 43_3, MC 1350-225.
7. *Arbusculidium* cf. *A. filamentosum* (Vavrdová 1965) Vavrdová 1972 emend. Fatka and Brocke 1999, Toca da Moura Complex, sample 27, slide 27_3, MC 1275-110.
8. *Schizodiacrodium* cf. *S. firmum* (Burmann 1970) Sarjeant and Varvdová 1997, Toca da Moura Complex, sample 27, slide 27_4, MC 1378-122.
9. *Lophosphaeridium* sp., Toca da Moura Complex, sample 27, slide 27_4, MC 1505-78.
10. *Veryhachium trispinosum* "complex" (Eisenack 1938) Stockmans and Willière, 1962, Toca da Moura Complex, sample 32, slide 32_3, MC 1381-142.
11. *Actinotodissus* cf. *A. longitaleosus* Loeblich and Tappan 1978, Toca da Moura Complex, sample 27, slide 27_3, MC 1425-80.
12. *Villosacapsula* cf. *V. irroratum* (Loeblich and Tappan 1969) Fensome, Williams, Sedley Barss, Freeman and Hill 1990, Toca da Moura Complex, sample 27, slide 27_3, MC 1405-190.
13. *Multiplicisphaeridium ramusculosum* (Deflandre) Lister, 1970, Toca da Moura Complex, sample 30, slide 30, MC 1410-139.

Plate III. Selected reworked palynomorphs from the middle to upper Silurian of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 7)

1. *Diexallophasis* sp., Toca da Moura Complex, sample 27, slide 27_3, MC 1410-205.
2. *Diexallophasis* cf. *D. sanpetrensis* (Cramer 1964b ex Cramer 1970a) Dorning 1981, Toca da Moura Complex, sample 27, slide 27_3, MC 1335-53.
3. *Geron* sp., Toca da Moura Complex, sample 27, slide 27_3, MC 1390-190.
4. *Pardaminela* sp., Toca da Moura Complex, sample 27, slide 27_3, MC 1175-225.
5. *Veryhachium* cf. *V. valiente* Cramer 1964, Toca da Moura Complex, sample 27, slide 27_3, MC 1350-175.
6. *Neoveryhachium carminae* (Cramer 1964b) Cramer 1970, Toca da Moura Complex, sample 34, slide 34, MC 1430-86.
7. *Chomotriletes* sp., Toca da Moura Complex, sample 32, slide 32_3, MC 1279-208.
8. cf. *Riculasphaera* sp., Toca da Moura Complex, sample 27, slide 27_4, 1362-78.
9. *Polyedrixium* sp., Toca da Moura Complex, sample 34, slide 34_2, MC 1334-109.
10. *Dictyotidium* sp., Toca da Moura Complex, sample 27, slide 27_3, MC 1405-65.
11. *Cymatiosphaera* sp.1, Toca da Moura Complex, sample 32, slide 32_3, MC 1255-87.
12. *Stellinium micropolygonale* (Stockmans and Willière) Playford 1977, Toca da Moura Complex, sample 34, slide 34_2, MC 1091-89.

Plate IV. Selected reworked palynomorphs from the Lower Devonian to lower Carboniferous of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 8)

1. *Stellinium micropolygonale* (Stockmans and Willière) Playford 1977, Santa Susana Formation, sample 43, slide 43_3, MC 1350-175.
2. *Stellinium micropolygonale* (Stockmans and Willière) Playford 1977, Santa Susana Formation, sample 43, slide 43_3, MC1245-140.
3. *Stellinium comptum* Wicander and Loeblich 1977, Toca da Moura Complex, sample 32, slide 32_3, MC 1325-50.
4. *Craterisphaeridium* sp., Toca da Moura Complex, sample 30, slide 30_1, MC 1349-104.
5. *Daillydium* sp., Toca da Moura Complex, sample 27, slide 27_3, MC 1335-175.
6. *Chomotriletes multivittatus* Playford 1978, Toca da Moura Complex, sample 34, slide 34_3, MC 1050-206.
7. *Cymatiosphaera* sp. 2, Toca da Moura Complex, sample 27, slide 27_4, MC 1428-49.
8. *Cymatiosphaera* sp. 3, Toca da Moura Complex, sample 27, slide 27_4, MC 1208-78.
9. *Winwaloeusia* sp., Toca da Moura Complex, sample 27, slide 27_4, MC 1275-114.
10. *Pterospermella* sp. 1, Toca da Moura Complex, sample 27, slide 27_3, MC 1465-65.
11. *Pterospermella* sp. 2, Santa Susana Formation, sample 43, slide 43_3, MC 1382-100.
12. *Navifusa bacilla* (Deunff 1955) Playford 1977, Toca da Moura Complex, sample 30, slide 30_3, 1382-213.

Plate V. Selected reworked palynomorphs from the Lower Ordovician to Lower Devonian of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 9)

1. *Quadrisporites variabilis* (Cramer) Jardiné, Combaz, Magloire, Peniguel and Vachey 1972, Toca da Moura Complex, sample 27, slide 27_3, MC 1350-122.
2. *Dyadospora murusattenuata* Morphon Strother and Traverse 1979 sensu Steemans, Le Hérissé and Bozdogan 1996, Toca da Moura Complex, sample 30, slide 30_1, MC 1271-173.
3. *Sphaerasaccus* sp., Toca da Moura Complex, sample 34, slide 34_2, MC 1227-216.
4. *Quadrisporites variabilis* (Cramer) Jardiné, Combaz, Magloire, Peniguel and Vachey 1972, Toca da Moura Complex, sample 27, slide 27_4, MC 1545-154.
5. *Quadrisporites* sp., Toca da Moura Complex, sample 32, slide 32_3, MC 1428-72.
6. *Gneudnaspora divellomedia* (Chibrikova) Balme, 1988, var. *minor* Breuer, Al-Ghazi, Al-Ruwaili, Higgs, Steemans, Wellman 2007, Toca da Moura Complex, sample 32, slide 32_3, MC 1451-26.
7. *Tetrahedraletes medinensis* Strother and Traverse 1979, Toca da Moura Complex, sample 32, slide 32_3, MC 1245-231.
8. *Tetrahedraletes medinensis* Strother and Traverse 1979, Toca da Moura Complex, sample 34, slide 34_3, MC 1312-185.
9. *Rimosotetras problematica* Burgess 1991, Santa Susana Formation, sample 43, slide 43_3, MC 1334-196.
10. *Imperfectotriletes* sp., Toca da Moura Complex, sample 32, slide 32_3, MC 1173-34.
11. *Imperfectotriletes varvdovae* (Richardson) Steemans, Higgs and Wellman 2000, Toca da Moura Complex, sample 34, slide 34_3, MC 1334-177.
12. *Gneudnaspora chibrikovae* (Steemans, Higgs, Wellman) Breuer, Al-Ghazi, Al-Ruwaili, Higgs, Steemans, Wellman 2007, Toca da Moura Complex, sample 30, slide 30_3, MC 1377-128.
13. *Artemopyra radiata* (Strother) Burgess and Richardson, 1995, Santa Susana Formation, sample 43, slide 43_3, MC 1320-160.
14. *Gneudnaspora plicata* (Burgess and Richardson) Breuer, Al-Ghazi, Al-Ruwaili, Higgs, Steemans, Wellman 2007, Toca da Moura Complex, sample 32, slide 32_3, MC 1356-131.
15. *Gneudnaspora plicata* (Burgess and Richardson) Breuer, Al-Ghazi, Al-Ruwaili, Higgs, Steemans, Wellman 2007, Toca da Moura Complex, sample 34, slide 34_3, MC 1347-188.

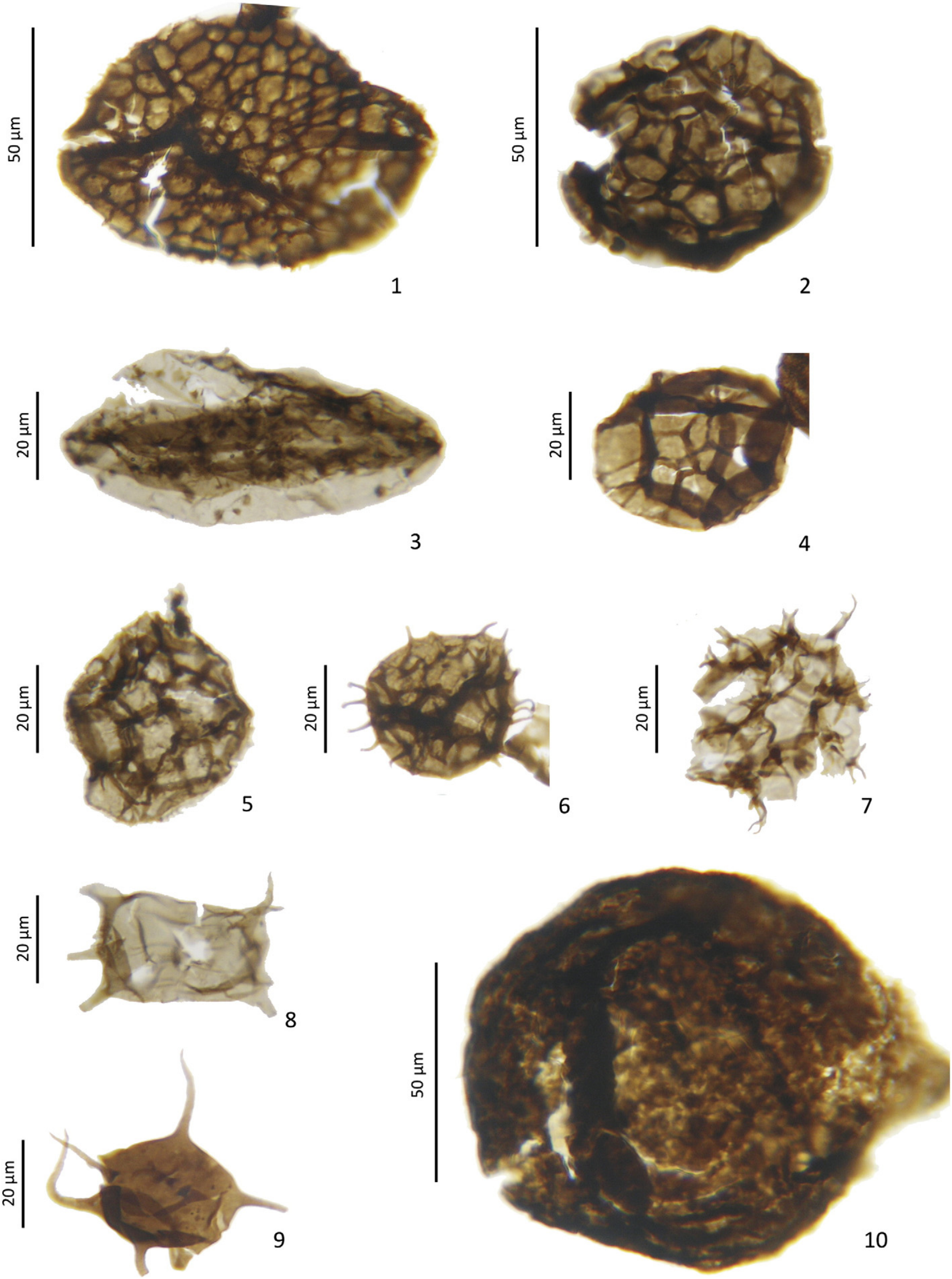
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Plate I

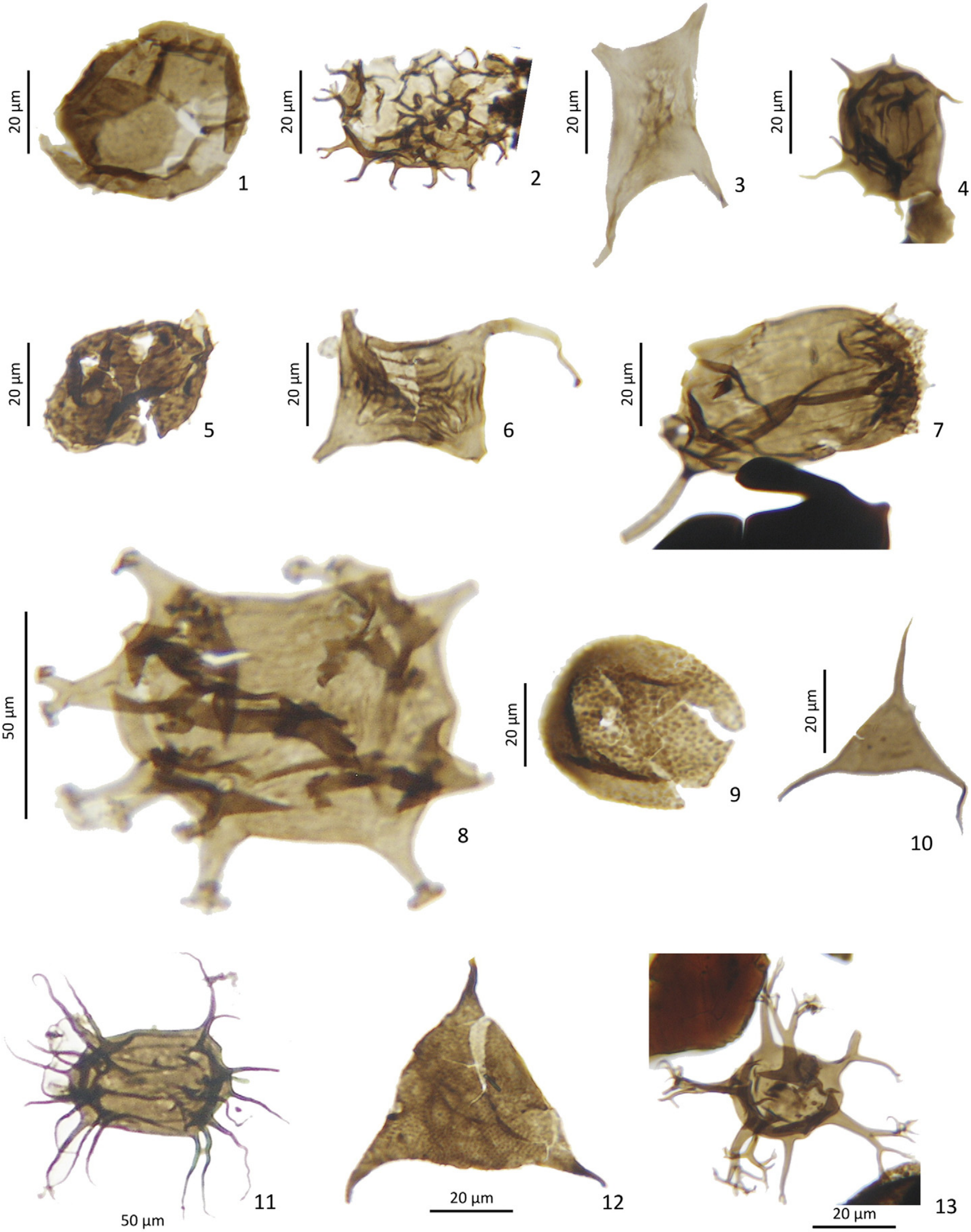


Plate II. *(caption on page 4)*.

