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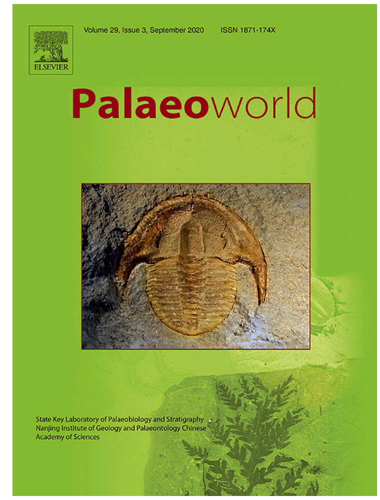

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Late Devonian–Early Carboniferous palynology of the CSDP-2 Borehole in the southern Yellow Sea, China

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Abstract

Late Devonian–Early Carboniferous spores recovered from the depths of 2140 m to 2031.3 m in the CSDP-2 Borehole in the southern Yellow Sea are systematically documented to characterize palynological associations for the stratigraphic correlation. The taxonomic study identifies 96 species belonging to 48 genera, including a re-examination of 33 previously described and indeterminate species. Three palynological associations are established for the Wutong Formation in the CSDP-2 Borehole. In ascending order, these are the late Famennian *Aneurospora asthenolabrata–Geminospora lemurata* (AL) Association from the proposed Guanshan Member, the latest Famennian *Cymbosporites circinatus–Asperispora acuta* (CA) Association from the lower part of the proposed Leigutai Member, and the

Tournaisian *Auroraspora macra–Lophozonotriletes involutus* (MI) Association of the upper part of the latter member. The AL and CA associations are correlated with the palynological assemblages in the Guanshan Member, and those in the lower to middle parts of the Leigutai Member of the Wutong Formation that outcrops in the suburbs of Nanjing and southern Jiangsu. The MI Association is similar to those derived from the uppermost beds of the subsurface Wutong Formation and is dated as early Tournaisian.

Keywords: Spores; Famennian; Tournaisian; South China Block; Yellow Sea; Wutong Formation

1. Introduction

The southern Yellow Sea Basin is located between the Chinese mainland and the Korean Peninsula. It is an extensional basin that was active in the Mesozoic and Cenozoic, although its formation was earlier on a reactivated Mesozoic and Paleozoic basin. According to the lithostratigraphic features of the deposits and their distribution, five secondary tectonic units have been recognized from north to south in the southern Yellow Sea Basin: the Qianliyan Uplift, the Northern Depression, the Central Uplift, the Southern Depression, and the Wulansha Uplift (Fig. 1) (Yao et al., 2005; Hou et al., 2008; Zhang et al., 2013; Pang et al., 2016).

The Central Uplift developed on the basement of Precambrian metamorphosed substrate and experienced four tectonic states; Cambrian–Early Paleozoic craton, the Late Paleozoic–early Middle Triassic Marine platform, the Late Triassic–Paleogene uplift and the Neogene–Quaternary depression (Yao et al., 2005; Hou et al., 2008; Zhang et al., 2013; Pang et al., 2016). The CSDP-2 drilling project penetrated the Central Uplift with about 2843.18 m of section to cover the Lower Triassic to Upper Ordovician marine deposits in the region.

The present paper focuses on the Late Devonian–Early Carboniferous miospores from the CSPD-2 Borehole (Fig. 2) with the aim of better understanding of the Devonian–Carboniferous boundary in the southern Yellow Sea Basin.

2. Geological setting

In the CSPD-2 Borehole, the Wutong Formation, which straddles the Devonian–Carboniferous boundary, unconformably overlies the Lower Silurian Fentou Formation and is overlain by Kinling Formation. The Wutong Formation is 287.9 m thick (2027.1 m–2315 m) and lithologically subdivided into the Guanshan Member in the lower and the Leigutai Member in the upper. The Leigutai Member is 60.7 m thick (2027.1 m–2087.8 m) and characterized by greyish-white, greyish-black, and grey fine- to medium grained quartz sandstones, occasionally intercalated with black muddy silt- and mudstones (Fig. 2). Only the upper part of the Guanshan Member (2087.8 m–2138.4 m), characterized by dark greyish, greyish-black fine silty-sandstones, and silty-mudstones (Fig. 2), was palynologically investigated.

3. Materials and methods

Seventeen core samples were collected from the Wutong Formation of the CSPD-2 Borehole (Fig. 2). Standard HCl–HF–HCl palynological preparation techniques were used with 50 g of rock processed for each sample (Wood et al., 1996). Following demineralization, the organic residues were sieved through a 10 μm mesh. The residues were then mounted in glycerine jelly and the edges of the coverslip sealed with wax.

Only eleven samples from the following depths 2031.3 m, 2034.7 m, 2072.1 m, 2075.6 m, 2081.2 m, 2081.8 m, 2087.3 m, 2123.1 m, 2127.9 m, 2133.3 m and 2138.4 m of the CSPD-2 Borehole are productive in palynomorphs. Because the thermal maturation of the palynomorphs is not very high, TAI 2.5–3 on the scale of Staplin (1969), they were not oxidized during maceration. Palynomorphs were studied and photographed with an Olympus BX51 microscope. All slides are stored in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China.

4. Palynological associations of the Wutong Formation in the CSDP-2 Borehole

The eleven productive samples yield assemblages dominated by trilete spores. Some samples contain minor quantities of acritarchs. Based on the ranges of selected miospore species (Fig. 2), three palynological associations have been established in the Devonian–Carboniferous interval. In ascending order, these are *Aneurospora asthenolabrata–Geminospora lemurata* (AL) Association of the Guanshan Member, the *Cymbosporites circinatus–Asperispora acuta* (CA) in the Leigutai Member and the *Auroraspora macra–Lophozonotriletes involutus* (MI) Association of the uppermost part in the Wutong Formation.

4.1. *Aneurospora asthenolabrata–Geminospora lemurata* (AL) Association

4.1.1. Characterization and composition of the association

Forty-four miospore species belonging to twenty-eight genera were recovered in the AL Association. The characteristic spore taxa are *Aneurospora asthenolabrata*, *Apiculiretusispora hunanensis*, *A*. cf. *granulata*, *A*. sp. A, *Auroraspora evanida*, *Convolutispora fromensis*, *C*. cf. *tuberculata*, *C*. cf. *tenuis*, *Cymbosporites acanthaceus*, *C*. *chinensis*, *C*. *dimerus*, *Densosporites anulatus*, *D*. sp. A, *D*. sp. *B*, *Dictyotriletes cancellothyris*, *Dictyotriletes* sp., *Diducites* cf. *mucronatus*, *D*. sp., *Discernisporites micromanifestus*, *Endosporites* sp., *Euryzonotriletes* sp., *Geminospora lemurata*, *Grandispora gracilis*, *G*. cf. *microseta*, *Grandispora* sp. A, *Grandispora* sp. B, *G*. sp. C, *Granulatisporites adnatoides*, *Knoxisporites literatus*, *K*. *triradiatus*, *Lophozonotriletes* cf. *famenensis*, *Lycospora denticulata*, *Punctatisporites minor*, *Reticulatisporites subalveolatus*, *Retispora lepidophyta*, *Retusotriletes rotundus*, *Spelaeotriletes* sp. A, *Spelaeotriletes* sp. B, *Stenozonotriletes* sp., *Stereisporites* sp. (Figs. 3–5). Among these, *Grandispora* sp. A, *Grandispora* sp. C, *Diducites* sp. and *Apiculiretusispora* spp. are the most common species.

4.1.2. Stratigraphic occurrence

The AL Association is found in the Guanshan Member of the Wutong Formation and ranges from 2123.1 m to 2138.4 m in CSDP-2 Borehole (Fig. 2).

4.1.3. Palynological correlation and age

The present association is approximately correlated to the *Aneurospora asthenolabrata–Radiizonates longtanensis* (AL) Assemblage first described from the Guanshan Member that is exposed in the suburbs of Nanjing, although *Aneurospora asthenolabrata* and *Radiizonates longtanensis* comprise more than 30% of the AL Assemblage in Nanjing (Lu, 1994). *Aneurospora asthenolabrata* is a diagnostic species first recorded from the late Famennian Shaodong Formation in Hunan (Hou, 1982). *Cymbosporites chinensis* and *C. dimerus* were recorded from the lower part of the Leigutai Member in the South China Block (Ouyang and Chen, 1989). *Punctatisporites minor*, *Retusotriletes rotundus*, *Apiculiretusispora hunanensis*, *Grandispora gracilis*, *G.* cf. *microseta*, *Geminospora lemurata* and *Retispora lepidophyta* are all typically the late Famennian miospore species. There are some Devonian–Carboniferous transitional miospore species such as *Auroraspora evanida*, *Convolutispora* cf. *tuberculata*, *Convolutispora* spp., *Discernisporites micromanifestus*, *Knoxisporites literatus* and *K. triradites* in the AL Association. It is noteworthy that some other species such as *Granulatisporites adnatoides*, *Lycospora denticulata* and *Densosporites anulatus* in the AL Association have only been recovered from Carboniferous deposits. However, given the earlier appearance of some lycopods (e.g., protolepidodendrids in the Middle Devonian) in China (Li and Cai, 1979), the presence of their spores in a late Famennian assemblage is not surprising. In all, we conclude that the AL Assemblage should be late Famennian in age.