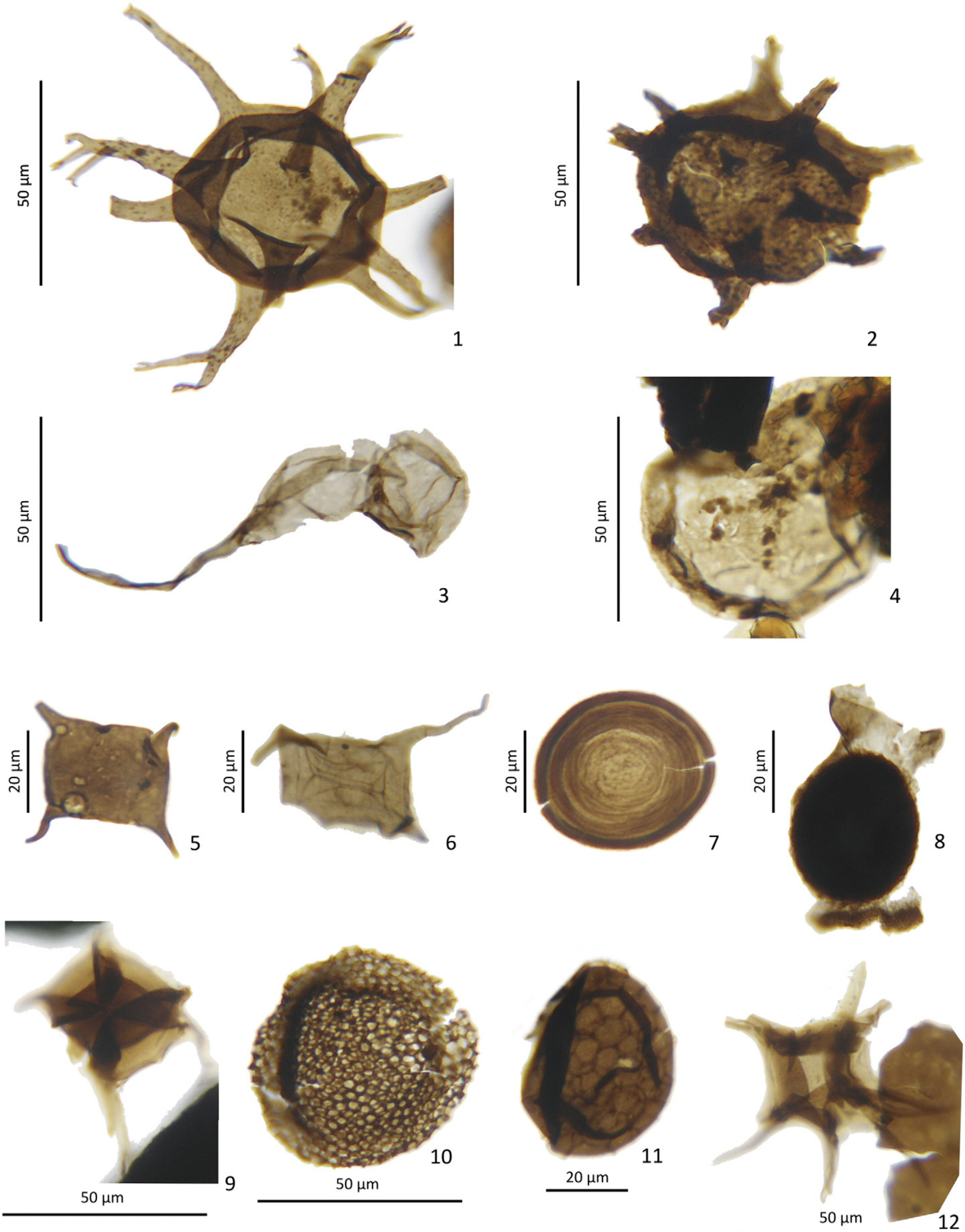


Plate III. *(caption on page 4).*

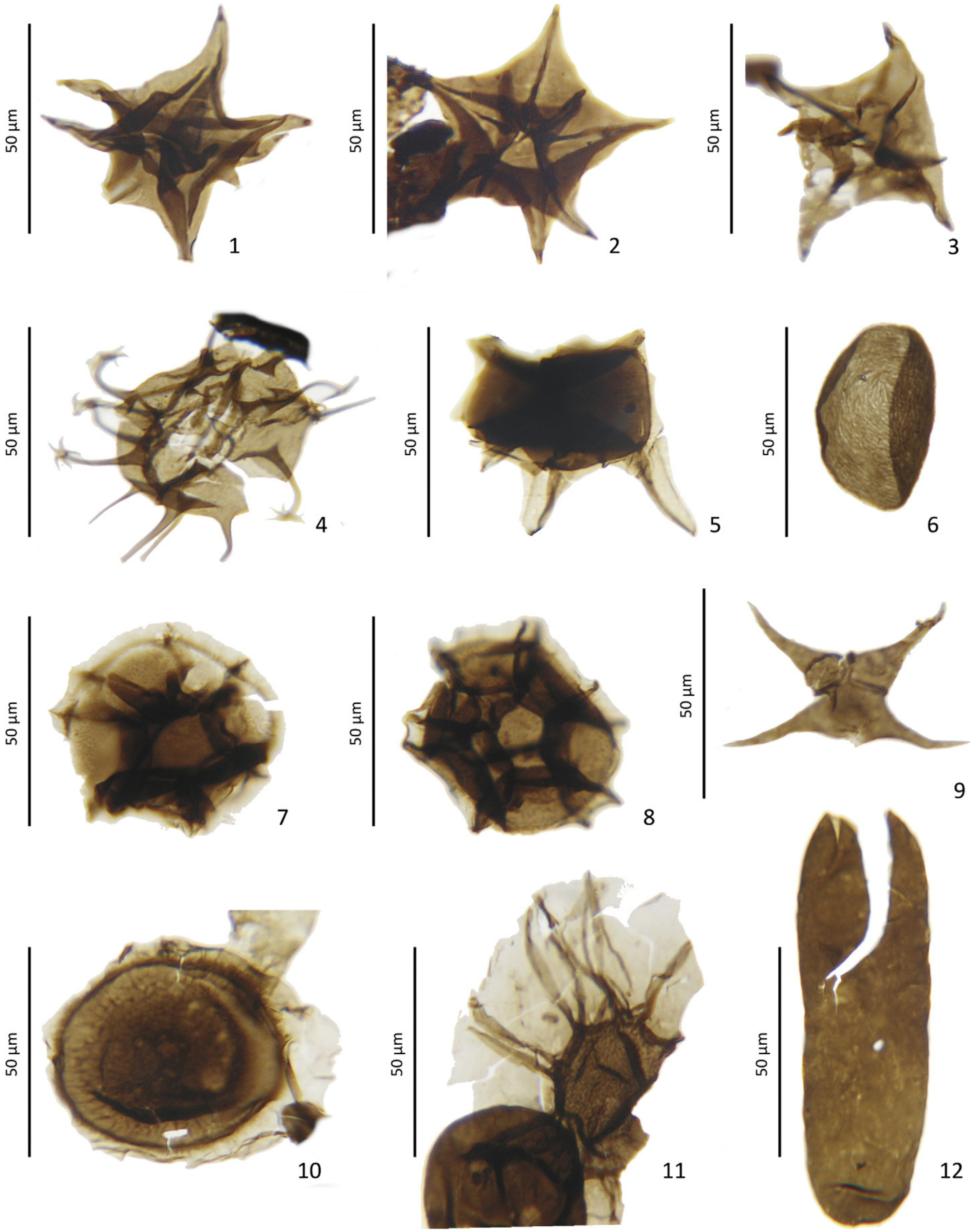


Plate IV. *(caption on page 4).*

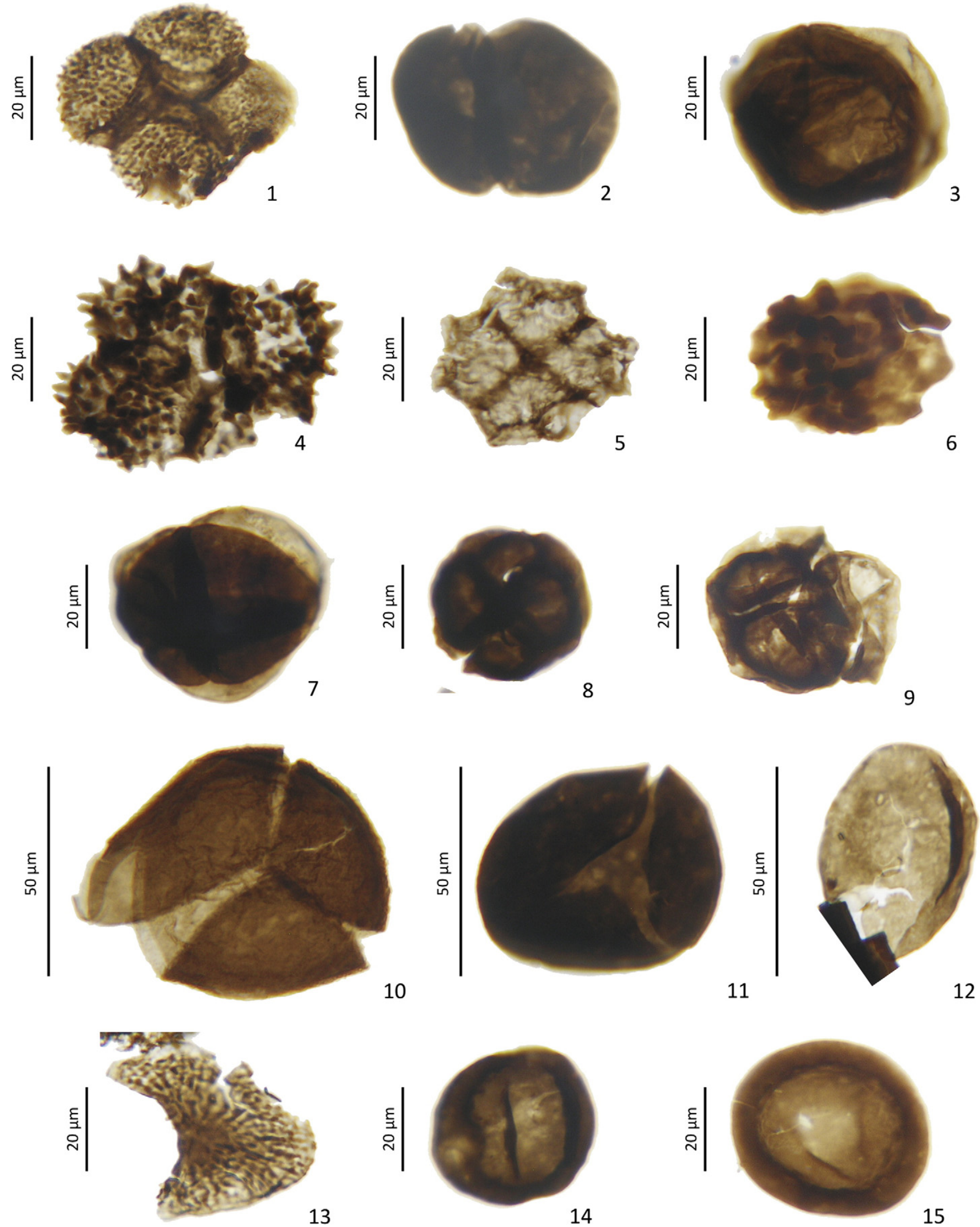


Plate V. *(caption on page 4).*

The Toca da Moura Complex consists mainly of shales, bioturbated thin bedded sandstones, slumps of mixed shale/sandstones and limestones, and volcanic and sub-volcanic rocks composed of basalts, andesites, rhyolites, felsic pyroclastic rocks, diabases and microdiorites forming a 400 m thick succession (Gonçalves, 1985; Santos et al., 1987). Palynological studies of the Toca da Moura Complex shales, collected from several outcrop locations, yielded in situ miospores from the CM, Pu and NM miospore biozones, of late Tournaisian to mid late Visean age (Cunha, T., in Andrade et al., 1991; Pereira et al., 2006). Reworked palynomorphs, which range in age from Cambrian to Tournaisian, were recognized by Pereira et al. (2006) in the Toca da Moura Complex.

Lower Paleozoic outcrops from which the reworked palynomorphs may derive are recorded in the Ossa Morena Zone, as well as, Mid to late Paleozoic age successions from the South Portuguese Zone (Cunha and Vanguestaine, 1988; Pereira et al., 1999; Piçarra et al., 1999; Oliveira et al., 2004; Pereira et al., 2006, 2007; Borges et al., 2008; Pereira et al., 2008a, 2008b; Lopes et al., 2009; Pereira et al., 2010; Piçarra et al., 2011; Lopes et al., 2012).

The Santa Susana Formation sediments rest unconformably on the Toca da Moura Complex lithologies and comprise gray to black shales and coarse conglomerates at the base of the succession, followed by alternations of sandstones, dark gray siltstones and shales, with occasional, in the upper part of the succession, layers of coal with a thickness in excess of 200 m (Gonçalves and Carvalhosa, 1984; Oliveira and Matos, 1991). According to Andrade et al. (1955) and Machado et al. (2012), the thickness of the Santa Susana Formation increases towards the south–southeast. Previous macroflora and palynological studies of the Santa Susana Formation indicate a late Moscovian to Kasimovian age (Sousa and Wagner, 1983; Fernandes, 1998, 2001; Machado et al., 2012), based on outcrop sampling from its upper part.

Plate VI. Selected reworked palynomorphs from the Lower Ordovician to Lower Devonian of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC).

1. *Ambitisporites asturicus* (Rodriguez) Breuer 2007, Toca da Moura Complex, sample 34, slide 34_3, MC 1404-179.
2. *Synorisporites* sp., Toca da Moura Complex, sample 34, slide 34_3, MC 1364-148.
3. *Chelinospora* sp., Toca da Moura Complex, sample 27, slide 27_1, MC 1438-150.
4. *Ambitisporites asturicus* (Rodriguez) Breuer 2007, Santa Susana Formation, sample 43, slide 43_3, MC 1340-180.
5. *Synorisporites verrucatus* Richardson and Lister 1969, Toca da Moura Complex, sample 32, slide 32_3, MC1261-94.
6. *Retusotriletes maculatus* McGregor and Camfield 1976, Toca da Moura Complex, sample 30, slide 30_1, MC 1370-158.
7. *Emphanisporites* cf. *E. protophanus* Richardson and Ioannides 1973, Toca da Moura Complex, sample 27, slide 27_3, MC 1375-138.
8. *Ambitisporites avitus* Hoffmeister 1959, Toca da Moura Complex, sample 27, slide 27_3, MC 1370-165.
9. *Apiculiretusispora arcidecus* Richardson, Rodriguez and Sutherland 2001, Toca da Moura Complex, sample 27, slide 27_4, MC 1278-219.
10. *Archaeozonotriletes chulus* (Cramer) Richardson and Lister 1969, Toca da Moura Complex, sample 32, slide 32_3, MC 1243-166.
11. *Apiculiretusispora brandtii* Streel 1964, Toca da Moura Complex, sample 27, slide 27_4, MC 1496-92.
12. *Brochotriletes robustus*, (Scott and Rouse) McGregor, 1973, Toca da Moura Complex, sample 42, slide 42_3, MC 1382-155.
13. *Archaeozonotriletes chulus* (Cramer) Richardson and Lister 1969 Toca da Moura Complex, sample 27, slide 27_3, MC 1175-196.
14. *Dictyotriletes subgranifer* McGregor 1973, Toca da Moura Complex, sample 30, slide 30_3, MC 1279-63.
15. *Brochotriletes foveolatus* Naumova 1953, Toca da Moura Complex, sample 32, slide 32_3, MC 1165-151.
16. *Amicosporites splendidus* Cramer 1967, Toca da Moura Complex, sample 27, slide 27_3, MC 1450-70.
17. *Dictyotriletes emsiensis* (Allen) McGregor 1973, Toca da Moura Complex, sample 27, slide 27_3, MC 1352-180.