4.2. *Cymbosporites circinatus–Asperispora acuta* (CA) Association

4.2.1. Characterization and composition of the association

Ninety-eight miospore taxa were identified in the CA associations. They include *Acanthotriletes simplex*, *Anapiculatisporites mucronata*, *Apiculiretusispora nitida*, *A. hunanensis*, *A.* sp. B, *Asperispora acuta*, *A. naumovae*, *Auroraspora macra*, *Baculatisporites* cf. *atratus*, *Baculatisporites*? sp., *Cordylosporites* cf. *papillatus*, *Crassispora* cf. *kosankei*, *Cymbosporites circinatus*, *Densosporites anulatus*, *D.* sp.

B, *Dibolisporites* cf. *coalitus*, *D*. sp., *Dictyotriletes*? sp., *Discernisporites micromanifestus*, *Endoculeosporites gradzinskii*, *Euryzonotriletes*? sp., *Grandispora gracilis*, *Grandispora* cf. *microseta*, *Grandispora* sp. C, *Indotriradites explanatus*, *Knoxisporites literatus*, *Laevigatosporites*? sp., *Lophozonotriletes rarituberculatus*, *Punctatisporites recavus*, *Radiizonates longtanensis*, *Retispora lepidophyta* var. *minor*, *Spinozonotriletes* cf. *senticosus*, *Vallatisporites* cf. *pusillites* and acritarch *Gorgonisphaeridium* sp. (Figs. 5–9). Among these, *Apiculiretusispora nitida* and *Cymbosporites circinatus* are much more abundant. A few specimens of *Cycadopites*? sp. were also observed in the samples of the CA Association. It is possible that the presence of these miospores is resulted from the contamination during palynological sample processing.

4.2.2. Stratigraphic occurrence

The CA Association is found in the Leigutai Member of the Wutong Formation and ranges from 2034.7 m to 2087.3 m in CSDP-2 Borehole (Fig. 2).

4.2.3. Palynological correlation and age

The common appearance of *Apiculiretusispora* and *Retusotriletes* in the CA Association implies an age no younger than latest Devonian as they were mainly produced by Devonian ferns (Balme, 1995). Most miospore species in the CA Association such as *Anapiculatisporites mucronata*, *Aneurospora asthenolabrata*, *Apiculiretusispora gannanensis*, *A. hunanensis*, *A. nitida*, *Asperispora acuta*, *Radiizonates longtanensis*, *Cymbosporites chinensis*, *C. dimerus*, *C. acanthaceus*, *C. circinatus*, *Dibolisporites coalitus*, *Geminospora lemurata*, *Periplecotriletes* cf. *amplectus*, *Punctatisporites recavus*, *Retispora* cf. *lepidophyta* var. *minor* were generally considered as typical late Famennian components in the South China Block (Hou, 1982; Ouyang and Chen, 1987a, 1987b, 1989; Lu, 1994, 1995; Ouyang et al., 2017), although most of them are endemic in China. *Geminospora lemurata* is usually considered as a worldwide indicator for the Givetian–early Frasnian. It was probably produced by *Archaeopteris* or other plants related to the Archaeopteridales (Balme, 1995). However, *Archaeopteris* is often recovered from the Frasnian to Famennian in South China and also in the 2081.2 m–2081.8 m interval of the CSDP-2 Borehole core (Bai et al., 2019; Guo et al., 2019). *Retispora lepidophyta* and *R. lepidophyta* var. *minor* are widely distributed in the upper Famennian of South China. Although the detailed morphology of the present specimens is not as typical as that found in Tibet, Russia and Europe (Kedo, 1957, 1974; Streel, 1967; Clayton et al., 1977; Gao, 1983; Oshurkova, 2003; Liu et al., 2019), their presence is still significant. As specimens are rare, we regard them for reference rather than a leading species of the present assemblages.

There are also a few miospore taxa typical around the Devonian–Carboniferous boundary in the CA Association, such as *Auroraspora macra*, *A. evanida*, *Baculatisporites* cf. *atratus*, *Convolutispora fromensis*, *Cordylosporites* cf. *papillatus*, *Discernisporites micromanifestus*, *Foveosporites* cf. *pellucidus*, *Indotriradites explanatus*, *Knoxisporites literatus*, *Lophozonotriletes rarituberculatus*, *Lycospora* spp., *Spinozonotriletes* cf. *uncatus*, *S.* cf. *senticosus*, *Vallatisporites* cf. *pusillites* in the CA Association. *Crassispora* cf. *kosankei*, *Densosporites anulatus*, *Granulatisporites adnatoides*, *Knoxisporites triradites*, *Reticulatisporites subalveolaris*, *Retusotriletes nigritellus*, *Spinozonotriltes uncatus* and *Densosporites anulatus*, which are considered as typical Carboniferous species in Euramerica, also occur in the CA Association. However, regarding the presence of the index miospores species *Retispora* cf. *lepidophyta* var. *minor* and the dominance of the typical late Famennian components in the CA Association, we are inclined to assign a latest Famennian age to the CA Association. This age designation was corroborated by fossil plants *Archaeopteris* and *Shougangia*? recovered from the 2081.2 m–2081.8 m interval of the CSDP-2 Borehole core (Bai et al., 2019; Guo et al., 2019).

The presence of spinate acritarchs *Gorgonisphaeridium* sp. and *Bosedinia*? sp. (Figs. 7t, 9l, m) in the CA Association indicates a marine depositional environment. There are some similar taxa shared by the AL Association of Guanshan Member and the CA Association of Leigutai Member, such as *Apiculiretusispora hunanensis*, *Cymbosporites chinensis*, *Densosporites anulatus*, *D.* sp. B, *Discernisporites* *micromanifestus*, *Grandispora microseta*, *G*. sp. C, *Knoxisporites literatus*, *Stenonotriletes* sp. and a single *Retispora lepidophya*. The continuous appearance of these miospore taxa in the upper Famennian in the borehole core in the southern Yellow Sea indicates there is no major depositional hiatus in this interval.

4.3. *Auroraspora macra–Lophozonotriletes involutus* (MI) Association

4.3.1. Characterization and composition of the association

The MI Association is characterized by the frequent occurrence of *Lophozonotriletes involutus* (Fig. 9f–i) and *Auroraspora macra*. Other stratigraphically important miospores taxa are *Apiculiretusispora commixta*, *Discernisporites micromanifestus*, *Grandispora echinata*, *Knoxisporites pristinus*, *Leiotriletes microthelis*, *Lycospora* sp. and *Tumulispora rarituberculata* (Fig. 10). The MI Association is tentatively correlated with the *Dibolisporites distinctus–Auroraspora macra* (DM) Assemblage derived from the uppermost part of the Leigutai Member in the Baoying Borehole, central Jiangsu (Ouyang and Chen, 1989. pl. 4), as both palynological assemblages share *Auroraspora macra*, *Discernisporites micromanifestus*, *Crassispora* sp., *Densosporites* sp., and possibly *Schopfites claviger* Sullivan (Ouyang and Chen, 1989, pl. 4, fig. 10) which is somewhat similar to the present *Lophozonotriletes involutus*. The DM Assemblage was correlated with the VI Zone of Western Europe, so we are inclined to assign the MI Association to the early Tournaisian (Ouyang and Chen, 1989).

Some species had a stratigraphic range spanning from the Upper Devonian to Lower Permian. However, the two nominated species for this association, especially *Lophozonotriletes involutus*, usually occurred in Lower Carboniferous deposits. Remarkably, there is a morphological transition between *L. involutus* and the azonate forms with round verrucae such as *Cycloverrutriletes* Schulz, 1964. A few specimens assigned to *L. involutus* here are also quite comparable to *Lophotriletes subverrucosus* (Jushko) ex Kedo, 1963 (p. 50, pl. 3, fig. 79; 45–50 µm) and *Lophotriletes mesogrumosus* Kedo, 1963 (p. 51, pl. 4, fig. 82; 86 µm, possibly with a narrow cingulum). Some of them are cingulate–cavate and are closely similar to those miospores identified as *Archaeozonotriletes famenensis* Naumova (see Kedo, 1963, p. 72, pl. 7, fig. 170; 66 µm) in the same stratigraphic horizon, i.e., the Tournaisian (PM–M zones = VI Zone, Malvina) in the Pripyat Depression, Belarus (Kedo, 1963). Thus, the possibility that one single parent plant species yielded these four species of the Pripyat material should not be ruled out. In addition, the camerate spore *Lophozonotriletes involutus* seems also comparable to *Spelaeotriletes pretiosus* (Playford) Neves et Belt (see Higgs et al., 1988, p. 74, pl. 13, figs. 16–18, PC–CM Zone), but the latter initially described from the Horton Group in Canada is much larger, and the rounded verrucae occasionally bear apiculate spines (average 149 µm, Playford, 1964, p. 19, text-fig. 1a, pl. 4, figs. 5–7).

In short, we conclude that the borehole core yielding the MI Association are most likely early Tournaisian in age.

4.3.2. Stratigraphic ocurrence

The MI Association was recovered from one sample from a depth of 2031.3 m of the CSDP-2 representing the uppermost part of Wutong Formation (Fig. 2).

4.3.3. Palynological correlation and age

Dolostones with a thickness of 13.5 m were reportedly found between 2040.2 m and 2053.7 m of CSDP-2 Borehole and thought to be an equivalent facies change of the Kinling Limestone (Kinling Formation, middle Tournaisian s.l.). If this is true, it implies that the MI assemblage should be recovered from the Gaolishan Formation. Nevertheless, the *Lycospora denticulata–Apiculatisporis pineatus* (DP) Assemblage from the Gaolishan Formation, dated as late Tournaisian–early Visean as discussed by Ouyang and Chen (1987a, 1987b, 1989), is quite different from the present MI assemblage. For example, *Lycospora denticulata* reaches 73% in the association with the typical Tournaisian forms *Claytonispora distincta* and *Diatomozonotriletes* cf. *curiosus* in the Gaolishan Formation, whereas in the MI assemblage, these two forms are absent and only small numbers of *Lycospora* were observed. Thus, we are inclined to consider that the MI Association was recovered from the uppermost part of the

Wutong Formation rather than from the lowermost part of Gaolishan Formation.

To sum up, the MI Association rather appears to be Carboniferous (late Tn1b to Tn2) than Devonian (late Famennian) in age.

5. Conclusions

The palynological investigations of the CSDP-2 Borehole demonstrate that the Devonian–Carboniferous Wutong Formation occurs in the southern Yellow Sea. Three palynological associations are established for the Wutong Formation in the CSDP-2 Borehole. In ascending order, these are the late Famennian *Aneurospora asthenolabrata–Geminospora lemurata* (AL) Association from the proposed Guanshan Member, the latest Famennian *Cymbosporites circinatus–Asperispora acuta* (CA) Association from the lower part of the proposed Leigutai Member, and the Tournaisian *Auroraspora macra–Lophozonotriletes involutus* (MI) Association of the upper part of the latter member. Analogous Hangenberg shales have not been observed in the Famennian outcrop and borehole of the Wutong Formation. It indicates a different palaeoenvironment in South China Block during the Devonian–Carboniferous transition. However, CSDP-2 Borehole shows some intercalated black muddy silt- and mudstones in the Guanshan Member and Leigutai Member of Wutong Formation that would be worth further studying.

6. Remarks on some known and indeterminate miospore species

Aneurospora asthenolabrata (Hou) Lu, 1994

(Figs. 4f, 5z, 8a, b)

1982 *Retusotriletes asthenolabrata* – Hou, p. 87, pl. 1, figs. 5, 7.

1994 *Aneurospora asthenolabrata* (Hou) – Lu, pl. 5, figs. 34–39.

Remarks: The two specimens (59–69 μm) identified here are very similar to *Retusotriletes asthenolabrata* Hou, 1982 (p. 87, pl. 1, figs. 5, 7) from the Shaodong Formation (late Famennian) in central Hunan, in size and morphology. The species has been recorded from the contemporaneous strata in Jiangsu and Jiangxi, South China and from the Qizilaf Formation (Famennian–Tournaisian) in southern Xinjiang (Ouyang et al., 2017).

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan and Leigutai members (2127.9 m, 2081.2 m–2021.8 m).

Apiculiretusispora hunanensis (Hou) Ouyang et Chen, 1987a

(Fig. 3e, h)

1982 *Granulatisporites hunanensis* – Hou, p. 83, pl. 1, figs. 12, 13.

1983 *Geminospora nanus* – Gao, p. 200, pl. 3, figs. 20–23.

1983 *Geminospora parvibasilaris* – Gao, p. 200, pl. 3, fig. 19.

1987a *Apiculiretusispora hunanensis* (Hou) – Ouyang and Chen, p. 39, pl. 8, figs. 15–19.

A partial synonymy was given in Ouyang et al. (2017).

Remarks: The specimens are relatively small (18–37 μm, based on 4 specimens) and assigned to *A. hunanensis* (Hou) (originally 24–34 μm) for their general identity in appearance. It is a common element in late Famennian assemblages in South China.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m, 2133.3 m).

Capillatisporites cf. *multisetus* (Luber) Oshurkova, 2003

(Fig. 10d)

1938 *Azonotriletes multisetus* – Luber in Luber and Waltz, pl. 5, fig. 61.

1941 *Azonotriletes multisetus* – Luber in Luber and Waltz, p. 95, pl. 8, fig. 122a, b.

2003 *Capillatisporites multisetus* (Luber) – Oshurkova, p. 87.

Remarks: The present specimen is closely similar to *Azonotriletes multisetus* Luber in Luber and Waltz, 1941 (p. 95, pl. 8, fig. 122a, b) from Middle Carboniferous strata in Kazakhstan. The latter (40–60 μm) is also characterized by having a subcircular–circular outline, an indistinct trilete mark, and remarkably short and very tiny hair-like spines closely spaced on exine surface, up to 100 along the equatorial margin. Oshurkova (2003, p. 87) transferred the species to genus *Capillatisporites* Sivertseva. However, this genus seems hard to differentiate from the genus *Apiculatasporites* Ibrahim as they have a similar ornamentation, as noted by Jansonius and Hills, 1976.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, the uppermost layer of Leigutai Member (2031.3 m).

Apiculiretusispora sp. A

(Fig. 3m–p)

Remarks: Among the known species under genus *Apiculiretusispora* (Oshurkova, 2003; Ouyang et al., 2017), the present species is quite similar to *Apiculiretusispora plicata* (Allen) Streel, 1967 (p. 33, pl. 2, fig. 31) which has also been recorded from the Upper Devonian in China, however, it differs from the latter in having distal linear processes.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m).

Apiculiretusispora sp. B

(Fig. 6r)

Remarks: The present specimen differs from the more than 40 known species assigned to this genus, mainly from the Lower–Middle Devonian of China (Ouyang et al., 2017), in having a characteristic baculiform ornamentation. It differs from some *Baculatisporites* species, such as *B. atratus* (Naumova) Lu, 1999, in having perfect equatorial arcuate ridges and a membranous labra.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2075.6 m).

Asperispora acuta (Kedo) Van der Zwan, 1980b

(Fig. 9n, r–t, t')

1963 *Archaeozonotriletes acutus* – Kedo, p. 71, pl. 7, fig. 167.

1963 *Acanthotriletes* aff. *ignotus* – Kedo, p. 41, pl. 2, fig. 47.

1980b *Asperispora acuta* (Kedo) – Van der Zwan, p. 227, pl. 13, figs. 1, 4.

Remarks: The present specimens are similar to *Acanthotriletes* aff. *ignotus* Kedo, 1963 (p. 41, pl. 2, fig. 47). According to the original description of *Acanthotriletes ignotus* Kedo, 1957 (p. 17, pl. 1, fig. 18), the holotype of this species is an azonate spore, ca. 66 µm in diameter, with robust (biform) coni ornamentation. Kedo (1963) characterized *A*. aff. *ignotus* as "the exine dense, with (equatorially) thickened margin." The line drawing in Kedo shows a well-developed cingulum. We thus conclude that *A*. aff. *ignotus* should not be assigned to *A*. *ignotus*, and that it is a synonym of another species, i.e., *Archaeozonotriletes acutus* Kedo 1963 (p. 71, pl. 7, fig. 167; 60 µm). We agree with the separation of *Asperispora* from the *Densospores* (broad sense) by Staplin and Jansonius (1964). *Asperispora acuta* is known from the upper Famennian–Tournaisian of South China Block and southern Tibet (Lu, 1994; Ouyang et al., 2017, p. 335, pl. 33, figs. 1–5).

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m–2081.8 m).

Baculatisporites cf. *atratus* (Naumova) Lu, 1999

(Fig. 7e)

1953 *Lophotriletes atratus* – Naumova, p. 123, pl. 18, fig. 17.

1999 *Baculatisporites atratus* (Naumova) – Lu, p. 48, pl. 4, figs. 18–21.

Remarks: The specimen (35 µm) is identified as *Baculatisporites atratus*, which was first recorded from the Famennian of the Russian Platform (Naumova, 1953, p. 123, pl. 18, fig. 17). However, the bacula in the Russian specimen are much shorter than in the present specimen and the same species identified by Lu L.C. from the Devonian–Carboniferous transition in Northern Xinjiang. Consequently, the specific identification is tentative.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2075.6 m).

Baculatisporites sp.

(Fig. 8m, m')

Remarks: The present specimen appears similar to *Raistrickia corynoges* Sullivan as identified by Byvsheva and Umnova (1992, p. 529, pl. 1, fig. 20) from the Lower Carboniferous (M Zone) of the Russian Platform. However, the latter spore differs in being larger (ca. 80 µm including bacula) and with much longer bacula (15–16 µm in length). *Raistrickia corynoges*, as illustrated in Clayton et al., 1977 (pl. 7, fig. 7; Tn3) shows a long baculate-spinate ornamentation.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m, 2081.8 m).

Convolutispora cf. *tuberculata* (Waltz) Hoffmeister et al., 1955

(Fig. 3s)

1938 *Azonotriletes tuberculatus* – Waltz in Luber et Waltz, p. 12, pl. 1, fig. 12.

1941 *Azonotriletes tuberculatus* – Waltz in Luber et Waltz, p. 34, pl. 2, fig. 22.

1955 *Convolutispora tuberculata* (Waltz) – Hoffmeister et al., p. 384.

Remarks: The present specimen (44 µm in diameter) is somewhat similar to the one recorded from the Lower Carboniferous in Russia (Luber et Waltz, 1941, pl. 2, fig.

22; Oshurkova, 2003) but differs in its small size (44 μm) in comparison with the size of 50–90 μm of the latter. Here we assign the present specimen to *Convolutispora* following Hoffmeister et al. (1955) rather than to *Verrucosisporites* Potonié et Kremp, 1955.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2133.3 m).

Cordylosporites cf. *papillatus* (Naumova) Playford in Playford and Satterthwaitt, 1985

(Fig. 6s, t)

1938 *Aptera papillata* – Naumova, p. 27, pl. 3, fig. 2.

1971 *Reticulatisporites papillatus* (Naumova) – Playford, p. 31, pl. 10, figs. 11, 12.