Plate VII. Selected reworked palynomorphs from the Upper Devonian to lower Tournaisian of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 12)

1. *Retusotriletes triangulatus* (Streel) Streel 1967, Toca da Moura Complex, sample 30, slide 30-1, MC 1289-101.
2. *Grandispora tabulata* Loboziak, Streel, Burjack 1988, Toca da Moura Complex, sample 32, slide 32-3, MC 1321-145.
3. *Retispora lepidophyta* (Kedo) Playford 1976, Toca da Moura Complex, sample 27, slide 27-3, MC 1205-110.
4. *Retusotriletes triangulatus* (Streel) Streel 1967, Toca da Moura Complex, sample 27, slide 27-3, MC 1430-140.
5. *Colatisporites* sp., Toca da Moura Complex, sample 34, slide 34-2, MC 1376-189.
6. *Pustulatisporites* sp., Toca da Moura Complex, sample 27, slide 27-4, MC1123-162.
7. *Rugospora lactucosa* Higgs, Clayton, Keegan 1988, 32_3_1, Toca da Moura Complex, sample 32, slide 32-3, MC 1434-88.
8. *Umbonatisporites distinctus* Clayton 1971, Toca da Moura Complex, sample 30, slide 30-1, MC 1403-127.
9. *Crassispora trychera* Neves and Ioannides 1974, Toca da Moura Complex, sample 27, slide 27-3, MC 1332-65.
10. *Schopfites claviger* Sullivan emend. Higs, Clayton and Keegan 1988, Toca da Moura Complex, sample 27, slide 27-4, MC 1446-177.

Plate VIII. Selected palynomorphs from the lower Tournaisian to Visean (SL Biozone) of the SDJ1 borehole, Jongeis region. The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 13)

1. *Lophotriletes* sp., Toca da Moura Complex, sample 32, slide 32-3, MC 1427-152.
2. *Granulatisporites* micrgranifer Ibrahim 1933, Toca da Moura Complex, sample 34, slide 34-3, MC 1203-203.
3. *Raistrickia nigra* Love 1960, Santa Susana Formation, sample 42, slide 42_3, MC 1360-165.
4. *Vallatisporites* sp., Toca da Moura Complex, sample 27, slide 27-3, MC 1425-85.
5. *Torispora securis* Balme 1952, Santa Susana Formation, sample 43, slide 43_3, MC 1310-235.
6. *Punctatosporites* sp., Santa Susana Formation, sample 43, slide 43_3, MC 1280-140.
7. *Radiizonates* sp., Santa Susana Formation, sample 43, slide 43_3, MC 1305-225.
8. *Endosporites globiformis* (Ibrahim) Schopf, Wilson and Bentall 1944, Santa Susana Formation, sample 43, slide 43_3, MC 1300-100.
9. *Knoxisporites triradiatus* Hoffmeister, Staplin and Malloy 1955, Santa Susana Formation, sample 43, slide 43_3, MC 1215-175.
10. *Reticulatisporites danzei* (Agrali) Urban 1971, Santa Susana Formation, sample 44, slide 44_3, MC 1510-85.

Plate IX. Selected spores recovered from the Carboniferous (OT Biozone) of the museum sample STS15, SSF (Jongeis coal mine). The plate caption gives the taxonomic name of the figured specimen, followed by the unit, sample number, slide number and microscopic coordinates (MC). (see on page 14)

1. *Triquitrites tribullatus* (Ibrahim) Schopf, Wilson and Bentall 1944, Santa Susana Formation, sample STS15, slide STS15_1, MC 1375-65.
2. *Triquitrites sculptilis* Balme 1952, Santa Susana Formation, sample STS15, slide STS15_1, MC 1500-135.
3. *Savitrisporites nux* (Buterworth and Williams) Smith and Buterworth, 1967, Santa Susana Formation, sample STS15, slide STS15_1, MC 1445-155.
4. *Densosporites* sp., Santa Susana Formation, sample STS15, slide STS15_1, MC 1450-135.
5. *Thymospora pseudothiessenii* (Konsanke) Alpern and Doubinger 1973, Santa Susana Formation, sample STS15, slide STS15_1, MC 1264-152.
6. *Cirratriradites saturni* (Ibrahim) Schopf, Wilson and Bentall 1944, Santa Susana Formation, sample STS15, slide STS15_1, MC 1310-55.
7. *Dictyotriletes muricatus* (Kosanke) Smith and Butterworth 1967, Santa Susana Formation, sample STS15, slide STS15_1, MC 1402-100.
8. *Raistrickia saetosa* (Loose) Schopf, Wilson and Bentall 1944, Santa Susana Formation, sample STS15, slide STS15_1, MC 1310-215.
9. *Vestispora* sp., Santa Susana Formation, sample STS15, slide STS15_1, MC 1375-245.
10. *Florinites* sp., Santa Susana Formation, sample STS15, slide STS15_1, MC 1220-35.