1985 *Cordylosporites papillatus* (Naumova) – Playford and Satterthwait, p. 145, pl. 6, figs. 8–10.

Remarks: Two poorly preserved specimens are illustrated. However, the unique mushroom-like processes on the equatorial contour of present specimens allow a potential identification as *Cordylosporites papillatus* (Playford and Satterthwait, 1985, p. 145, pl. 6, figs. 8–10). It should be noted that the same species has also been recovered from Upper Devonian strata in Jiangsu (Lu, 1994, 1995) and Hunan, though those are smaller (50–67 μm) compared to the present specimens (65–91 μm).

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2087.3 m).

Densosporites sp. A

(Fig. 4d, e)

Remarks: Our specimens differ from other known species of the genus (Smith and Butterworth, 1967; Ouyang et al., 2017) in having a granulate central body. *Densosporites* *granulosus* Kosanke, 1950 (p. 32, pl. 6, fig. 8) recorded from Pennsylvanian of Illinois differs from the present species in its larger size (45–56 μm), and in particular, by having a relatively thicker cingulum "with minor spine-like projections" along the equatorial margin and in the absence of trilete labra.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m, 2133.3 m).

Densosporites sp. B

(Figs. 3r, 4t, 7j)

Remarks: By their characteristic spinae in distal and equatorial surface, the present specimens distinguish themselves from all known species classified as Densospores (e.g., Staplin and Jansonius, 1964) and Densosporites.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2138.4 m, 2127.9 m) and Leigutai Member (2087.3 m).

Dibolisporites sp.

(Fig. 6j, n–p)

Remarks: The specimens are somewhat similar to *Claytonispora distincta* (Clayton) Playford, 1976 (see Clayton et al., 1977, pl. 5, fig. 9, VI Subzone; pl. 7, fig. 6, CM Zone; Ouyang et al., 2017, p. 220, pl. 105, figs. 3, 11), however, they differ from the latter in having much more and rather robust spinae along the periphery and on the distal surface.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2034.7 m).

Diducites cf. *mucronatus* (Kedo) Van Veen, 1978

(Fig. 5i)

Remarks: The present specimen appears somewhat similar to *D. mucronatus* Van Veen (1980, p. 275, pl. 3, fig. 8; pl. 4, figs. 5, 7; pl. 5, figs. 1–6) from the Late Famennian in southern Ireland. However, the exine of the latter often displays a distinct limbus and a microspinate ornamentation, which is almost absent along the periphery. Moreover, the central body of the latter appears proportionally smaller and less darkened. Thus we prefer to tentatively identify our spores as *D. mucronatus*.
Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m).

Diducites sp.
(Fig. 5a–h)

Remarks: Present specimens share similar size and sculpture of exoexine with *Diducites mucronatus* (Kedo) emend. Van Veen, 1980 (p. 275, pl. 3, fig. 8; pl. 4, figs. 5, 7; pl. 5, figs. 1–6) from the Famennian of southern Ireland, however, they differ by having more distinct spinose ornaments on the exoexine surface and the equatorial margin, the relatively larger and darker central body (endexine) as well as in the usual absence of an equatorial limbus.
Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m, 2133.3 m).

Discernisporites micromanifestus (Hacquebard) Sabry et Neves, 1971
(Figs. 5j, 7d, 8v, y, z, 10p)

1957 *Endosporites micromanifestus* – Hacquebard, p. 317, pl. 3, fig. 18.
1963 *Endosporites micromanifestus* – Playford, p. 652, pl. 93, figs. 17, 18.
1963 *Hymenozonotriletes granulatus* – Kedo, p. 63, pl. 5, figs. 125–127.
1971 *Discernisporites micromanifestus* (Hacquebard) – Sabry and Neves, p. 1445, pl. 3, fig. 11.
1971 *Endosporites micromanifestus* – Playford, p. 52, pl. 17, fig. 17.

Remarks: The present specimens (36–48 μm) resemble the type specimen from the Tournaisian Horton Group in Nova Scotia, Canada, although the latter is larger (58–100 μm).

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m–2081.8 m).

Endoculeosporites gradzinskii Turnau, 1975

(Fig. 7a–c)

Remarks: The present specimens differ from the species assigned to *Auroraspora* (see Van der Zwan, 1980a, 1980b; Oshurkova, 2003) in having characteristic papillae on the exoexine.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2087.3 m).

Endosporites sp.

(Fig. 5x)

Remarks: The present specimen is morphologically comparable to *Grandispora velata* (Eisenack) Playford, 1971 from the Givetian. However, it differs from the latter in having a velum with an equatorial limbus, a more robust sculpture, as well as a smaller central body. It also differs from both *Endosporites formosus* Kosanke, 1950 and *E. globiformis* (see Ouyang et al., 2017, pp. 596–597) as well as other species of the same genus by the characteristic sculpture.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2133.3 m).

Foveosporites cf. *pellucidus* Playford et Helby, 1968

(Fig. 8g, k)

1968 *Foveosporites pellucidus* – Playford and Helby, p. 111, pl. 10, figs. 2–6.

1993 *Foveosporites* cf. *pellucidus* – He and Ouyang, pl. 2, fig. 1.

Remarks: The present specimens are 48–53 μm in diameter and quite similar to those recorded from the lower part of the Xihu Formation (late Famennian) in western Zhejiang (He and Ouyang, 1993), although the species was first recovered from Carboniferous deposits in Australia.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m–2081.8 m).

Grandispora sp. A

(Fig. 4u–w)

Remarks: The present specimens are somewhat similar to *Grandispora senticosus* (Ischenko) Playford, 1963. However, these specimens are from the Tournaisian of the Donets Basin and the line drawings in Ischenko (1956, p. 87, pl. 16, fig. 200) show that it is larger (67–70 μm) and has a darker central body and more spinae rather than coni along the periphery.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2133.3 m).

Grandispora sp. B

(Fig. 4p)

Remarks: The morphological feature of the present species is somewhat similar to that of *Dibolisporites echinaceus* (Eisenack) Richardson, recovered from Eifelian–Givetian in Canada and *Dibolisporites spinotuberosus* (Luber) Ouyang from the Visean of Kazakhstan (Luber, 1955) and Xinjiang, China (Ouyang et al., 2003) respectively. However, our specimens differ from species of *Dibolisporites* in having internally thickened cingulum and larger biform conic sculpture.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m).

Grandispora sp. C

(Figs. 4g, z, 7o–s, 9c, d)

Description: Triangular in equatorial outline with rounded or slightly acute corners, 57–66 µm in diameter (based on ten specimens, spines included), holotype 66 µm; trilete rays with distinct labra, 1.5–4 µm wide, extending to the inner margin of cingulum, occasionally open and forming an inner triangular transparent region (Fig. 7s); equatorial cingulum ca. 4–6 µm wide, sometimes the inner boundary of the central body is invisible, thus appearing to be a specimen of *Crassispora*; exine (cingulum excluded) thin, secondary folds may present, at least distally, and equatorially ornamented with small and short spines, mostly ≤ 2 µm in diameter and height, occasionally a few coni coalesce at their bases, coni ca. 20 in number along equatorial margin, moderately dense on distal surface. Yellowish-brown to brownish dark in color.

Comparison: The new species differs from other known species assigned to *Grandispora* and *Crassispora* (Ouyang et al., 2017) in having small spines mixed with coni, irregularly distributed along the equatorial outline.

Type locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2087.3 m, 2081.2 m–2081.8 m, 2127.9 m).

Knoxisporites pristinus Sullivan, 1968

(Fig. 10r)

1968 *Knoxisporites pristinus* Sullivan, p. 123, pl. 27, figs. 1–5.

Remarks: The present specimen is very similar to the species illustrated from the

Schopfites claviger–Auroraspora macra (CM) Zone (Tn2–3) of Western Europe (Clayton et al., 1977, pl. 7, fig. 16; ca. 88 μm) except that they are a little larger (102 μm).

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; the uppermost layer of the Wutong Formation (2031.3 m).

Lophozonotriletes involutus Kedo, 1963

(Fig. 10f–i)

1963 *Archaeozonotriletes famenensis* Naumova – Kedo, p. 72, pl. 7, fig. 170.

1963 *Lophotriletes mesogrumosus* – Kedo, p. 51, pl. 4, fig. 82.

1963 *Lophozonotriletes involutus* – Kedo, p. 89, pl. 10, fig. 249.

1963 *Lophozonotriletes subverrucosus* – Jushko in Kedo, p. 50, pl. 3, fig. 19.

Remarks: These specimens are so identified because they share transitional features between *Azonotriletes*/*Zonotriletes* and *Cavatitriletes*/*Acavatitriletes*. For instance, Fig. 10f is an azonate spore. It could be ascribed to the genus *Cycloverrutriletes* Schulz from Triassic, if it was solitarily observed. However, the majority of the present specimens show cingulate-zonate or cavity-like characters (Fig. 10g, h). Therefore, it is improper to use that generic name. On the other hand, we notice that a similar phenomenon does exist in Kedo (1963), e.g., the azonate spore is similar with *Lophotriletes subverrucosus* Jushko in Kedo (1963, p. 50, pl. 3, fig. 19; 45–50 μm) or *Lophotriletes mesogrumosus* Kedo, 1963 (p. 51, pl. 4, fig. 82; 86 μm). While the spore on Fig. 10h can be compared with *Lophozonotriletes involutus* Kedo (1963, p. 89, pl. 10, fig. 249; 79 μm) or *Archaeozonotriletes famenensis* Naumova, 1953 ex Kedo (1963, p. 72, pl. 72, pl. 7, fig. 170; 66 μm). It is noteworthy that just like the here identified taxon, the possibility of these 3–4 taxa derived from one single parent plant species population could not be excluded entirely.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, the uppermost Leigutai Member (2031.3 m).

Punctatisporites minor (Ouyang et Chen) Ouyang in Ouyang et al., 2017
(Fig. 3a)

1987a *Trimontisporites minor* – Ouyang and Chen, p. 25, pl. 1, fig. 8.
1994 *Trimontisporites minor* – Lu, pl. 1, fig. 7.

Remarks: Present specimen is closely similar to *Trimontisporites minor* Ouyang et Chen, 1987a (21–31 µm), which was first recorded from the lower part of the Leigutai Member (late Famennian) in Jiangsu. *Punctatisporites micropalmipedies* Zhou identified by Lu L.C. (see Ouyang et al., 2017, pl. 4, fig. 9) from the same horizon at Longtan in Nanjing suburbs. The present specimen falls into a similar size range as *P. micipalmipedites* Zhou, 1980 (p. 16, pl. 1, figs. 4, 5; 32–38 um). However, the latter is from the Early Permian Upper Shihhetse Formation in Shandong (age updated by Wu et al., in press) and is distinguished by its slender labra with three thick bifurcations.
Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2138.4 m).

Radiizonates longtanensis Lu, 1994
(Fig. 8r–t)

1994 *Radiizonates longtanensis* – Lu, p. 174, pl. 4, fig. 20; pl. 5, figs. 10–16.

Remarks: The specimens (46–52 µm) are identified as *Radiizonates longtanensis* Lu, 1994 by their characteristic cingulum with an inner radiate fish fin-bone like structure and other features such as the robust labra. This species has been recorded from the upper Famennian–Tournaisian in Jiangsu and Hunan (Lu, 1994; Ouyang et al., 2017, p. 501, pl. 60, figs. 1–4).
Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m–2081.8 m).

Reticulatisporites subalveolaris (Luber) Oshurkova, 2003

(Fig. 3v)

1938 *Azonotriletes subalveolaris* – Luber in Luber and Waltz, p. 25, pl. 5, fig. 72.

1941 *Azonotriletes subalveolatus* – Luber in Luber and Waltz, p. 100, pl. 9, fig. 132.

2003 *Reticulatisporites subalveolaris* (Luber) – Oshurkova, p. 102.

Remarks: The present specimen (60 μm in diameter) is quite similar to *R. alveolatus* Luber in Luber and Waltz (1938, pl. 1, fig.10) and Luber and Waltz (1941, p.33, pl. 2, fig. 21) Oshurkova, 2003. However, the latter is 120–140 μm in diameter and much larger than the present specimen. Thus, we are inclined to assign it to *R. subalveolaris* (Luber) Oshurkova, 2003, which was described as 50–90 μm in size.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m).

Retusotriletes nigritellus (Luber) Foster, 1979

(Fig. 8c, d)

1941 *Azonotriletes nigritellus* – Luber, p. 53, pl. 12, fig. 18.

1979 *Retusotriletes nigritellus* (Luber) – Foster, p. 30, pl. 1, figs. 7, 16.

A partial synonymy was given in Foster (1979).

Remarks: The present specimens are very similar to *Azonotriletes nigritellus* Luber (in Luber and Waltz, 1941, p. 53, pl. 12, fig. 18) from the Upper Carboniferous in the Kuznetsk Basin, which is characterized by having a subcircular outline, a short trilete mark with a subtriangular darkened area, and are 30–40 μm in diameter. Foster (1979, p. 30, pl. l, figs. 7, 16) correctly transferred the species to *Retusotriletes*.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2081.2 m–2081.8 m).

Spelaeotriletes sp. A

(Fig. 5s–w)

Remarks: The present specimens share features of both *Aratrisporites* and *Retispora*. It is somewhat similar to *Aratrisporites saharaensis* Clayton et Owens from the Visean of Libya (Loboziak et al., 1986; Clayton, 1996, pl. 2, fig. 7), however, the latter differs in having a thicker exoexine with a dense ornamentation of coni/grana and in size (ca. 82 μm).

Type locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2127.9 m–2138.4 m).

Spinozonotriletes cf. *senticosus* (Ischenko) Playford, 1963

(Fig. 7f, g)

1963 *Spinozonotriletes senticosus* (Ischenko) – Playford, p. 657, pl. 4, fig. 20; pl. 5, figs. 10–16.

Remarks: The identified specimens are 60–65 μm (spinae included) in diameter. Spinae are no more than 4–7 μm long and 20–30 in number along the equator. These specimens are somewhat similar to those described by Playford (1963, p. 657). In the comparison of Playford (1963), he pointed out that *S. uncatus* may be conspecific with *Acanthozonotriletes senticosus* Ischenko, 1956 (p. 87, pl. 16, fig. 200), which is smaller (67–70 μm), but otherwise very similar. Our specimens are more similar to *A. senticosus* both in size and ornamentation; however, whether they have a central body or not is hard to ascertain, thus the specific identification is tentative.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2087.3 m).

Spinozonotriletes cf. *uncatus* Hacquebard, 1957

(Fig. 4y)

1957 *Spinozonotriletes uncatus* – Haquebard, p. 316, pl. 3, figs. 8–10.

1977 *Spinozonotrilees uncatus* – Clayton et al., pl. 9, fig. 21.

Remarks: Present two specimens (65–70 μm, spinae included) are similar to *Spinozonotriletes uncatus* from the Mississippian Horton Group, Nova Scotia, Canada. It was also reported by Clayton et al., 1977 (pl. 9, fig. 21; 100 μm) from TC Zone of Western Europe, which is possibly Visean in age (see Playford, 1963). However, the trilete labra in present specimens are very unclear due to darkening of the spore body. Thus, the present identification is tentative. *Hymenozonotriletes microincisus* Kedo, as shown in Kedo, 1976 (pp. 217–220, pl. 29, fig. 74), which was recorded from Middle Devonian to the upper part of Eifelian in Prebaltica differs from the present specimens by having a complete membranous zona and distinct trilete labra.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2138.4 m).

Stenozonotriletes sp.

(Figs. 4b, c, 6q)

Remarks: The specimen described here is distinguished from other species assigned to the same genus in having a narrow irregular cingulum of variable thickness and tightly spaced small grana on the exine.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Guanshan Member (2123.1 m, 2138.4 m) and Leigutai Member (2087.3 m).

Vallatisporites cf. *pusillites* (Kedo) Dolby et Neves, 1970

(Fig. 6k)

1963 *Hymenozonotriletes pusillites* – Kedo, p. 66, pl. 6, figs. 138–142.

1970 *Vallatisporites pusillites* (Kedo) – Dolby and Neves, p. 639, pl. 2, figs. 1–4.

Remarks: The poorly preserved specimen is 48 μm in diameter and somewhat similar to *Hymenozonotriletes pusillit*es Kedo, 1963 (p. 66, pl. 6, figs. 138–142; 45–60 μm). The latter is widely distributed in the upper Famennian of the world and often co-occurs with *Retispora lepidophyta*.

Locality and horizon: Southern Yellow Sea, CSDP-2 Borehole; Wutong Formation, Leigutai Member (2087.3 m).

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Fig. 1. Tectonic outline map of the southern Yellow Sea Basin and the location of the CSPD-2 Borehole.

Fig. 2. Lithology of the Late Devonian–Early Carboniferous Wutong Formation at the CSDP-2 Borehole and vertical distribution of selected miospores

Fig. 3. Selected miospores from the AL Association in the southern Yellow Sea, China. Specimens are arranged by depth. (a) *Punctatisporites minor* (Ouyang et Chen) Ouyang in Ouyang et al., 2017, 2138.4 m. (b) *Geminospora lemurata* Balme, 2127.9 m. (c, d) *Lophozonotriletes* cf. *famenensis* (Naumova) Gao; (c) 2127.9 m; (d) 2133.3 m. (e, h) *Apiculiretusispora hunanensis* (Hou) Ouyang et Chen, 1987a; (e) 2127.9 m; (h) 2133.3 m. (f) *Granulatisporites adnatoides* (Potonié et Kremp) Smith et Butterworth, 1967, 2123.1 m. (g) *Stereisporites* sp., 2133.3 m. (i, j) *Anapiculatisporites* cf. *hystricosus* Playford, 1964; (i) 2138.4 m; (j) 2133.3 m. (k) *Retusotrilettes rotundus* (Streel) Lele et Streel, 2138.4 m. (l) *Apiculiretusispora* cf. *granulata* Owens, 2133.3 m. (m–p) *Apiculiretusispora* sp. A, 2127.9 m. (q) *Convolutispora fromensis* Balme et Hassel, 2127.9 m. (r) *Densosporites* sp. B, 2127.9 m. (s) *Convolutispora* cf. *tuberculata* (Waltz) Hoffmeister et al., 1955, 2133.3 m. (t) *Convolutispora* cf. *tenuis* Menendez et Pöthe de Baldis, 2127.9 m. (u) *Dictyotriletes cancellothyris* (Waltz) Zhu, 2127.9 m. (v) *Reticulatisporites subalveolaris* (Luber) Oshurkova, 2003, 2127.9 m. (w) *Euryzonotriletes* sp., 2138.28 m.