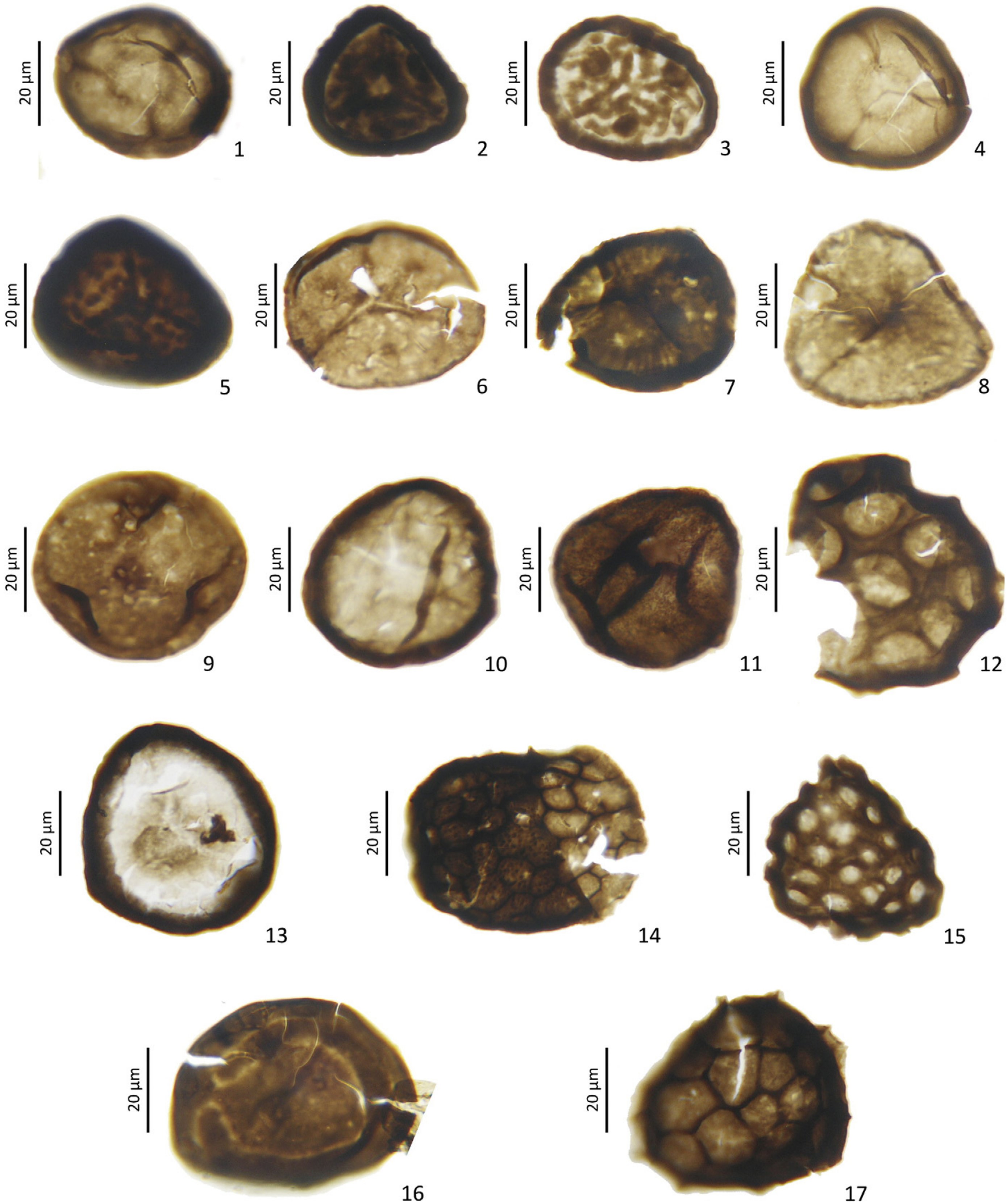


Plate VI

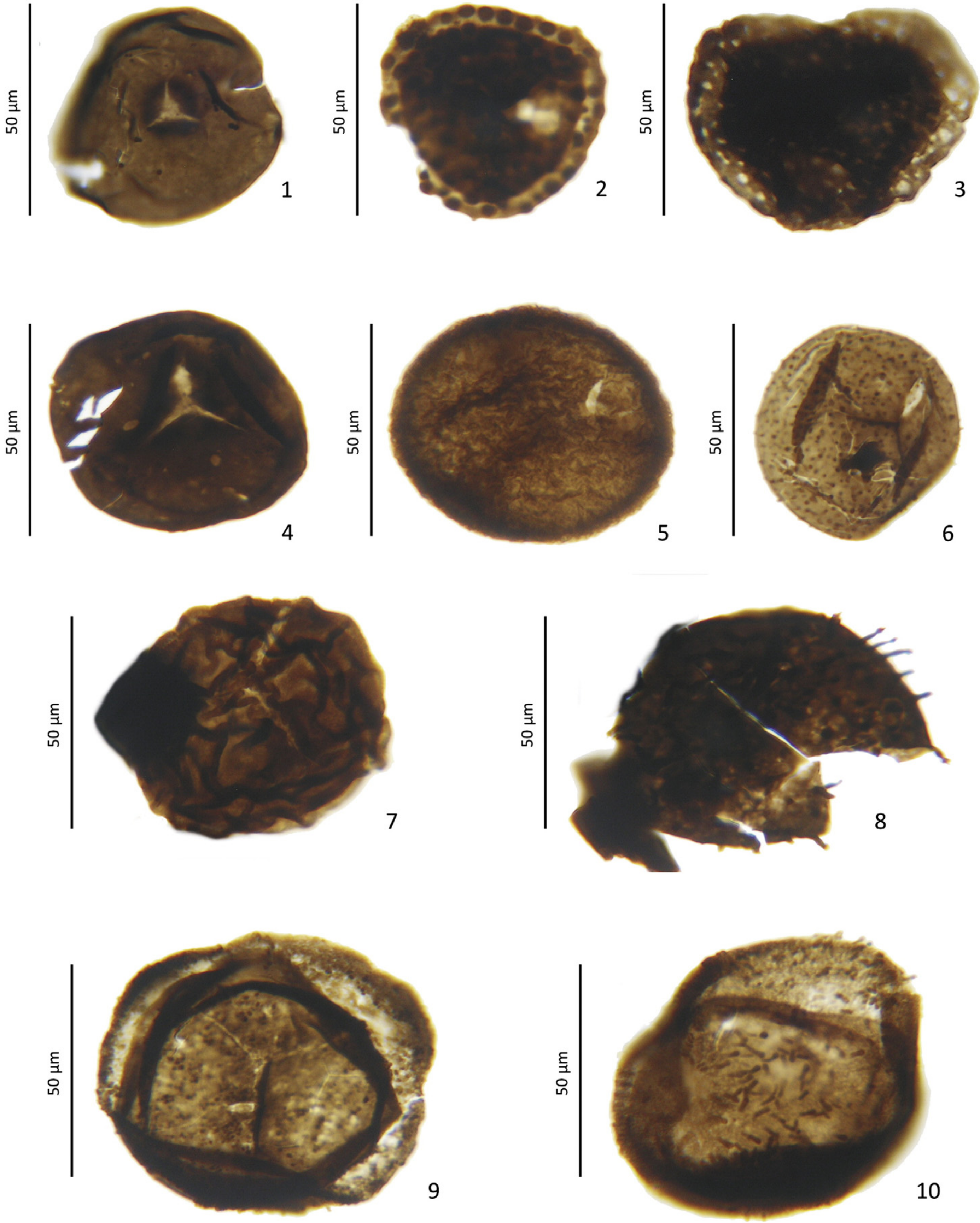


Plate VII. *(caption on page 10).*

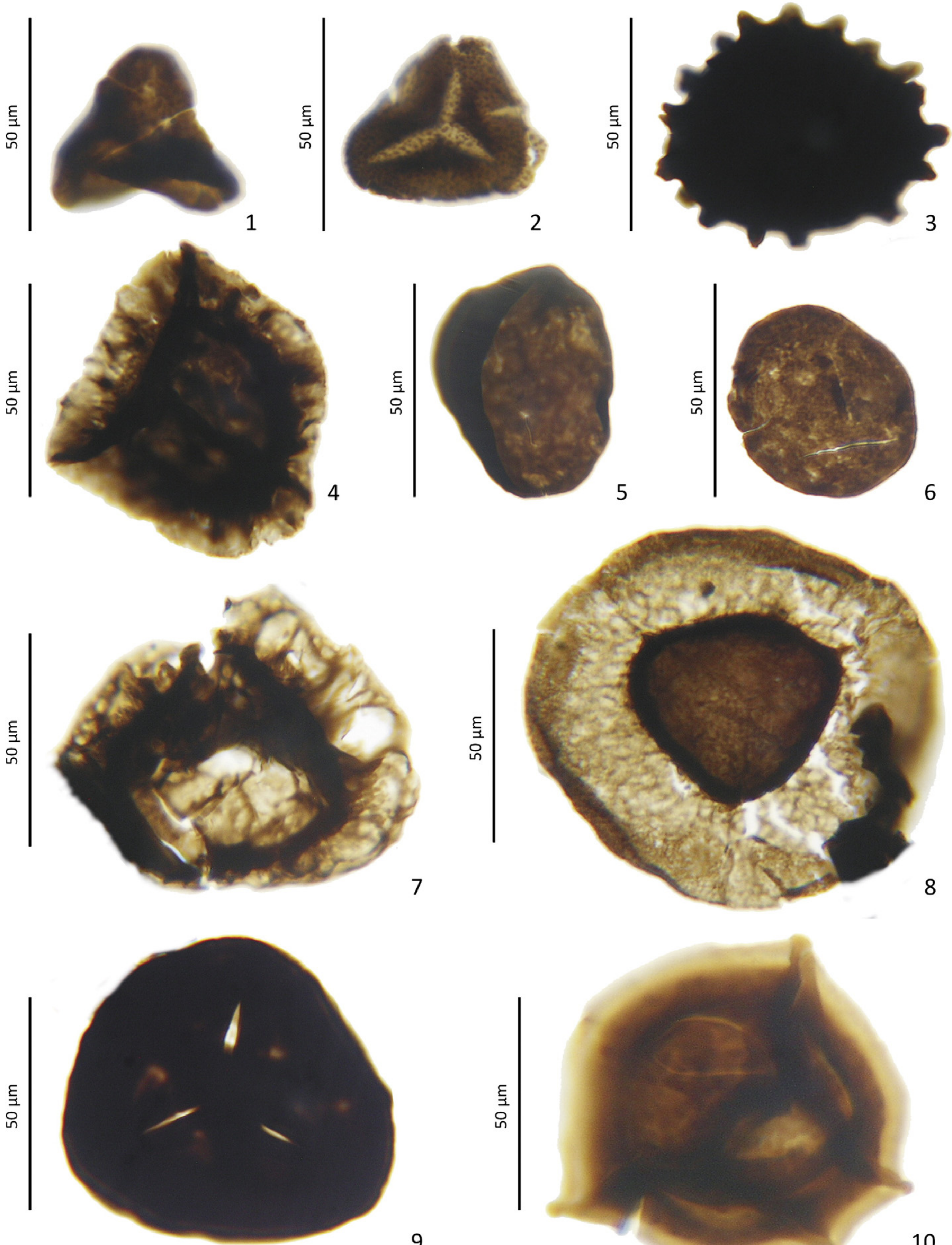


Plate VIII. *(caption on page 10).*

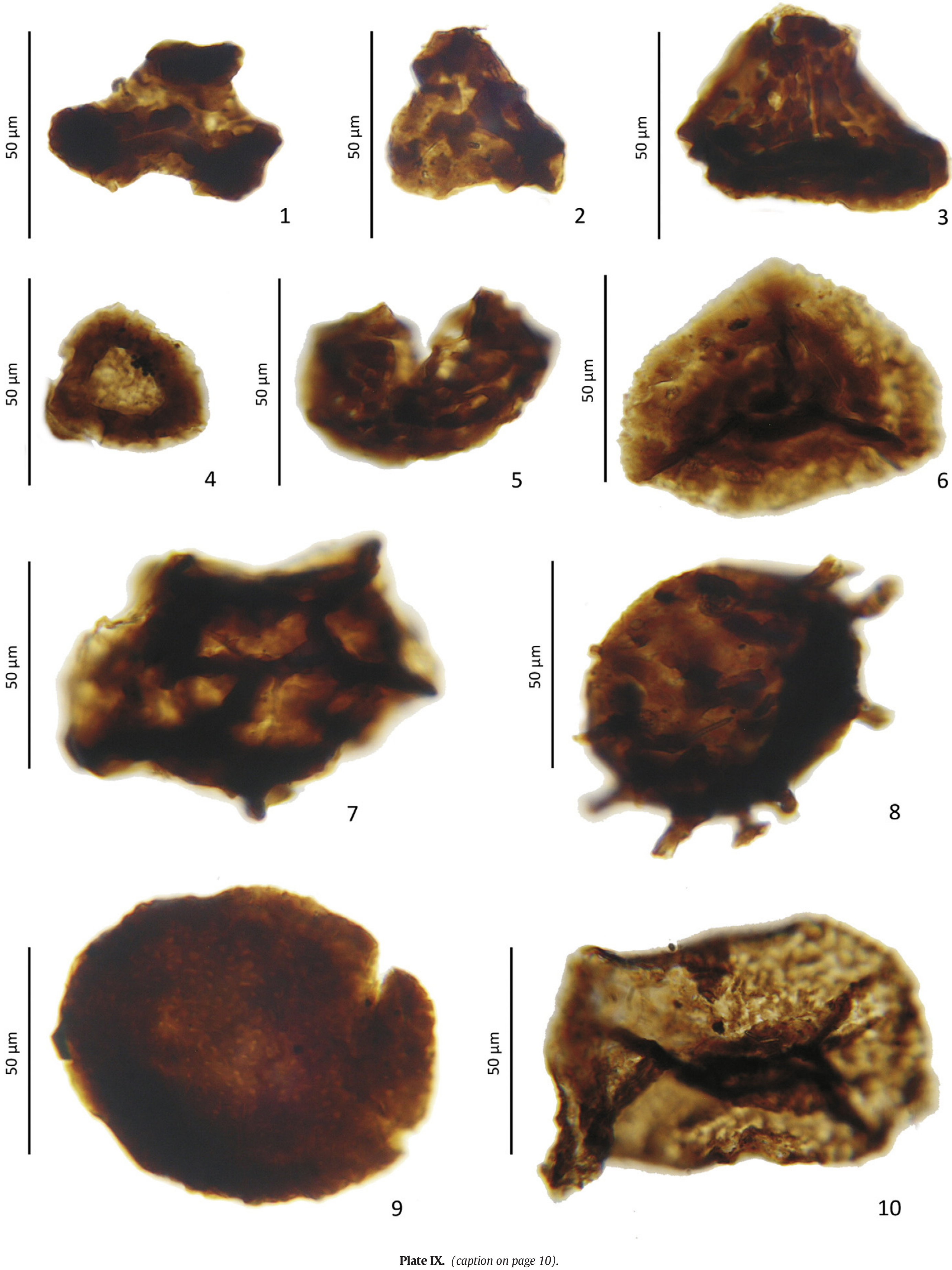


Plate IX. *(caption on page 10).*

The Santa Susana Formation conglomerates frequently include clasts of igneous rocks assigned to the Toca da Moura Complex and Beja Massif igneous lithologies. This suggests that an important episode of tectonic uplift and erosion was coeval with the development of the Santa Susana Basin (SSB) (Andrade et al., 1955; Gonçalves, 1985; Santos et al., 1987; Oliveira et al., 2006; Pereira et al., 2006; Oliveira et al., 2013), which resulted in an intra-mountain sedimentary environment during the Pennsylvanian (Domingos et al., 1983; Oliveira et al., 1991; Carvalhosa and Zbyzewski, 1994; Almeida et al., 2006; Oliveira et al., 2007; Machado et al., 2012).

The Santa Susana Formation crops out in three main locations, Jongeis, Remeiras, and Vale de Figueiras. Several coal layers were recognized in the upper part of the sedimentary succession, but only in Jongeis was the coal exploited in an underground mine that was active from 1927 to 1944 (Sousa and Wagner, 1983). Several boreholes, among them boreholes Cj and Dj (data adapted from Andrade et al., 1955), and included in the geological cross section (Fig. 2), were drilled in the 1950s, in order to recognize the Santa Susana Formation in the subsurface, but all failed to discover workable coal seams. Oliveira and Matos (1991) conducted a geophysical study in order to investigate the stratigraphy and structure of the Santa Susana Formation in depth. Following the results of that study, the SDJ1 borehole was planned and drilled reaching a total depth of 404.5 m (see Fig. 1 for location, and Figs. 2 and 3 for details).

3. Materials and methods

Twenty samples of gray to black shales, recovered from the cores of the SDJ1 borehole were palynologically investigated, with 16 samples yielding moderate to well preserved palynomorphs (Figs. 2 and 3). Furthermore, a dark shale sample (STS15) with thin lenses of coal collected near the main coal seam of the Jongeins coal mine and stored in the LNEG Geological Museum stratigraphic collection, in Lisbon, was also processed for palynomorphs for comparison to the SDJ1 borehole samples.

All samples were treated by standard palynological laboratory procedures to extract and concentrate the organic residues (Wood et al., 1996). The slides were examined using a transmitted light BX40 Olympus microscope equipped with an Olympus C5050 digital camera. All samples, residues, and slides are stored in the LNEG, Geological Survey of Portugal, S. Mamede Infesta, Portugal.

4. Palynology

Stratigraphically important and typical taxa recovered are illustrated in Plates I–IX. The stratigraphic ranges of select palynomorph taxa and the miospore zonal schemes used are shown in Tables 1–3.

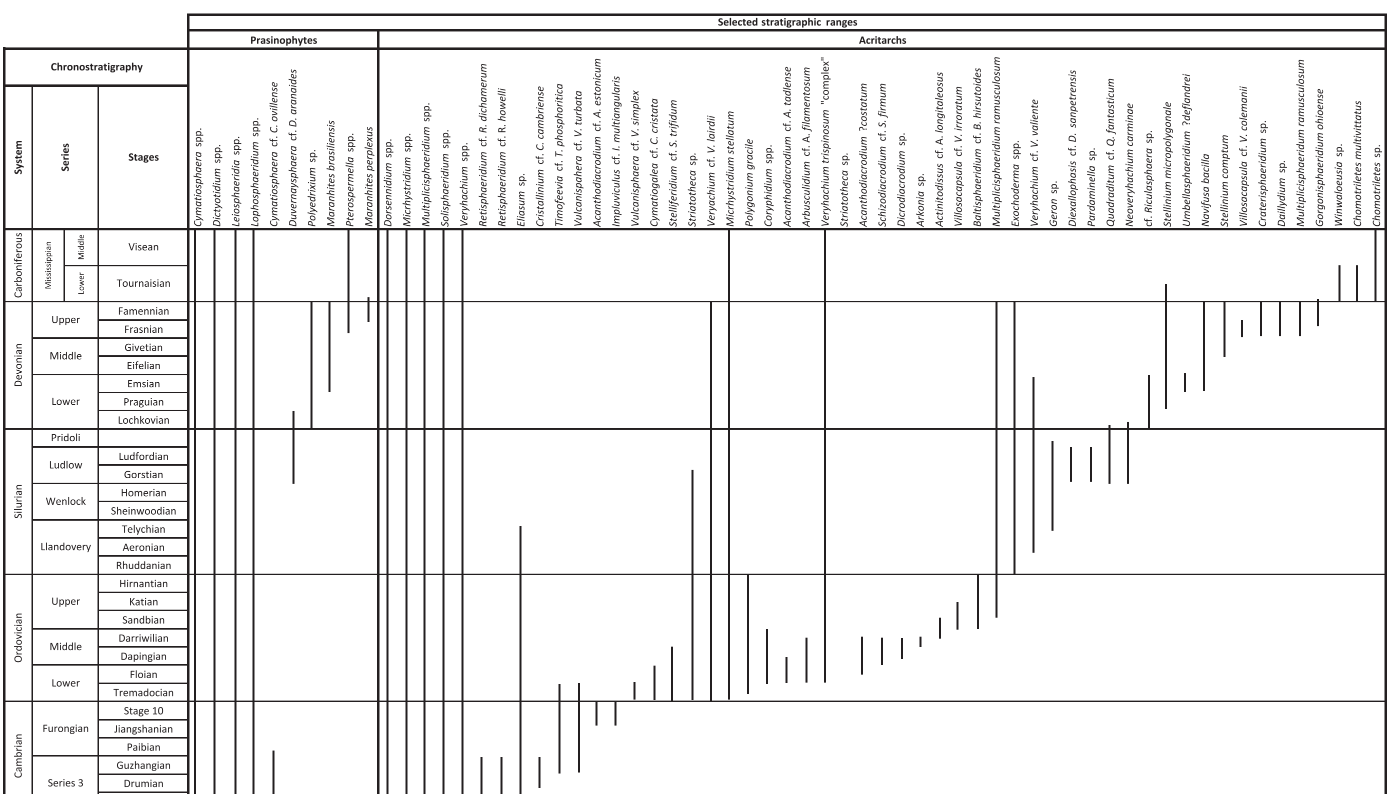
Identifications and stratigraphic distribution of the identifiable acritarchs are from Downie (1984), Martin and Dean (1988), Mette (1989), Fensome et al. (1990), Martin (1993), Molyneux et al. (1996), Le Hérissé et al. (2000), and Playford (2003). For the miospores, the zonal schemes used are from Smith and Buterworth (1967), Clayton et al. (1977), Richardson and McGregor (1986), Streel et al. (1987), Higgs et al. (1988), Burgess and Richardson (1995), Clayton (1996), Steemans et al. (1996), Streel et al. (2000), Richardson et al. (2001), Clayton et al. (2003), Rubinstein and Vaccari (2004), Breuer et al. (2007), Pereira et al. (2007, 2008a, 2008b), and Vecoli et al. (2011).

4.1. Palynostratigraphy of the borehole SDJ1

The SDJ1 borehole was sampled at seven different intervals as follows (Figs. 2 and 3):

(A) The bottom seven meters of the borehole (404.5 to 397.8 m depth) consists of tectonically disrupted gray to black shales and siltstones. The two palyniferous samples (404.0 and 400.6 m)

Table 1
Stratigraphic distribution of selected prasinophyte and acritarch species recovered. For those taxa listed as cf., the stratigraphic range of the species is shown. The acritarch distribution follows Downie (1984), Martin (1993), Martin and Dean (1988), Fensome et al. (1990), Molyneux et al. (1996), Le Hérissé et al. (2000), and Playford (2003).



yielded a poorly preserved miospore assemblage assigned to the SL Biozone of mid Moscovian age. Taxa in this assemblage are *Calamospora* sp., *Crassispora* cf. *Crassispora kosankei*, *Densosporites* spp., *Endosporites globiformis*, *Laevigatosporites*sp., *Leiotriletes* sp., *Lophotriletes* sp., *Punctatosporites* sp., *Radiizonates* sp., *Reticulatisporites polygonalis*, *Reticulatisporites danzei*, *Torispora* sp., and the index species *Torispora securis*, that allowed the zonal assignment. This age indicates a time gap with respect to the ages obtained in the higher shale beds of the borehole. Therefore, this seven meter interval of sediments has the same age of the Santa Susana Formation.

In terms of structural interpretation, the fact that the lithologies of interval A are tectonically disrupted is indicative that the Toca da Moura Complex has been thrusted over the Santa Susana Formation (Fig. 2). This interpretation implies that compressive Variscan tectonism took place *post* Santa Susana Formation deposition, i.e., later than the late Moscovian.

(B) The interval between 397.8 m and 390.7 m in depth, and from which one sample was collected, is composed of gray to black shales. The lone palyniferous sample (397.7 m) yielded miospores assigned to the NM Biozone of mid late Visean age (based on the presence of *Raistrickia nigra*), which denotes the same age as the Toca da Moura sediments. Together with similar lithological characteristics, this indicates that the sample belongs to the Toca da Moura Complex. The entire miospore assemblage is comprised of *Apiculiretusispora* sp., *Auroraspora* sp., *Colatisporites* sp., *Dibolisporites* sp., *Discernisporites micromanifestus*, *Granulatisporites microgranifer*, *Leiotriletes* sp., *Microreticulatisporites* sp., *Punctatisporites* sp., *Retusotriletes* sp., *Rugospora* sp., *Triquitrites* spp., and *Vallatisporites galearis*.

(C) This interval (390.7–384.4 m in depth) consists of rhyodacite volcanic rocks interbedded with intermediate acid volcanic rocks and thin layers of black shales which were barren of palynomorphs.

(D) The interval from 377.8 m to 298.1 m in depth consists of rhyodacite volcanic rocks interbedded with siltstone and dark shale beds. The four palyniferous samples (377.8, 339.5, 336.8, and 305.8 m) yielded a moderately preserved association of miospores, also assigned to the NM Biozone, and based on the occurrence of *Raistrickia nigra*. The rest of the miospore assemblage contained *Colatisporites* sp., *Dictyotriletes* sp., *Discernisporites micromanifestus*, *Lycospora pusilla*, *Punctatisporites* sp., *Retusotriletes* sp., and *Vallatisporites ciliaris*.

(E) This interval, from 298.1 m to 231.1 m in depth, consists mainly of gray to black shales, microconglomerates and rare sandstone beds. A thin intercalation of intermediate-acid volcanic rocks was also registered. Five shale samples (294.8, 292.1, 273.9, 255.8, 240.2 m) yielded abundant and moderately well preserved miospores assigned to the NM Biozone of mid late Visean age. The assemblages are diverse and abundant and comprised of *Anaplanisporites* sp., *Apiculiretusispora* sp., *Auroraspora* sp., *Colatisporites decorus*, *Dibolisporites* sp., *Discernisporites micromanifestus*, *Granulatisporites microgranifer*, *Leiotriletes* sp., *Microreticulatisporites* sp., *Punctatisporites* sp., *Raistrickia nigra*, *Triquitrites* spp., *Vallatisporites* sp., and *Waltzispora* sp.