Fig. 4. Selected miospores from the AL Association in the southern Yellow Sea, China. Specimens are arranged by depth. (a) *Knoxisporites literatus* (Waltz) Playford, 1963, 2127.9 m. (b, c) *Stenozonotriletes* sp.; (b) 2123.1 m; (c) 2138.4 m. (d, e) *Densosporites* sp. A; (d) 2127.9 m; (e) 2133.3 m. (f) *Aneurospora asthenolabrata* (Hou) Lu, 1994, 2127.9 m. (g, z) *Grandispora* sp. C, 2127.9 m. (h–j) *Lycospora denticulata* Bharadwaj; (h, i) 2138.4 m; (j) 2127.9 m. (k, l) *Cymbosporites acanthaceus* (Naumova) Obukhovskaya ex Oshurkova, 2003, 2127.9 m. (m, n) *Cymbosporites chinensis* Ouyang et Chen, 1987b; (m) 2133.3 m; (n) 2138.4 m. (o) *Cymbosporites dimerus* Ouyang et Chen, 1987b, 2127.9 m. (p) *Grandispora* sp. B, 2127.9 m. (q, r) *Lophozonotriletes* cf. *famenensis* (Naumova) Gao; (q) 2133.3 m; (r) 2127.9 m. (s) *Densosporites anulatus* (Loose) Smith et Butterworth, 1967, 2133.3 m. (t) *Densosporites* sp. B, 2138.4 m. (u–w) *Grandispora* sp. A; (u, v) 2133.3 m; (w) 2123.1 m. (x) *Samarispories* sp., 2127.9 m. (y) *Spinozonotriletes* cf. *uncatus* Hacquebard, 1957, 2138.4 m. (aa) *Knoxisporites triradiatus* Hoffmeister et al., 1955,

2133.3 m.

Fig. 5. Selected miospores from the AL and CA associations in the southern Yellow Sea, China. Specimens are arranged by depth. (a–h) *Diducites* sp.; (a) 2127.9 m; (b, c) 2133.3 m; (d, g, h) 2127.9 m; (e) 2133.3 m; (f) 2133.3 m. (i) *Diducites* cf. *mucronatus* (Kedo) Van Veen, 1978, 2127.9 m. (j) *Discernisporites micromanifestus* (Hacquebard) Sabry et Neves, 1971, 2087.3 m. (k) *Grandispora* cf. *microseta* Streel in Becker et al., 1974, 2127.9 m. (l) *Auroraspora evanida* (Kedo) Van der Zwan, 1980a, 2127.9 m. (m) *Retispora lepidophyta* (Kedo) Playford, 1971, 2133.3 m. (n) *Grandispora microseta* (Kedo) Streel in Becker et al., 1974, 2133.3 m. (o) *Grandispora gracilis* (Kedo) Streel, 2133.3 m. (p–r) *Spelaeotriletes* sp. B; (p) 2138.4 m; (q) 2133.3 m; (r) 2138.4 m. (s–w) *Spelaeotriletes* sp. A; (s) 2138.4 m; (t, u) 2133.3 m; (v, w) 2127.9 m. (x) *Endosporites* sp., 2133.3 m. (y) *Grandispora* sp. C, 2127.9 m. (z) *Aneurospora asthenolabrata* (Hou) Lu, 1994, 2127.9 m.

Fig. 6. Selected miospores from the the AL and CA associations in the southern Yellow Sea, China. Specimens are arranged by depth. (a) *Punctatisporites recavus* Ouyang et Chen, 1987b, 2087.3 m. (b) *Dictyotriletes*? sp., 2087.3 m. (c, d) *Dibolisporites* cf. *coalitus* Ouyang et Chen, 1987b, 2087.3 m. (e) *Acanthotriletes simplex* (Naumova) Kedo, 1963, 2087.3 m. (f) *Anapiculatisporites mucronata* Ouyang et Chen, 1987b, 2087.3 m. (g, m) *Knoxisporites literatus* (Waltz) Playford, 1963, 2087.3 m. (h, i) *Cymbosporites circinatus* Ouyang et Chen, 1987b, 2072.1 m. (j, n–p) *Dibolisporites* sp., 2034.7 m. (k) *Vallatisporites* cf. *pusillites* (Kedo) Dolby et Neves, 1970, 2075.6 m. (l) *Apiculiretusispora nitida* Owens, 2087.3 m. (q) *Stenozonotriletes* sp., 2087.3 m. (r) *Apiculiretusispora* sp. B, 2075.6 m. (s, t) *Cordylosporites* cf. *papillatus* (Naumova) Playford in Playford and Satterthwaitt, 1985, 2087.3 m.

Fig. 7. Selected miospores from the AL and CA associations in the southern Yellow Sea, China. Specimens are arranged by depth. (a–c) *Endoculeosporites gradzinskii*

Turnau, 1975, 2087.3 m. (d) *Discernisporites micromanifestus* (Hacquebard) Sabry et Neves, 1971, 2087.3 m. (e) *Baculatisporites* cf. *atratus* (Naumova) Lu, 1999, 2075.6 m. (f, g) *Spinozonotriletes* cf. *senticosus* (Ischenko) Playford, 1963, 2087.3 m. (h) *Grandispora* cf. *G. gracilis* (Kedo) Streel in Becker et al., 1974, 2087.3 m. (i) *Grandispora* cf. *microseta* (Kedo) Streel in Becker et al., 1974, 2075.6 m. (j) *Densosporites* sp. B, 2087.3 m. (k) *Auroraspora* sp., 2087.3 m. (l–n) *Baculatisporites*? sp., 2075.6 m. (o–s) *Grandispora* sp. C, 2087.3 m. (t) *Gorgonisphaeridium* sp., 2087.3 m.

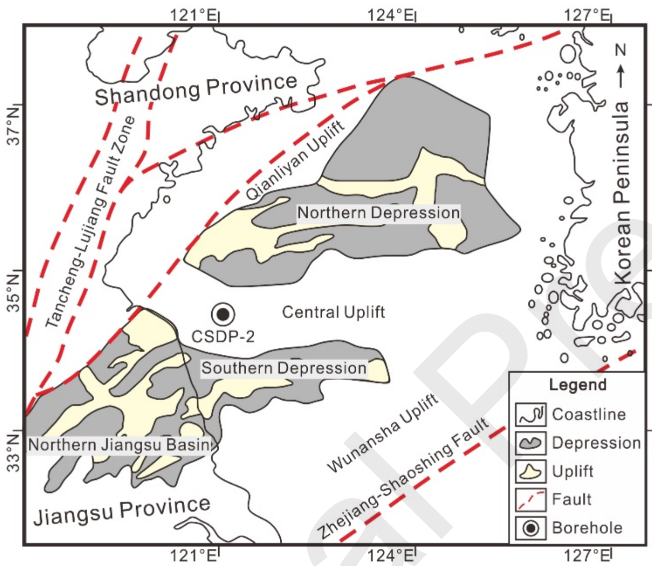
Fig. 8. Selected miospores from recovered from 2081.2 m–2081.8 m interval of the CSPD2 Borehole in the southern Yellow Sea, China. (a, b) *Aneurospora asthenolabrata* (Hou) Lu, 1994. (c, d) *Retusotriletes nigritellus* (Luber) Foster, 1979. (e) *Foveosporites* sp. (f) *Convolutispora* cf. *planus* Hughes et Playford. (g, k) *Foveosporites* cf. *pellucidus* Playford et Helby, 1968. (h) *Convolutispora* sp. (i) *Periplecotriletes* cf. *amplectus* (Naumova) ex Waltz in Luber et Waltz, 1938. (j) *Auroraspora* cf. *A. macra* Sullivan. (l, l') *Periplecotriletes* sp. (m, m') *Baculatisporites* sp. (n, o) *Knoxisporites literatus* (Waltz) Playford, 1963. (p, q) *Crassispora* cf. *kosankei* (Potonié et Kremp) Bharadwaj. (r–t) *Radiizonates longtanensis* Lu, 1994. (u) *Spinozonotriletes* sp. (v, y, z) *Discernisporites micromanifestus* (Hacquebard) Sabry et Neves, 1971. (w, x) *Apiculiretusispora gannanensis* Wen et Lu.