This mid late Visean age does not agree with the previous interpretation from this interval, which was based only on lithologic grounds that correlated it to the continental coal-bearing sediments of the Santa Susana Formation (Oliveira and Matos, 1991).

(F) The succession between 231.1 m and 75.3 m depth is non-palyniferous and is composed of rhyodacite volcanic rocks without interbedded sediments.

(G) This interval, from 75.3 to 3.5 m in depth, consists of dark gray shales interbedded with intermediate-acid and basic volcanic rocks. The shales yielded miospore assemblages assigned to the mid late Visean age (NM Biozone). Four samples (57.0, 33.2, 30.0, 11.0 m) were palyniferous and contained rare specimens of *Raistrickia nigra*. The complete assemblage included *Acanthotriletes* sp., *Anaplanisporites* sp., *Apiculiretusispora* sp., *Auroraspora* sp., *Colatisporites* sp., *Discernisporites micromanifestus*, *Lycospora pusilla*, *Lycospora* sp.,?*Procoronaspora* sp., *Punctatisporites* sp., *Vallatisporites ciliaris*, and *V. vallatus*.

4.2. Reworked palynomorphs in SDJ1 borehole

Together with the Carboniferous miospores described, the palyniferous assemblages also contained a high percentage of reworked palynomorphs (prasinophyte, acritarchs and miospores) ranging from mid Cambrian to early Tournaisian in age from the top of the borehole to a depth of 397.7 m, and in the last seven meters depth, ranging from the mid Cambrian to mid Visean. Reworking is an important signature throughout the borehole and represents a valuable tool for interpreting regional tectonism and the evolution of the OMZ during the Variscan Orogeny.

The reworked material identified in the SDJ1 samples is grouped into six stratigraphic intervals: sub-assemblage 1, middle to (?)upper Cambrian; sub-assemblage 2, Lower to Middle Ordovician (Tremadocian to Darriwilian); sub-assemblage 3, middle to upper Silurian (Homerian to Pridoli); sub-assemblage 4, Lower Devonian (Lochkovian to Emsian); sub-assemblage 5, Upper Devonian (Frasnian to Fammenian); and sub-assemblage 6, lower Carboniferous (Tournaisian).

For each sampled interval (A–G) studied in the borehole, the quantitative composition of reworked acritarchs and miospores recovered is shown in Fig. 4. The long ranging species were discounted in the statistical analysis. A total of 150 specimens were counted for each sample. Each graphic pie diagram in Fig. 4 for the five palyniferous sampled intervals (A, C, D, F, G) shows the average for the in situ assemblage (mid late Visean, Biozone NM and Moscovian Biozone SL), and the reworked sub-assemblages (1 to 6).

The analysis shows that the average percentage of the reworked material ranges between 90 and 96% when compared to the in situ palynomorphs (*ca.* 4–10%). This ratio of in situ to reworked is consistent throughout the borehole. In addition, the percentages relative to each other of the six reworked assemblages are also similar in all of the studied samples.

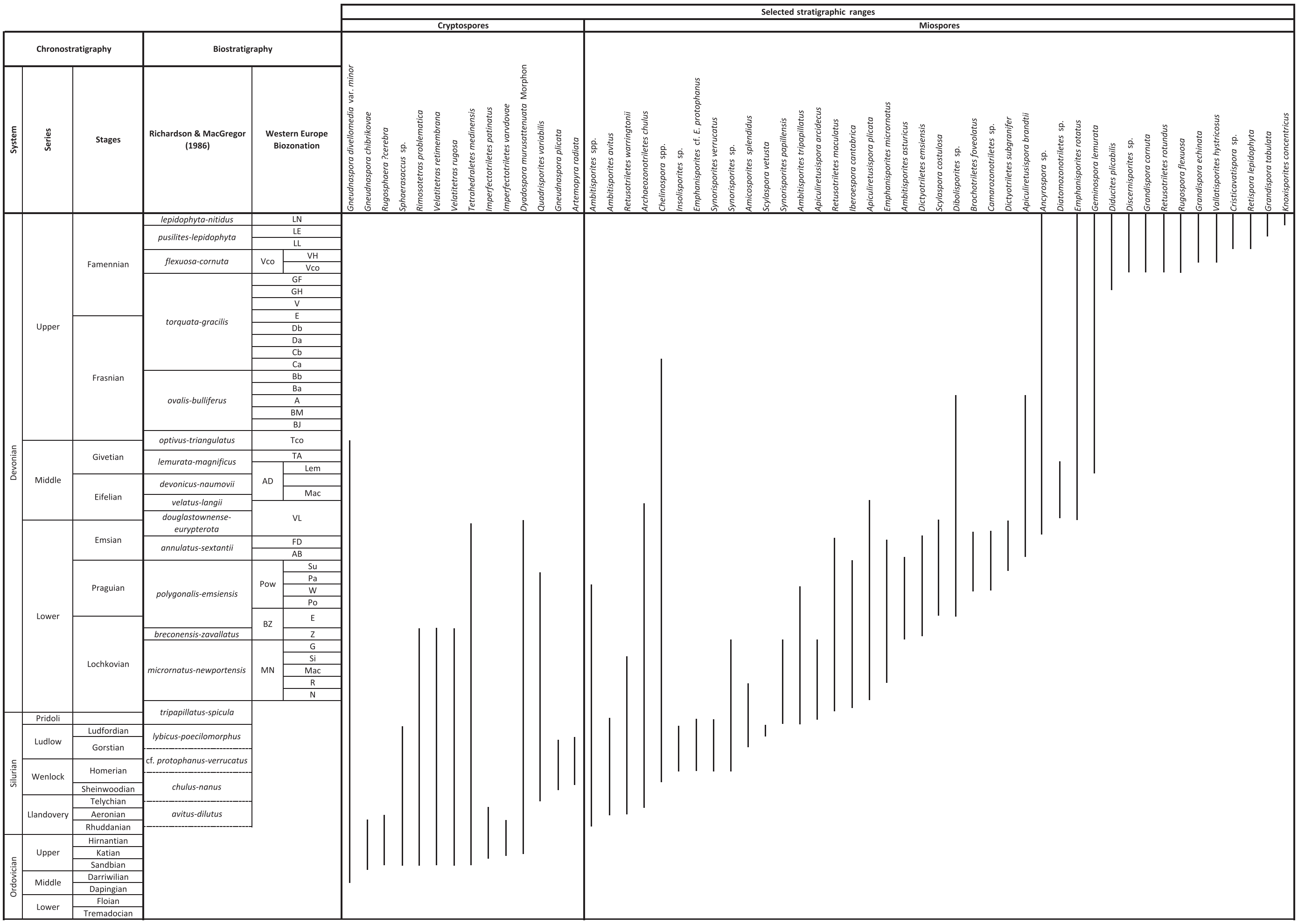
The prasinophytes and acritarchs identified are generally dominated by such genera as *Cymatiosphaera*, *Dictyotidium*, *Dorsennidium*, *Leiosphaeridia*, *Lophosphaeridium*, *Micrhystridium*, *Multiplicisphaeridium*, *Solisphaeridium* and *Veryhachium*. Because of their long stratigraphic range, these genera seldom provide valuable stratigraphic information. However, many of the species are age diagnostic (Downie, 1984; Fensome et al., 1990; McClean and Chisholm, 1996; Molyneux et al., 1996; Le Hérissé et al., 2000; Playford, 2003) (Table 1).

Cryptospore species are also present in small percentages (ca. 0.5%) throughout the borehole. Taxa include *Artemopyra radiata*, *Dyadospora murusattenuata* Morphon, *Imperfectotriletes patinatus*, *Imperfectotriletes vavrdovae*, *Gneudnaspora chibrikovae*, *Gneudnaspora divellomedia* var. *minor*, *Gneudnaspora plicata*, ?*Hispanaediscus* sp., *Quadrisporites variabilis*, *Rimosotetras problematica*, *Rugosphaera* sp., *Rugosphaera* ?*cerebra*, *Sphaerasaccus* sp., *Tetrahedraletes medinensis*, *Velatitetras retimembrana*, and *Velatitetras rugosa* (Plate V). This assemblage indicates source areas with rocks of Early Ordovician to Early Devonian age (Burgess and Richardson, 1995; Steemans et al., 1996; Rubinstein and Vaccari, 2004; Breuer et al., 2007; Vecoli et al., 2011).

Several genera and species of prasinophytes, acritarchs and miospores are also key markers with restricted stratigraphic ranges (Tables 1–3). Although poor preservation of some specimens hinders identification to the species level, positive attribution to the cf. or species level is possible for most of the reworked taxa.

These reworked taxa are placed below in their respective stratigraphic interval, sub-assemblage, and in ascending stratigraphic order.

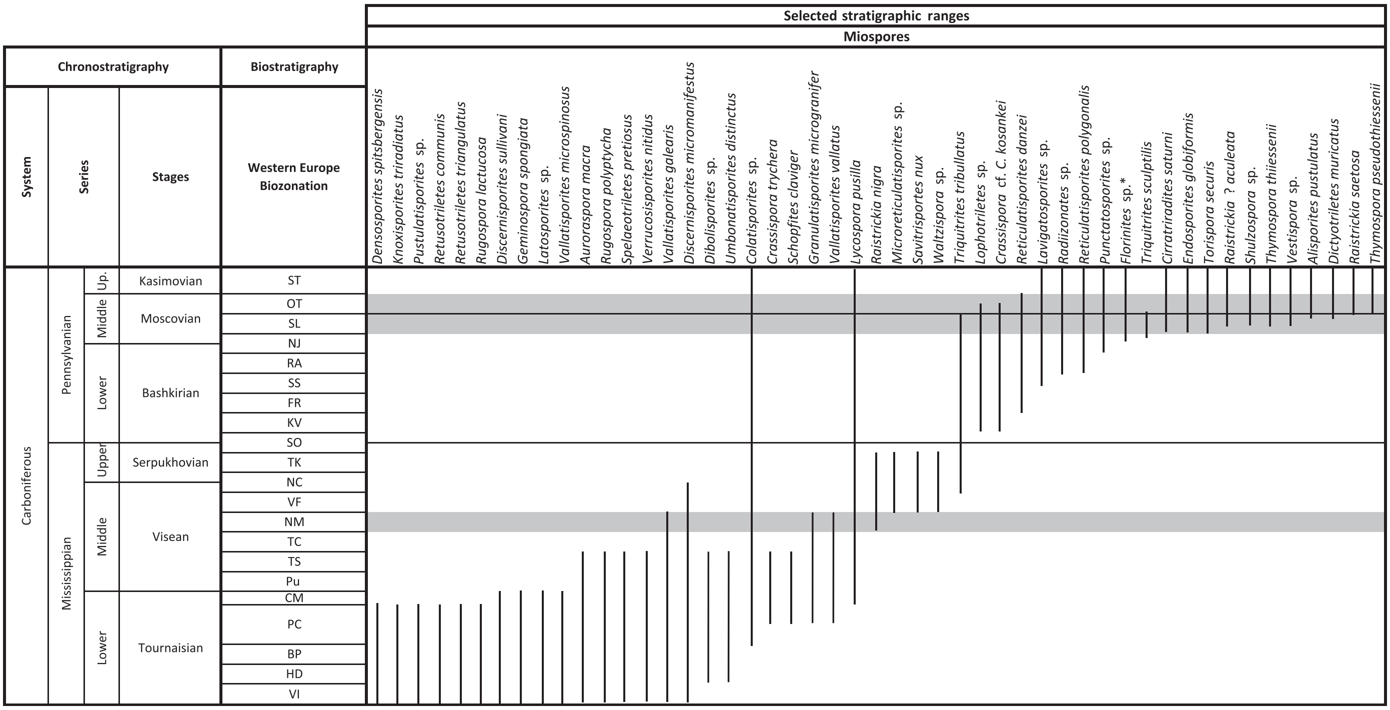
Table 2
Stratigraphic distribution of selected reworked spore (cryptospores and miospore) species recovered from the Ordovician to the Devonian time interval.
The cryptospore distribution is after Richardson and McGregor (1986), Burgess and Richardson (1995), Steemans et al. (1996), Richardson et al. (2001), Rubinstein and Vaccari (2004), Breuer et al. (2007), and Vecoli et al. (2011). Miospore distributions follows Richardson and McGregor (1986), Higgs et al. (1988), and Pereira et al., 2008a, 2008b.



It should also be noted that not all of the listed taxa below are illustrated. For those taxa, a cf. and '(not illustrated)' designation is assigned.

- *middle to (?)uper Cambrian* (sub-assemblage 1) includes the acritarch and prasinophyte taxa *Acanthodiacrodium* cf. *Acanthodiacrodium estonicum*, *Cristallinium* cf. *Cristallinium cambriense*, *Cymatiosphaera* cf. *Cymatiosphaera ovillense*, *Eliasum* sp., *Impluviculus* cf. *Impluviculus multiangularis*, *Retisphaeridium* cf. *Retisphaeridium dichamerum*, *R.* cf. *Retisphaeridium howelii*, *Timofeevia* cf. *Timofeevia phosphoritica* and *Vulcanisphaera* cf. *Vulcanisphaera turbata*.
- *Lower to Middle Ordovician* (sub-assemblage 2) contains the acritarch taxa *Acanthodiacrodium ?costatum* (not illustrated), *A.* cf. *Acanthodiacrodium tadlense*, *Arbusculidium* cf. *Arbusculidium filamentosum*, *Arkonia* sp. (not illustrated), *Coryphidium* spp. (not illustrated), *Cymatiogalea* cf. *Cymatiogalea cristata*, *Polygonium gracile* (not illustrated), *Stelliferidium* sp., *S.* cf. *Stelliferidium trifidum*, *Striatotheca* sp., *Veryhachium* cf. *Veryhachium lairdii*, *Veryhachium trispinosum* "complex", and *Vulcanisphaera* cf. *Vulcanisphaera simplex*, indicative of the *messaoudensis–trifidum* assemblage (Molyneux et al., 2007). Also present are *Actinotodissus* cf. *Actinotodissus longitaleosus*, *Dicrodiacrodium* sp. (not illustrated), and *Schizodiacrodium* cf. *Schizodiacrodium firmum*, assigned to the Darriwillian, as well as *Baltisphaeridium* cf. *Baltisphaeridium hirsutoides* (not illustrated) and *Villosacapsula* cf. *Villosacapsula irroratum*. All of these taxa together, indicate an age interval that ranges from Tremadocian to Darriwillian.
- *middle to upper Silurian* (sub-assemblage 3) comprises *Diexallophasis* cf. *Diexallophasis sanpetrensis*, *Exochoderma* spp. (not illustrated), *Geron* sp., *Micrhystridium stellatum* (not illustrated), *Multiplicisphaeridium ramusculosum*, *Neoveryhachium carminae*, *Pardaminela* sp., *Quadraditum* cf. *Quadraditum fantasticum* (not illustrated), and *Veryhachium* cf. *Veryhachium valiente*. This lower diversity acritarch assemblage indicates a Ludlow age. Miospores present are *Ambitisporites* sp., *Ambitisporites avitus*, *Ambitisporites eslae*, *Amicosporites splendidus*, *Archaeozonotriletes chulus*, *Chelinospora* sp., *Emphanisporites* cf. *Emphanisporites protophanus*, *Insolisporites* sp., *Retusotriletes warringtonii*, *Scylaspora vetusta*, *Synorisporites* sp., *Synorisporites papillensis*, and *Synorisporites verrucatus*, indicating a late Wenlock to Pridoli age.
- *Lower Devonian* (sub-assemblage 4). The acritarch and prasinophyte sub-assemblage includes *Duvernaysphaera* cf. *Duvernaysphaera aranaides* (not illustrated), *Exochoderma* sp. (not illustrated), *Polyedryxium* sp., cf. *Riculasphaera* sp., *Stellinium micropolygonale*, *Umbellasphaeridium ?deflandrei* (not illustrated), and *Veryhachium* cf. *Veryhachium valiente*. The miospores present are *Ambitisporites* sp., *Ambitisporites asturicus*, *Apiculiretusispora arcidecus*, *Apiculiretusispora brandtii*, *Apiculiretusispora plicata*, *Brochotriletes foveolatus*, *Brochotriletes robustus*, *Camarozonotriletes* sp., *Diatomozonotriletes*

Table 3
Stratigraphic distribution of selected reworked and in situ recovered spore assemblages (Carboniferous Period). * corresponds to a pre-pollen.
The distribution is based on Clayton et al. (1977), Streel et al. (1987), Higgs et al. (1988), Clayton (1996), Clayton et al. (2003), and Pereira et al. (2007, 2008a, 2008b).



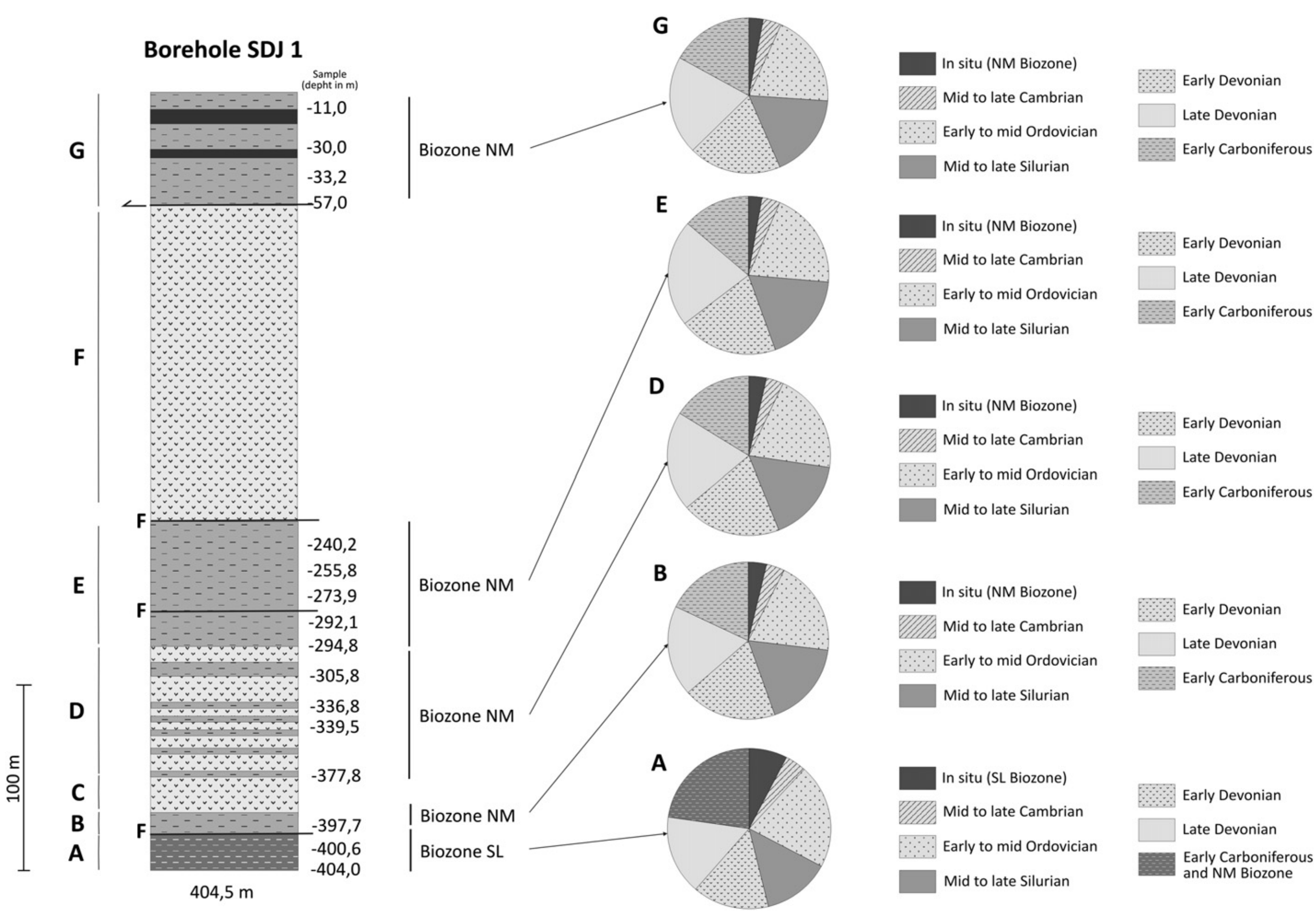


Fig. 4. Statistical data of the in situ and reworked palynomorphs (Log legend as Fig. 3). For each lithologic studied interval (A, C, D, F, G), a circular graphic is presented with the average percentages for the in situ assemblages (mid late Visean, NM biozone and Moscovian Biozone SL biozone) and reworked sub-assemblages (1 to 6).

sp., *Dibolisporites* sp., *Dictyotriletes emsiensis*, *Dictyotriletes subgranifer*, *Emphanisporites micrornatus*, *Iberoespora cantabrica*, *Retusotriletes maculatus*, *Retusotriletes warringtonii*, *Scylaspora* sp., *Scylaspora costulosa*, and *Synorisporites* sp., which, in total, indicate a Lochkovian to Emsian age.

- *Upper Devonian* (sub-assemblage 5) is recognized by the following acritarch taxa: *Craterosphaeridium* sp., *Daillydium* sp., *Gorgonisphaeridium ohioense* (not illustrated), *Multiplicisphaeridium ramusculosum*, *Navifusa bacilla*, *Stellinium comptum*, *Stellinium micropolygonale*, and *Villosacapsula* cf. *Villosacapsula colemanii* (not illustrated), and the prasinophytes *Maranhites brasiliensis* (not illustrated), *Maranhites perplexus*(not illustrated), and *Pterospermella* spp., all of which suggests a Frasnian–Famennian age. Miospores present include *Ancyrospora* sp., *Biornatispora* sp., *Cristicavatispora* sp., *Diducites plicabilis*, *Discernisporites* sp., *Emphanisporites rotatus*, *Geminospora lemurata*, *Grandispora cornuta*, *Grandispora echinata*, *Grandispora tabulata*, *Knoxisporites concentricus*, *Retispora lepidophyta*, *Retusotriletes rotundus*, *Rugospora flexuosa*, and *Vallatisporites hystricosus*. This miospore assemblage indicates a late Famennian age.
- *lower Carboniferous* (sub-assemblage 6) includes the acritarchs *Chomotriletes* sp., *Chomotriletes multivittatus* and *Winwaloeusia* sp., together with the miospores *Auroraspora macra*, *Crassispora trychera*, *Densosporites spitsbergensis*, *Discernisporites sullivani*, *Geminospora spongiata*, *Knoxisporites triradiatus*, *Latosporites* sp., *Punctatisporites irrasus*, *Pustulatisporites* sp., *Retusotriletes communis*, *Retusotriletes triangulatus*, *Rugospora lactucosa*, *Rugospora polyptycha*, *Rugospora ? vieta*, *Schopfites claviger*, *Spelaeotriletes* sp., *Spelaeotriletes pretiosus*, *Spinozonotriletes* sp., *Tumulispora* sp., *Umbonatisporites distinctus*, *Vallatisporites microspinosus*, *Verrucosisporites gibberosus*, and *Verrucosisporites nitidus*, giving an age assignment of Tournaisian (Clayton et al., 1977; Higgs et al., 1988; Pereira et al., 2007, 2008a, 2008b).

The first two samples of the borehole (404.0 m and 400.6 m), which were assigned a mid Moscovian age (SL Biozone), also contain reworked palynomorphs that ranged from the middle Cambrian to the mid Visean. Taking into account this new data and the reworked signature of the Toca da Moura Complex palynomorphs, the most probable source area for these reworked palynomorphs was the Toca da Moura Complex itself. The exposure and erosion of the Toca da Moura Complex during mid Moscovian times provided the reworked Visean palynomorphs together with all the reworked palynomorphs (middle Cambrian to Tournaisian) that were incorporated in the Toca da Moura Complex during previous episodes of exposure and erosion.

The fact that all of the sub-assemblages have a near constant proportion in all of the Toca da Moura Complex samples suggests that the source(s) of the reworked material remained the same and that deposition occurred in a relatively short time. By the final phase of the compressive regime, the Variscan Orogen had already acquired its main structures in the central regions of the Ossa Morena Zone. The regional folds and faults related to this compressive regime were formed and would have exposed at weathering and erosion levels, considerable outcrops formed with the Lower Paleozoic succession from the Ossa Morena and mid late Paleozoic rocks of the South Portuguese Zone. These successions served as the source for the reworked material, and could explain the constant percentages of the reworked sub-assemblages.

4.3. Sample from the SSB Collection of the Geological Museum (Jongeis coal mine)

Sample STS15 from the SSB (Jongeis coal mine) provided a moderately preserved assemblage assigned to the OT Miospore Biozone. Present is the guide species *Thymospora pseudothiessenii* (following Clayton et al., 2003), complemented by such typical mid late Moscovian miospores as *Alatisporites pustulatus*, *Cirratriradites* sp., *Cirratriradites saturni*, *Corbulispora* sp., *Densosporites* sp., *Dictyotriletes muricatus*, *Endosporites* sp., *Florinites* sp., *Leiotriletes* sp., *Raistrickia ? aculeata*, *Raistrickia saetosa*, *Savitrisporites nux*, *Thymospora thiiessenii*, *Triquitrites* sp., *Triquitrites sculptis*, *Triquitrites tribullatus*, *Shulzospora* sp., and *Vestispora* sp. In contrast to the reworked palynomorphs found in the lower levels of the Santa Susana Formation in the SDJ1 samples, the STS15 sample contained only an in situ miospore assemblage.

5. Provenance of the reworked palynomorphs

The volcano-sedimentary rocks of the Toca da Moura Complex are interpreted to have been deposited in an intra-arc basin in close association with the Beja Massif, a magmatic arc installed at the south border of the OMZ during the Late Devonian(?) to Mississippian (Oliveira et al., 1991, 2006).

The ages of the Toca da Moura Complex reworked palynomorphs include microfloras that range from middle Cambrian to Tournaisian. Establishing the link of reworked palynomorph assemblages between source terranes and basins can be very problematic in older mountain chains (Fig. 5). This certainly applies to the Variscan development of the OMZ, which is characterized by several episodes of uplift and erosion during its passive margin phase (Oliveira et al., 1991). These authors described several hiatuses in the stratigraphic record of the OMZ, the first encompassing the upper Cambrian, the second the Upper Ordovician, and the last the Middle Devonian. These hiatuses were attributed to periods of erosion related to the tectonics of global sea-level changes (Oliveira et al., 1991). It is unclear at this stage if these cycles of erosion were the main sources of the reworked palynomorphs in the Toca da Moura Complex, especially for the Lower Paleozoic assemblages.

In the present palynostratigraphic record of the OMZ, reworked palynomorphs appear for the first time in the Toca da Moura Complex (Pereira et al., 2006). Therefore, the ages of the reworked palynomorphs in the Toca da Moura Complex suggest that processes related to varying long and short cycles of erosion contributed sediments to the Toca da Moura Complex basin. The older reworked palynomorphs (middle Cambrian to Early Devonian) can be attributed to long-term global cycles of erosion that are possibly linked to mountain building processes and erosion of mountain chains. Conversely, the reworked Upper Devonian to Tournaisian palynomorphs, together with the Visean reworked palynomorphs, correspond to short cycles of erosion linked to the basin (TMC and SSB) processes formation.

However, the true significance of the reworked palynomorphs in the Toca da Moura Complex can only be understood by taking into account the regional context of the development of the Variscan Orogeny in the OMZ and SPZ. Therefore, the following discussion focuses on linking the possible source units cropping out in the Variscan basement of South Portugal and Spain, to the reworked material identified in the Toca da Moura Complex and Santa Susana Formation and described earlier in terms of the six stratigraphic age intervals.

In the Portuguese part of the OMZ, there is no biostratigraphic data assigned to the middle to late Cambrian. The occurrence of reworked mid to late Cambrian palynomorphs in the Toca da Moura Complex indicates that sedimentary rocks of this age must occur elsewhere in the OMZ. In the Hinojales area of the Spanish part of the OMZ, biostratigraphic data (acritarch microfloras) from the middle Cambrian Umbria-Pipeta Formation were identified by Mette (1989). The assemblage described by Mette (1989) includes *Cristallinium cambriense*, *Cristallinium randomense*?, *Eliasum asturicum*, *Eliasum llaniscum*, *Micrhystridium* spp. and *Timofeevia phosphoritica* which indicate a middle Cambrian age. Part of the Umbria-Pipeta Formation can be correlated, in terms of lithology, with the Portuguese Ossa and Fatuquedo formations in the Barrancos–Estremoz sector (Perdigão et al., 1982; Oliveira et al., 1991; Piçarra et al., 1992a, 1992b; Carvalhosa and Zbyzewski, 1994; Robardet et al., 1998; Piçarra, 2000; Araújo et al., 2006).