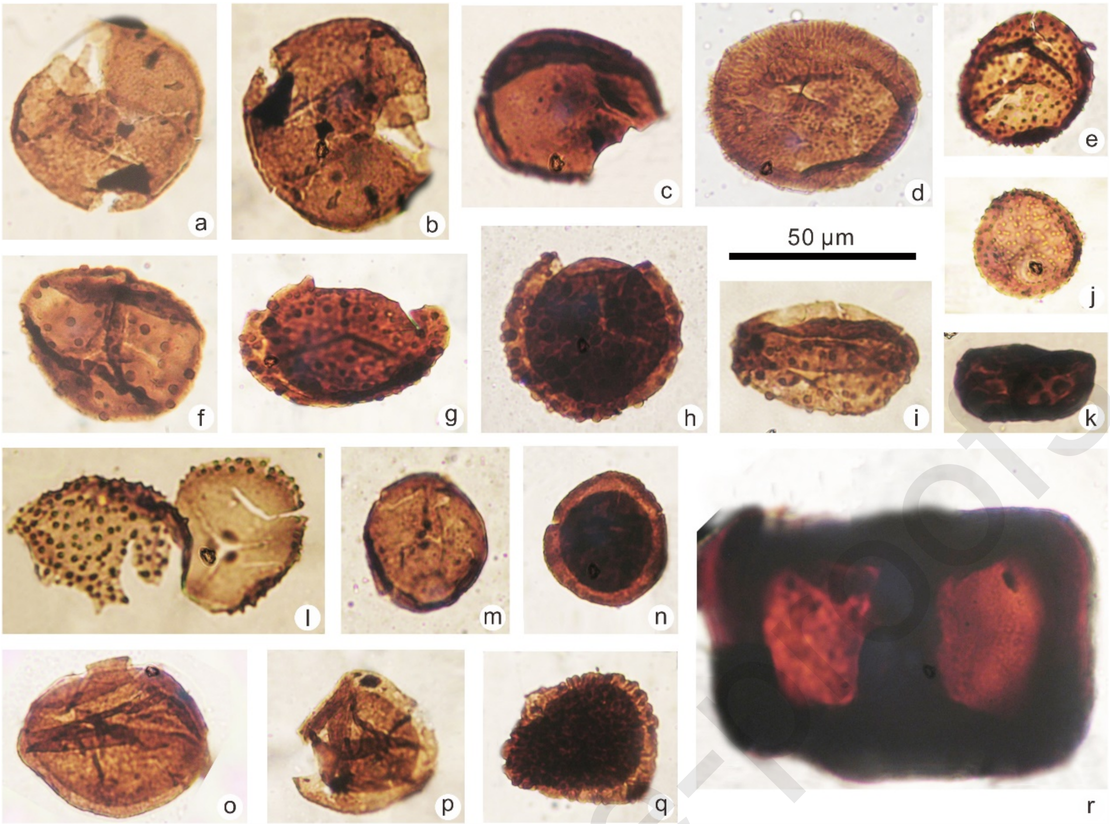
Fig. 9. Selected miospores from recovered from 2081.2 m–2081.8 m core of CSPD-2 Borehole in the southern Yellow Sea, China. (a) *Apiculiretusispora microrugosa* Lu, 1994. (b) *Lophozonotriletes rarituberculatus* (Luber) Kedo, 1957. (c, d) *Grandispora* sp. C. (e) *Asperispora naumovae* Staplin et Jansonius, 1964. (f–h) *Auroraspora macra* Sullivan. (i) *Laevigatosporites*? sp. (j) *Schweitzerisporites* cf. *maculatus* Kaiser. (k, k') *Retispora lepidophyta* var. *minor* Kedo in Kedo et Golubtsov. (l, m, m') *Bosedinia*? sp. (n, r–t, t') *Asperispora acuta* (Kedo) Van der Zwan, 1980b. (o) *Cycadopites*? sp. (p) *Indotriradites explanatus* (Luber) Playford. (q) A spinate

acritarch or trilete spore? (gen. et sp. indet.). (u) *Euryzonotriletes*? sp. or an acritarch (gen. et sp. indet.).

Fig. 10. Selected miospores from recovered from 2031.3 m core of the CSPD-2 Borehole in the southern Yellow Sea, China. (a, b) *Apiculiretusispora commixta* Lu, 1999. (c, m) *Leiotriletes microthelis* Wen et Lu. (d) *Capillatisporites* cf. *multisetus* (Luber) Oshurkova, 2003. (e, j) *Lycospora* sp. (f–i) *Lophozonotriletes involutus* Kedo, 1963. (k) *Tumulispora rarituberculata* (Luber) Potonié. (l) *Apiculatasporites minutus* (Gao) Ouyang in Ouyang et al., 2017. (n, q) *Auroraspora macra* Sullivan. (o) *Grandispora echinata* Hacquebard, 1957. (p) *Discernisporites micromanifestus* (Hacquebard) Sabry et Neves, 1971. (r) *Knoxisporites pristinus* Sullivan, 1968.

Late Devonian–Early Carboniferous spores recovered from the depths 2140 to 2031.28 m in the CSDP-2 Borehole in the southern Yellow Sea are systematically documented to characterize palynological associations for the stratigraphic correlation. The taxonomic study identifies 96 species belonging to 48 genera, including a re-examination of 33 previously described and indeterminate species. Three palynological associations are established for the Wutong Formation in the CSDP-2 Borehole. In ascending order, these are the late Famennian *Aneurospora asthenolabrata-Geminospora lemurata* (AL) Association from the proposed Guanshan Member, the latest Famennian *Cymbosporites circinatus-Asperispora acuta* (CA) Association from the lower part of the proposed Leigutai Member, and the Tournaisian *Auroraspora macra-Lophozonotriletes involutus* (MI) Association of the upper part of the latter member. The AL and CA associations are correlated with the palynological assemblages in the Guanshan Member, and those in the lower to middle parts of the Leigutai Member of the Wutong Formation outcrops in the suburbs of Nanjing and southern Jiangsu. The MI Association is similar to those derived from the uppermost beds of the subsurface Wutong Formation and is dated as early Tournaisian.