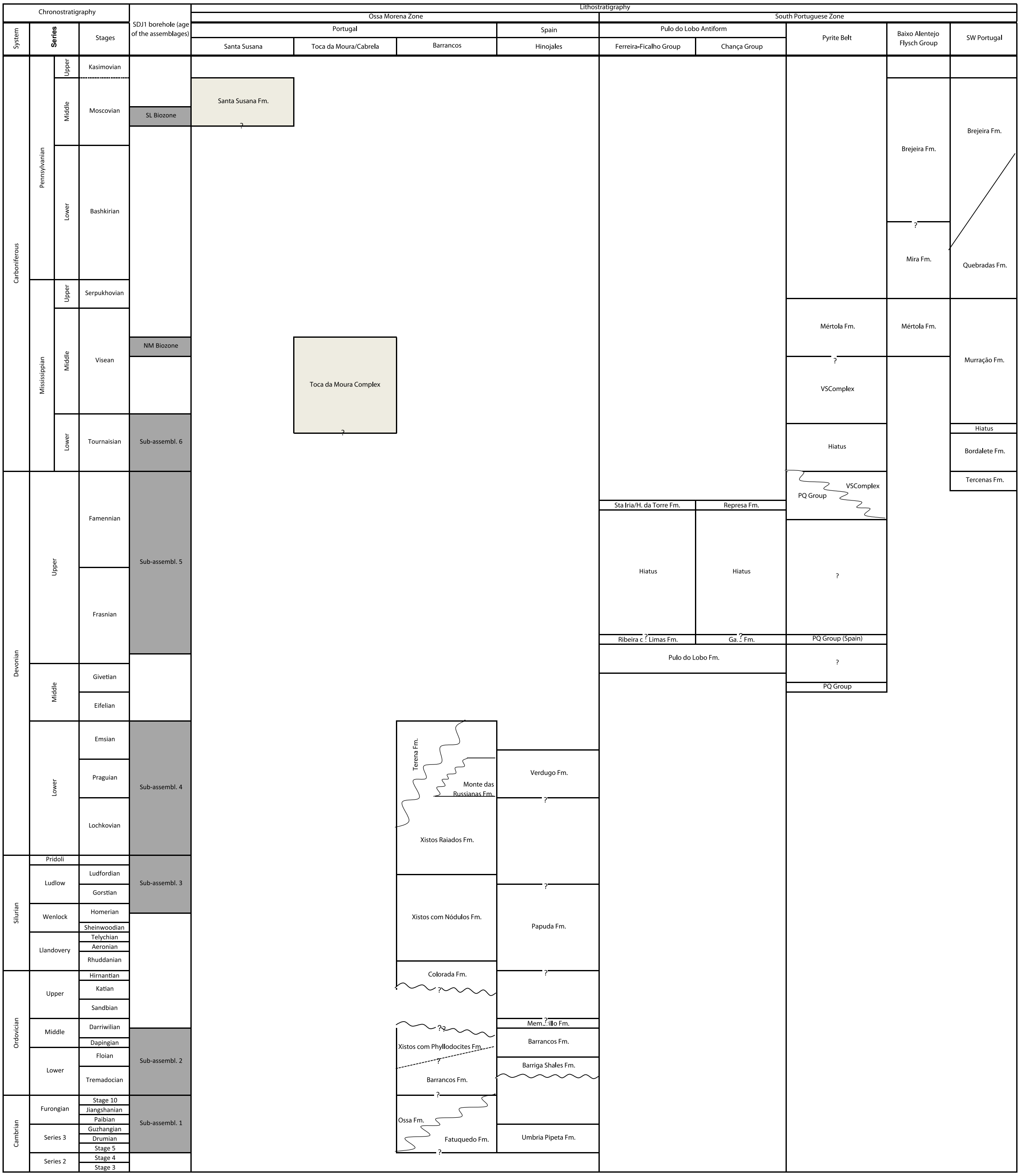


Fig. 5. Stratigraphic distribution of the studied Santa Susana Formation and Toca da Moura Complex and the age of the suggested provenance units (from ZOM and SPZ) for the reworked assemblages attained (Mette, 1989; Oliveira et al., 1991; Robardet et al., 1998; Araújo et al., 2006; Pereira et al., 2006; Pereira et al., 2008a).

The taxa recovered from sub-assemblage 1 – *Acanthodiacrodium* cf. *Acanthodiacrodium estonicum*, *Cristallinium* cf. *Cristallinium cambriense*, *Cymatiosphaera* cf. *Cymatiosphaera ovillense*, *Eliasum* sp., *Impluviculus* cf. *Impluviculus multiangularis*, *Retisphaeridium* cf. *Retisphaeridium dichamerum*, *R.* cf. *Retisphaeridium howelii*, *Timofeevia* cf. *Timofeevia phosphoritica*, and *Vulcanisphaera* cf. *Vulcanisphaera turbata* – are all genera and species that have their first appearance datum (FAD) in the middle Cambrian, but their stratigraphic range can extend into the upper Cambrian. The diagnostic species of the upper Cambrian, *T. phosphoritica* and *V. turbata*, also range into the Tremadoc (Mette, 1989; Palacios, 1997; Albani et al., 2006). Regarding this assemblage, the existence of upper Cambrian acritarchs is inconclusive. As stated in previous papers (Mette, 1989; Albani et al., 2006), the existence of upper Cambrian palynomorphs in the OMZ is still controversial and uncertain.

The middle Cambrian assemblage reported from the Umbria-Pipeta Formation in Spain, came from very rare and thin beds (Mette, 1989). Similar beds could have existed in the Ossa and Fatuquedo formations in Portugal, and could have been eroded. Thus, the reworked sub-assemblage 1, could either come from the Spanish part of the OMZ, or from its correlative Ossa and Fatuquedo formations, in Portugal.

A high percentage (ca. 20%) of the reworked material recovered from Toca da Moura Complex shales, indicates an Early to Middle Ordovician age. The acritarch assemblage indicates a Tremadocian to Darriwillian age. Acritarchs whose stratigraphic range extends into the Tremadoc, such as *Cymatiogalea cristata* and *Vulcanisphaera simplex* (Molyneux et al., 2007) are also present as cf. species in sub-assemblage 2. However, according to Molyneux et al. (2007), *C. cristata* does not extend above the Tremadocian. Moreover, the presence of *Coryphidium* spp., *Stelliferidium* spp., *S.* cf. *Stelliferidium trifidum*, *Veryhachium* cf. *Veryhachium lardii*, and *Veryhachium trispinosum* "complex", demonstrates similarities to sub-assemblage 4 (*messaoudensis–trifidum* assemblage) of Molyneux et al. (2007), which may also indicate a Late Tremadocian age. The presence of *Acanthodiacrodium* cf. *Acanthodiacrodium tadlense*, *Arbusculidium* cf. *Arbusculidium filamentosum* and *Striatotheca* sp. in the reworked assemblage may also suggest a slightly younger age correlated with the basal part of sub-assemblage 5 (*messaoudensis–trifidum* assemblage) indicating the lower base of the Floian stage (Molyneux et al., 2007).

The reworked Ordovician palynomorphs (sub-assemblage 2) in borehole SDJ1 have a regional correlation with the acritarch microflora described from the *Xistos com Phylodocites* Formation, from the Barrancos region (OMZ) in Portugal (Cunha and Vanguestaine, 1988; Borges et al., 2008; Piçarra et al., 2011; Lopes et al., 2012), and from the Barriga Shale Formation in the Cañaveral de León region, in Spain (OMZ) (Mette, 1989; Robardet et al., 1998; Servais and Mette, 2000).

Other taxa found in this sub-assemblage, such as *Acanthodiacrodium* ? *costatum*, *Actinotodissus* cf. *Actinotodissus longitaleosus*, *Dicrodiacrodium* sp. and *Schizodiacrodium* cf. *Schizodiacrodium firmum*, have stratigraphic ranges that extend to the Dapingian and early Darriwilian. This data suggests possible erosion from the middle part of the Ordovician succession from the OMZ. This agrees with the graptolite fauna recovered from the *Xistos com Phyllodocites* Formation, in the Barrancos region (OMZ) in Portugal, which yielded an early Darriwilian age (Piçarra et al., 2011), as well as with the acritarch assemblage identified from the Barrancos Formation in the Cañaveral de León region, in Spain (OMZ), that provided a late Arenig–early Llanvirn age (Mette, 1989; Robardet et al., 1998).

The middle to upper Silurian (sub-assemblage 3) and Lower Devonian (sub-assemblage 4) reworked miospore assemblages recovered can easily be correlated with those assemblages present in the *Xistos com Nódulos*, *Xistos Raiados*, and Terena formations, that are dated as late Wenlock (Homerian) to Emsian based in macro- and microfossils, from the Barrancos region (Portugal), OMZ, respectively (Rigby et al., 1997; Piçarra et al., 1998; Pereira et al., 1999; Piçarra et al., 1999; Piçarra, 2000; Lopes et al., 2009).

Mid Devonian sediments in the OMZ are restricted to the scarce reefal limestones and marls of the Odivelas Formation and Late Devonian age sediments are unknown in the OMZ. This means that one of the cycles of erosion marked by the Late Devonian and early Carboniferous reworked assemblages could have their sources in the South Portuguese Zone, where late Famennian and Tournaisian palynomorph assemblages are very well documented from the Pulo do Lobo Antiform, Iberian Pyrite Belt and the southwest Portugal sector (Pereira et al., 2006, 2007, 2008a, 2008b).

In the Pulo do Lobo Antiform, the flychoid units of the Ferreira–Ficalho (north limb) and Chança (south limb) groups yielded spores and acritachs that range in age from the Givetian to the late Famennian (Pereira et al., 2006).

In the Pyrite Belt, the Phyllite Quartzite Formation, dated early Givetian to late Fammenian, and based on acritarchs and miospores, and the Volcano Sedimentary Complex, dated as late Famennian and mid upper Visean, based on miospores (Oliveira et al., 2004; Pereira et al., 2010), could be the source of Famennian age reworked material.

Reworked Tournaisian miospore assemblages are also known in the Volcanic Sedimentary Complex (Oliveira et al., 2004) and these could also be a source for the Toca da Moura Complex.

The added Visean assemblages in the Santa Susana Formation reworked material may have been derived from the proper Toca da Moura Complex and also from the Mértola Formation turbidites of the Baixo Alentejo Group, in the SPZ.

In the southwest Portugal Sector, the Bordalete Formation, dated as Tournaisian in age based on miospores (Pereira, 1999), could possibly have contributed to the reworked Tournaisian assemblages. The presence of the same species is a common signature in the studied assemblages (Pereira et al., 2006, 2007, 2008a, 2008b).

6. Conclusions

From the study of borehole SDJ1 drilled in the Santa Susana region the following conclusions can be made:

1. The borehole crossed 397.7 m of acidic and basic volcanics and intercalated shales of the Toca da Moura Complex. The shales yielded the miospore *Raistrickia nigra*, a diagnostic species of the NM Biozone of mid late Visean age. The bottom seven meters, composed of tectonically disturbed shales, and ascribed to the Santa Susana Formation (SSF), have an age of mid Moscovian as evidenced by the presence of various miospore index species of Biozone SL.
2. The Toca da Moura Complex appears to have been thrusted over the Santa Susana Formation, as suggested by the tectonized shales at the unit's boundary, together with the reassessment of boreholes Cj and Dj (Andrade et al., 1955), and also geophysics (seismic) data (Fig. 2). This structural interpretation is different from the one proposed by Machado et al. (2012). The presence of Toca da Moura Complex rocks thrusted over the Santa Susana Formation in borehole SDJ1, indicates that the graben structure of the SSB, as suggested by Machado et al. (2012), was not preserved in the Jongeis outcrop. This interpretation implies that compressive Variscan tectonism took place in *post* Santa Susana Formation depositional time, i.e., later than the late Moscovian.
3. One of the most impressive features of the palynological assemblages in borehole SDJ1 is the high percentage of reworked palynomorphs in the studied Toca da Moura Complex and Santa Susana Formation samples:
   - The percentages of the reworked palynomorphs in the Toca da Moura Complex samples do not vary significantly throughout the borehole section. Additionally, the reworked assemblages do not show an inverted stratigraphy.
   - Six reworked palynomorph sub-assemblages of different ages were discriminated: i. middle to (?)upper Cambrian; ii. Lower to Middle Ordovician; iii. middle to upper Silurian; iv. Lower Devonian; v. Upper Devonian; vi. lower Carboniferous.
   - The ages of the reworked assemblages indicate that terrains with exposed sedimentary rocks from mid Cambrian to Tournaisian were being eroded during early Visean times in the provenance regions. In the OMZ sedimentary succession, there are several sections, both in Portugal and Spain, which could have acted as the source (Barrancos sections, in particular the Ossa, Fatuquedo, Barrancos, *Xistos com Phylodocites*, *Xistos com Nódulos*, Xistos Raiados, Monte das Russianas, and Terena formations) and Hinojales (Venta del Ciervo) sections (in particular the Umbría-Pipeta, Barriga, Membrillo, and Papudo formations), for the reworked palynomorphs in the Toca da Moura Complex.
   - Although, comprising minor percentages, the reworked Late Devonian–Tournaisian palynomorphs are important in the interpretation of the development of the Toca da Moura Complex. This reworked assemblage is very close to the age of the Toca da Moura Complex sedimentation, implying a short-term erosion cycle which can be correlated to the Toca da Moura Complex basin processes development. These erosional processes can be related to extensional tectonics affecting areas that are adjacent to the depocentre of the basin. The best candidates for the source areas are the SPZ (Ferreira–Ficalho and Chança groups, Phyllite Quartzite Formation, Volcano Sedimentary Complex,

Mértola and Bordalete formations). This provides further evidence supporting the proximity and connection of the OMZ and SPZ during Late Tournaisian–Visean times.

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References

Albani, R., Bagnoli, G., Bernárdez, E., Gutiérrez-Marco, J.C., Ribecai, C., 2006. Late Cambrian acritarchs from the "Túnel Ordovícico del Fabar", Cantabrian Zone, N Spain. Rev. Palaeobot. Palynol. 139, 41–52.
Almeida, P., Dias da Silva, I., Oliveira, H., Silva, J.B., 2006. Caracterização Tectono-Estratigráfica da Zona de Cisalhamento de Santa Susana (ZCSS) no Bordo SW da Zona de Ossa Morena (ZOM), (Portugal). Resumos VII Congresso Nacional de Geologia, Estremoz, Portugal, pp. 49–53.
Andrade, C., Guerreiro, A., Santos, R., 1955. Estudo por sondagens da região carbonífera do Moinho da Ordem. Commun. Serv. Geol. Portugal XXXVI, 199–255.
Andrade, A.S., Santos, J.F., Oliveira, J.T., Cunha, T., Munhá, J., Gonçalves, F., 1991. Excursão ao Complexo de Beja–S. Cristóvão. Magmatismo orogénico na transversal Odivelas–Santa Susana. Guia de Excursion XI Reunião sobre a Geologia do Oeste Peninsular, Huelva, pp. 47–54.
Araújo, A., Piçarra, J.M., Borrego, J., Pedro, J., Oliveira, J.T., 2006. As regiões central e sul da Zona de Ossa-Morena. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal no contexto da Ibéria. Universidade de Évora, Évora, pp. 151–172.
Borges, M., Pereira, Z., Sá, A., Piçarra, J.M., Ramalho, M., 2008. New records in old material: preliminary data on Floian Acritarchs — a surprising new world in the Nery Delgado Collection at the Geological Museum, Portugal. Abstracts 12th International Palynological Congress (IPC-XII 2008), 8th International Organization of Palaeobotany Conference (IOPC-VIII 2008) Joint Congress, Bonn, 2008, pp. 33–34.
Breuer, P., Al-Ghazi, B., Al-Ruwaili, M., Higgs, K., Steemans, P., Wellman, C., 2007. Early to middle Devonian miospores from northern Saudi Arabia. Rev. Micropaleontol. 50, 27–57.
Burgess, N.D., Richardson, J.B., 1995. Late Wenlock to Early Pridoli cryptospores and miospores from south and south-west Wales — Great Britain. Palaeontogr. Abt. B 236, 1–44.
Carvalhosa, A., Zbyzewski, G., 1994. Notícia Explicativa da folha 35-D (Montemor-o-Novo) à escala 1:50 000. Serviços Geológicos de Portugal, Lisboa, 1-86.
Clayton, G., 1996. Mississippian miospores. In: Jansonius, J., Mcgregor, D.C. (Eds.), Palynology: Principles and applications. American Association of Stratigraphic Palynologists Foundation, 2, pp. 589–596.
Clayton, G., Coquel, R., Doubinger, J., Gueinn, K.J., Loboziak, S., Owens, B., Streel, M., 1977. Carboniferous miospores of Western Europe: illustration and zonation. Med. Rijks Geol. Dienst. 29, 1–71.
Clayton, G., McClean, D., Owens, B., 2003. Carboniferous palynostratigraphy: recent developments in Europe. Abstract 15th International Congress on Carboniferous and Permian Stratigraphy, Utrecht, p. 103.
Cunha, T., Vanguestaine, M., 1988. Acritarchs of the "Xistos com Phyllodocites" Formation, Barrancos region, SE of Portugal. Commun. Serv. Geol. Portugal 74, 66–77.
Domingos, L.C.G., Freire, J.L.S., Silva, F.G., Gonçalves, F., Pereira, E., Ribeiro, A., 1983. The structure of the intramontane Upper Carboniferous Basins in Portugal. The Carboniferous of Portugal. Memórias — Nova Série, 29, pp. 187–194.
Downie, C., 1984. Acritarchs in British stratigraphy. Geological Society of London, Special Report, 17, pp. 1–26.
Fensome, R., Williams, G., Barrs, M., Freeman, J., Hill, J., 1990. Acritarchs and fossil prasinophytes: an index to genera, species and infraspecific taxa. Am. Assoc. Stratigr. Palynol. Found. Contrib. Ser. 25, 1–771.
Fernandes, J.P., 1998. Resultados preliminares del estudio palinológico de la Cuenca de Santa Susana (Alcácer do Sal, Portugal), Estudios palinológicos. Actas XI Simposio de Palinología A.P.L.E., Alcalá de Henares, p. 3.
Fernandes, J.P., 2001. Nuevos resultados del estudio palinológico de la Cuenca de Santa Susana (Alcácer do Sal, Portugal). In: Fombella Blanco, M.A., Fernández González, D., Valença Barrera, R.M. (Eds.), Palinología: Diversidad y Aplicaciones. Trabajos del XII Simposio de Palinología (A.P.L.E.). Universidad de León, León, pp. 95–99.
Gonçalves, F., 1985. Contribuição para o conhecimento geológico do Complexo Vulcano-sedimentar da Toca da Moura. Memórias Academia de Ciências de Lisboa, 26, pp. 263–267.
Gonçalves, F., Carvalhosa, A., 1984. Vol. D' Hommage au géologue. In: Zbyszewski, G. (Ed.), Subsídios para o conhecimento geológico do Carbónico de Santa Susana. Recherche de Civilisations, Paris, pp. 109–130.
Higgs, K., Clayton, G., Keegan, B.J., 1988. Stratigraphic and systematic palynology of the Tournaisian rocks of Ireland. Geol. Surv. Ireland Spec. Pap. 7, 1–93.
Le Hérissé, A., Servais, T., Wicander, R., 2000. Devonian acritarchs and related forms. Cour. Forsch.-Inst. Senckenberg 220, 195–205.
Lopes, G., Pereira, Z., Fernandes, P., Piçarra, J.M., Oliveira, J.T., 2009. Silurian to Lower Devonian palynomorphs from the Barrancos region, Ossa Morena Zone, Portugal — preliminary results. In: Fernandes, P., Pereira, Z., Oliveira, J.T., Clayton, C., Wicander, R. (Eds.), Abstracts CIMPLisbon'09. 2nd Joint Meeting of Spores/Pollen and Acritarch Subcommissions. Algarve University, Faro, pp. 63–68.
Lopes, G., Pereira, Z., Fernandes, P., Matos, J.X., Rosa, D., Oliveira, J.T., 2012. Provenance of the reworked Ordovician Palynomorphs in SDJ1 Borehole — Santa Susana Basin, Ossa Morena Zone, Portugal. In: Eble, C., O'Keefe, J. (Eds.), Abstracts Book. 45th Annual Meeting of AASP and Meeting of CIMP Subcommissions. University of Kentucky/Kentucky Geological Survey, Lexington, pp. 28–29.
Machado, G., Dias da Silva, I., Almeida, P., 2012. Palynology, Stratigraphy and Geometry of the Pennsylvanian continental Santa Susana Basin (SW Portugal). J. Iber. Geol. 38 (2), 429–448.
Martin, F., 1993. Acritarchs: a review. Biol. Rev. 68 (4), 475–538.
Martin, F., Dean, W.T., 1988. Middle and Upper Cambrian acritarch and trilobite zonation at Manuels River and Random Island, eastern Newfoundland. Geol. Surv. Can. Bull. 381, 1–91.
McClean, D., Chisholm, J., 1996. Reworked palynomorphs as provenance indicators in the Yeadonian of the Pennine Basin. Proc. Yorks. Geol. Soc. 51 (2), 141–151.
Mette, W., 1989. Acritarchs from the Lower Paleozoic rocks of the western Sierra Morena, SW-Spain, and biostratigraphic results. Geol. Palaeontol. 23, 1–19.
Molyneux, S.G., Le Hérissé, A., Wicander, R., 1996. Paleozoic phytoplankton. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications — Chapter 16. American Association of Stratigraphic Palynologists Foundation, 2, pp. 493–529.
Molyneux, S.G., Raevskaya, E., Servais, T., 2007. The *messaoudensis–trifidum* acritarch assemblage and correlation of the base of Ordovician Stage 2 (Floian). Geol. Mag. 144 (1), 143–156.
Oliveira, V., Matos, J.X., 1991. Prospecção e reconhecimento de carvões. Sector de Sta. Susana — Mina de Jongeis, Projecto de Sondagem nº SD.J.1. Serviço de Fomento Mineiro e Indústria Extractiva (Internal Report). Direcção-Geral de Geologia e Minas, pp. 1–8.
Oliveira, J.T., Oliveira, V., Piçarra, 1991. Traços gerais da evolução tectono-estratigráfica da Zona de Ossa Morena, em Portugal: síntese critica do estado actual dos conhecimentos. Commun. Serv. Geol. Portugal 77, 3–26.
Oliveira, J.T., Pereira, Z., Carvalho, P., Pacheco, N., Korn, D., 2004. Stratigraphy of the tectonically imbricated lithological succession of the Neves-Corvo Mine region, Iberian Pyrite Belt. Implications for the regional basin dynamics. Miner. Deposita 34, 422–436.
Oliveira, J.T., Relvas, J., Pereira, Z., Munhá, J.M., Matos, J.X., Barriga, F., Rosa, C., 2006. O complexo vulcano-sedimentar de Toca da Moura-Cabrela (Zona de Ossa Morena); Evolução tectono-estratigráfica e mineralizações associadas. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal no contexto da Ibéria. Universidade de Évora, Évora, pp. 181–206.
Oliveira, H., Silva, I.D.D., Almeida, P., 2007. Tectonic and stratigraphic description and mapping of the Santa Susana Shear Zone (SSSZ), the SW border of Ossa Morena Zone (OMZ), Barrancão — Ribeira de S. Cristóvão sector (Portugal): theoretical implications. Geogaceta 41 (3–6), 151–156.
Oliveira, J.T., Relvas, J., Pereira, Z., Munhá, J., Matos, J., Barriga, F., Rosa, C., 2013. O complexo vulcano-sedimentar de Toca da Moura — Cabrela (Zona de Ossa-Morena); evolução tectono-estratigráfica e mineralizações associadas. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal, vol. 1. Escolar Editora, Lisboa, pp. 621–645.
Palacios, T., 1997. Acritarcos del Cámbrico superior e Borobia, Soria: implicaciones bioestratigráficas. In: Grandal d'Anglade, A., Gutiérrez-Marco, J.C., Santos Fidalgo, L. (Eds.), Libro de Resúmenes y Excursiones. XIII Jornadas de Paleontología y V Reunión Internacional Proyecto, PICG, A Coruña, 351, pp. 90–91.
Perdigão, J.C., Oliveira, J.T., Ribeiro, A., 1982. Notícia explicativa da folha 44-B (Barrancos) à escala 1:50 000. Serviços Geológicos de Portugal, Lisboa, 1-52.
Pereira, Z., 1999. Palinoestratigrafia do Sector Sudoeste da Zona Sul Portuguesa. Commun. Inst. Geol. Miner. 86, 25–57.
Pereira, Z., Piçarra, J.M., Oliveira, J.T., 1999. Lower Devonian palynomorphs from the Barrancos region, Ossa Morena Zone, Portugal. Boll. Soc. Paleontol. Ital. 38 (2–3), 239–245.
Pereira, Z., Oliveira, V., Oliveira, J.T., 2006. Palynostratigraphy of the Toca da Moura and Cabrela Complexes, Ossa Morena Zone, Portugal. Geodynamic implications. Rev. Palaeobot. Palynol. 139, 227–240.
Pereira, Z., Matos, J.X., Fernandes, P., Oliveira, J.T., 2007. Devonian and Carboniferous palynostratigraphy of the South Portuguese Zone, Portugal — an overview. In: Pereira, Z., Oliveira, J.T., Wicander, R. (Eds.), Abstracts CIMPLisbon'07. 1st Joint Meeting of Spores/Pollen and Acritarch Subcommissions, LNEG, Lisbon, pp. 111–114.
Pereira, Z., Matos, J.X., Fernandes, P., Oliveira, J.T., 2008a. Devonian and Carboniferous palynostratigraphy of the South Portuguese Zone, Portugal. Commun. Geol. 94, 53–79.
Pereira, Z., Matos, J.X., Fernandes, P., Oliveira, J.T., 2008b. Palynostratigraphy and systematic palynology of the Devonian and Carboniferous Successions of the South Portuguese Zone, Portugal. Mem. Geol. 34, 1–181.
Pereira, Z., Matos, J.X., Fernandes, P., Jorge, R., Oliveira, J.T., 2010. Qual a idade mais antiga da Faixa Piritosa? Nova idade Givetiano inferior para o Grupo Filito-Quartzítico

(Anticlinal de S. Francisco da Serra, Faixa Piritosa). VIII Congresso Nacional de Geologia, Revista Electrónica de Ciências da Terra, 17 (13), pp. 1–4.

Piçarra, J.M., 2000. Estudo estratigráfico do sector de Estremoz-Barrancos, Zona de Ossa Morena, Portugal. (PhD Thesis) Litoestratigrafia e Bioestratigrafia do intervalo Câmbrico Médio?- Devónico Inferior.Universidade de Évora, Évora 1–268.

Piçarra, J.M., Gutiérrez-Marco, J.C., Oliveira, J.T., Robardet, M., Jaeger, H., 1992a. Bioestratigrafia do Silúrico da Zona de Ossa Morena (Portugal–Espanha). In: Gutiérrez-Marco, J.C., Saavedra, J., Rábano, I. (Eds.), Revisão crítica dos dados existentes. Paleozoico Inferior de Ibero-América, 1. Universidad de Extremadura, Badajoz, pp. 118–119.

Piçarra, J.M., Oliveira, V., Oliveira, J.T., 1992b. Paleozóico, Estratigrafia, Zona de Ossa Morena. In: Oliveira, J.T. (Coord.), Carta Geológica de Portugal à escala 1:200 000, Notícia explicativa da folha 8. Serviços Geológicos de Portugal, Lisboa, 17-25.

Piçarra, J.M., Gutiérrez-Marco, J.C., Lenz, A.C., Robardet, M., 1998. Pridoli graptolites from the Iberian Peninsula: a review of previous data and new records. Can. J. Earth Sci. 35, 65–75.

Piçarra, J.M., Le Menn, J., Pereira, Z., Gourvennec, R., Oliveira, J.T., Robardet, M., 1999. Novos dados sobre o Devónico inferior de Barrancos (Zona de Ossa Morena, Portugal). Instituto Tecnologico GeoMinero, Temas Geológico-Mineros, 26, pp. 628–631.

Piçarra, J.M., Pereira, Z., Gutiérrez-Marco, J.C., 2011. Ordovician graptolites and acritarchs from the Barrancos region (Ossa-Morena Zone, South Portugal). In: Gutiérrez-Marco, Rábano, I., García-Bellido, D. (Eds.), Ordovician of the World. Cuadernos del Museu Geominero, 14, pp. 429–439.

Playford, G., 2003. Acritarchs and prasinophyte phycomata; a short course. Am. Assoc. Stratigr. Palynol. Contrib. Ser. 41, 1–39.

Richardson, J.B., McGregor, D.C., 1986. Silurian and Devonian spores zones of the Old Red Sandstone Continent and adjacent regions. Geol. Surv. Can. Bull. 364, 1–79.

Richardson, J.B., Rodriguez, R.M., Sutherland, S.J.E., 2001. Palynological zonation of Mid-Palaeozoic sequences from the Cantabrian Mountains, NW Spain: implications for inter-regional and interfacies correlation of the Ludford/Pridoli and Silurian/Devonian boundaries, and plant dispersal patterns. Bull. Nat. Hist. Mus. 57, 115–162.

Rigby, J.K., Gutiérrez-Marco, J.C., Robardet, M., Piçarra, J.M., 1997. First articulated Silurian sponges from the Iberian Peninsula (Spain and Portugal). J. Paleontol. 71 (4), 554–563.

Robardet, M., Piçarra, J.M., Storch, P., Gutiérrez-Marco, J.C., Sarmiento, G., 1998. Ordovician and Silurian stratigraphy and faunas (graptolites and conodonts) in the Ossa Morena Zone of the SW Iberian Peninsula (Portugal and Spain). In: Gutiérrez-Marco, J.C., Rábano, I. (Eds.), Proceedings 6th International Graptolite Conference and Field Meeting, IUGS Subcommission on Silurian Stratigraphy. Instituto Tecnologico GeoMinero, Temas Geológicos-Mineros, 23, pp. 289–318.

Rubinstein, C., Vaccari, N., 2004. Cryptospore assemblages from the Ordovician/Silurian boundary in the Puna Region, North-West Argentina. Palaeontology 47 (4), 1037–1061.

Santos, J.F., Mata, J., Gonçalves, F., Munhá, J.M., 1987. Contribuição para o conhecimento geológico–petrológico da região de Santa Susana: o complexo vulcano-sedimentar da Toca da Moura. Commun. Serv. Geol. Portugal 73 (1/2), 29–48.

Servais, T., Mette, W., 2000. The messaoudensis–trifidum acritarch assemblage (Ordovician: late Tremadoc–early Arenig) of the Barriga Shale Formation, Sierra Morena (SW-Spain). Rev. Palaeobot. Palynol. 113, 145–163.

Smith, A.H.V., Buterworth, M.A., 1967. Miospores in the coal seams of the Carboniferous of Great Britain. Spec. Pap. Palaeontol. 1, 1–324.

Sousa, J.L., Wagner, R.H., 1983. General description of the Terrestrial Carboniferous Basins in Portugal and History of investigations. In: Sousa, J.L., Oliveira, J.T. (Eds.), The Carboniferous of Portugal. Memórias Serviços Geológicos Portugal, 29, pp. 117–126.

Steemans, P., Le Hérrissé, A., Bozdogan, N., 1996. Ordovician and Silurian cryptospores and miospores from southeastern Turkey. Rev. Palaeobot. Palynol. 93, 35–76.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., Steemans, P., 1987. Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenne-Rhenish regions. Rev. Palaeobot. Palynol. 50, 211–229.

Streel, M., Loboziak, S., Steemans, P., Bultynck, P., 2000. Devonian miospore stratigraphy and correlation with the global stratotype sections and points. In: Bultynck, P. (Ed.), Subcommission on Devonian Stratigraphy. Fossil groups important for boundary definition. Courier Forschungsinstitut Senckenberg, 220, pp. 9–23.

Vecoli, M., Delabroye, A., Spina, A., Hints, O., 2011. Cryptospore assemblages from Upper Ordovician (Katian–Hirnantian) strata of Anticosti Island, Québec, Canada, and Estonia: palaeophytogeographic and palaeoclimatic implications. Rev. Palaeobot. Palynol. 166, 76–93.

Wagner, R., Sousa, M.J.L., 1983. The Carboniferous megafloras of Portugal. A revision of identifications and discussion of stratigraphic ages. In: Sousa, M.J.L., Oliveira, J.T. (Eds.), The Carboniferous of Portugal. Memórias Serviços Geológicos Portugal, 29, pp. 127–152.

Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques—processing and microscopy. In: Jansonius, J., Mcgregor, D.C. (Eds.), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists Foundation, 1, pp. 29–50.