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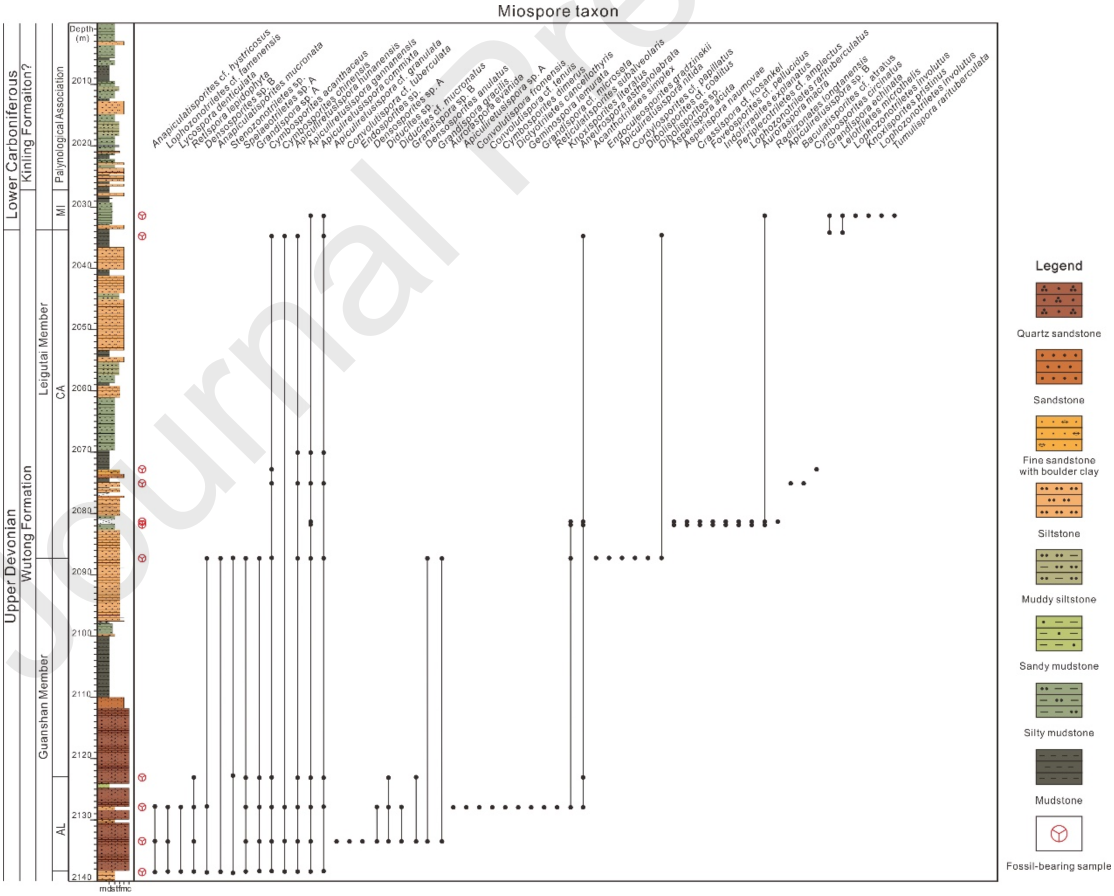
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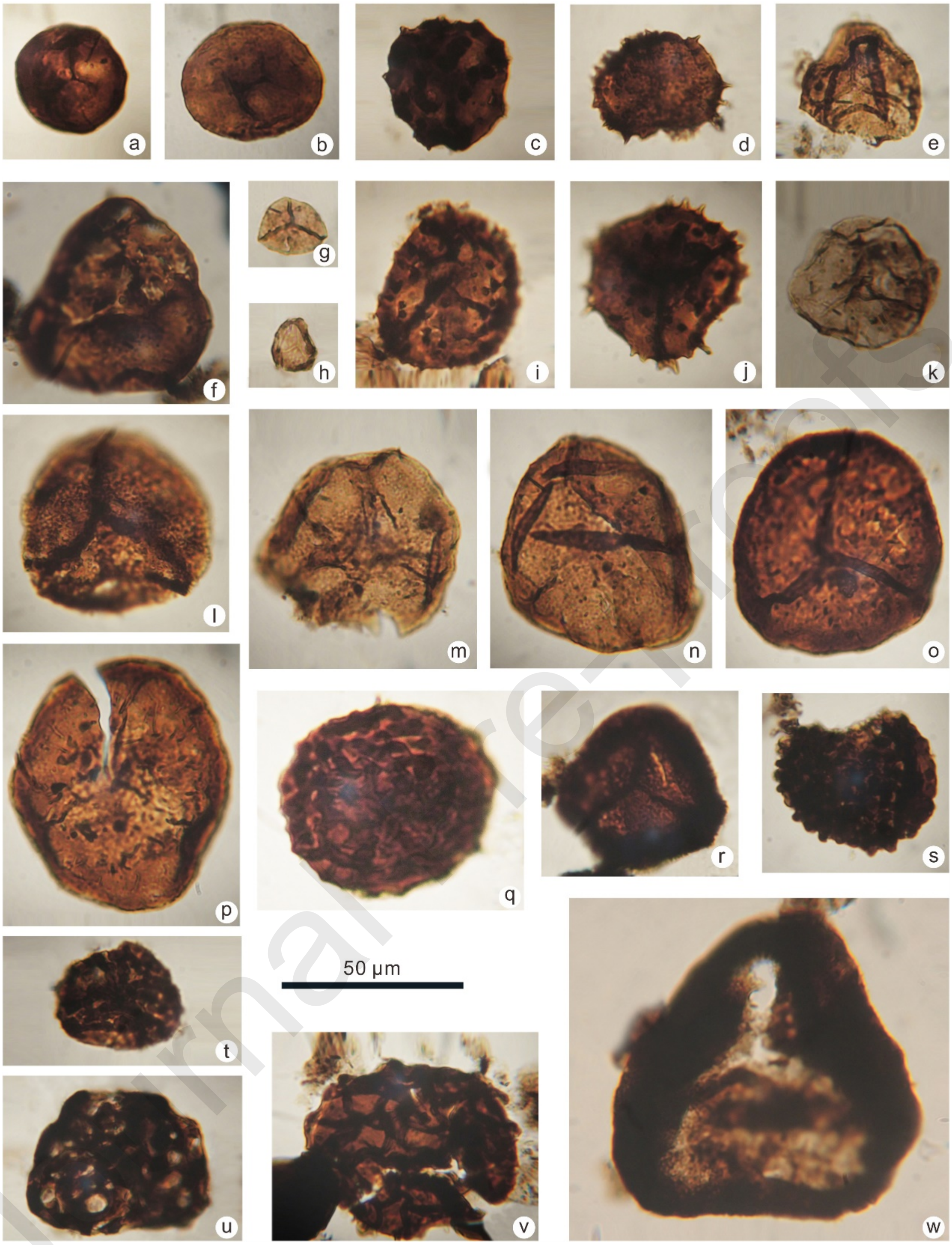
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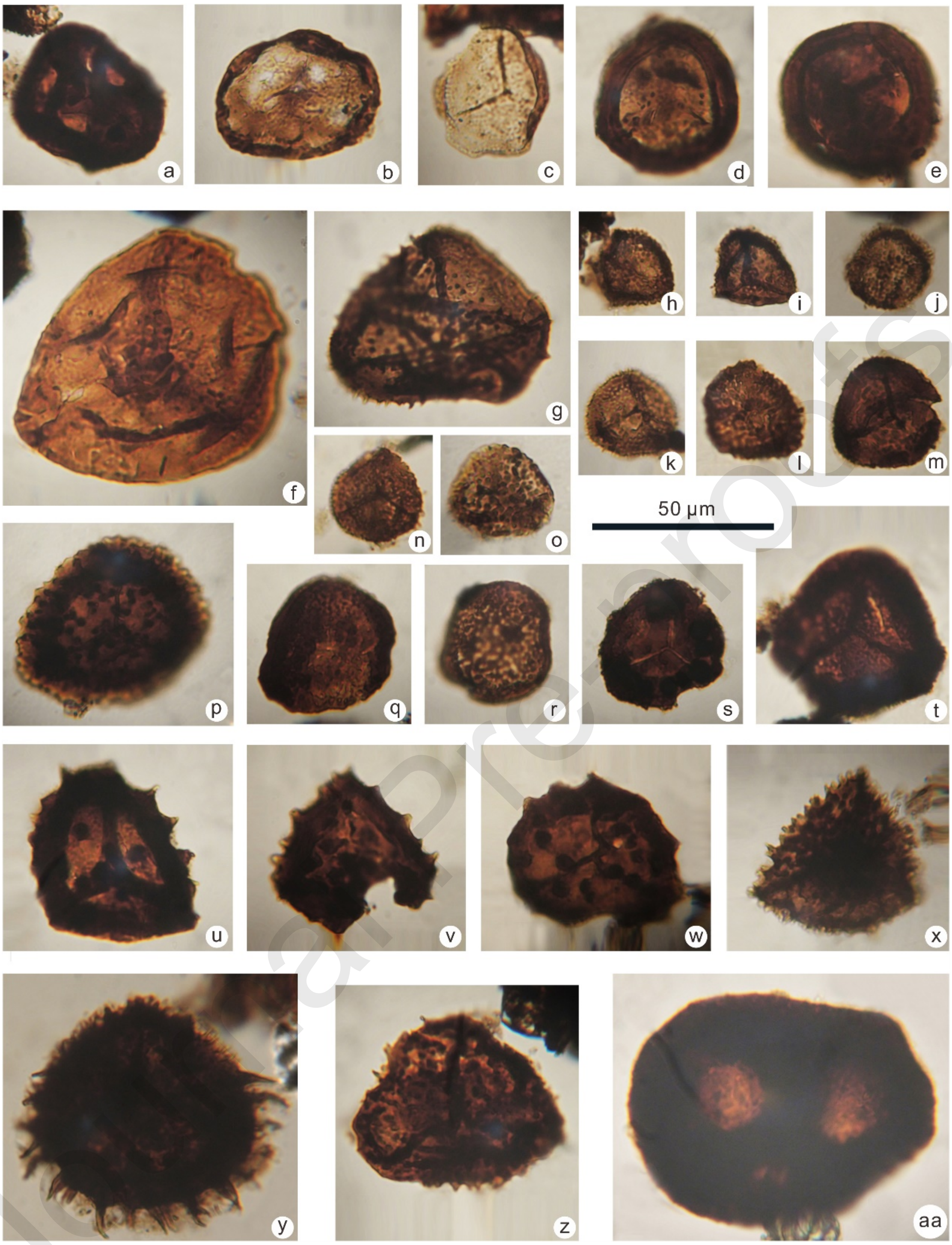
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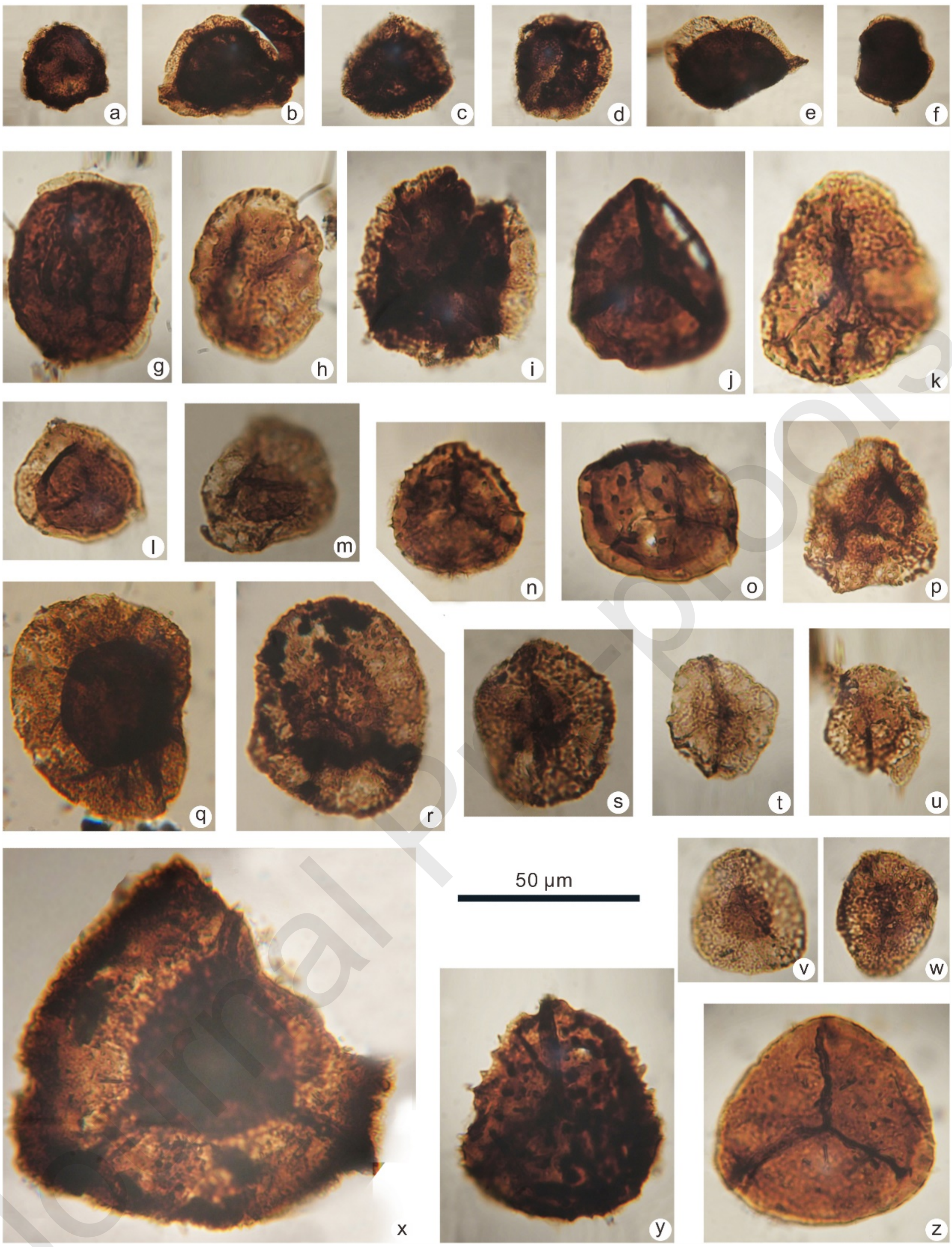
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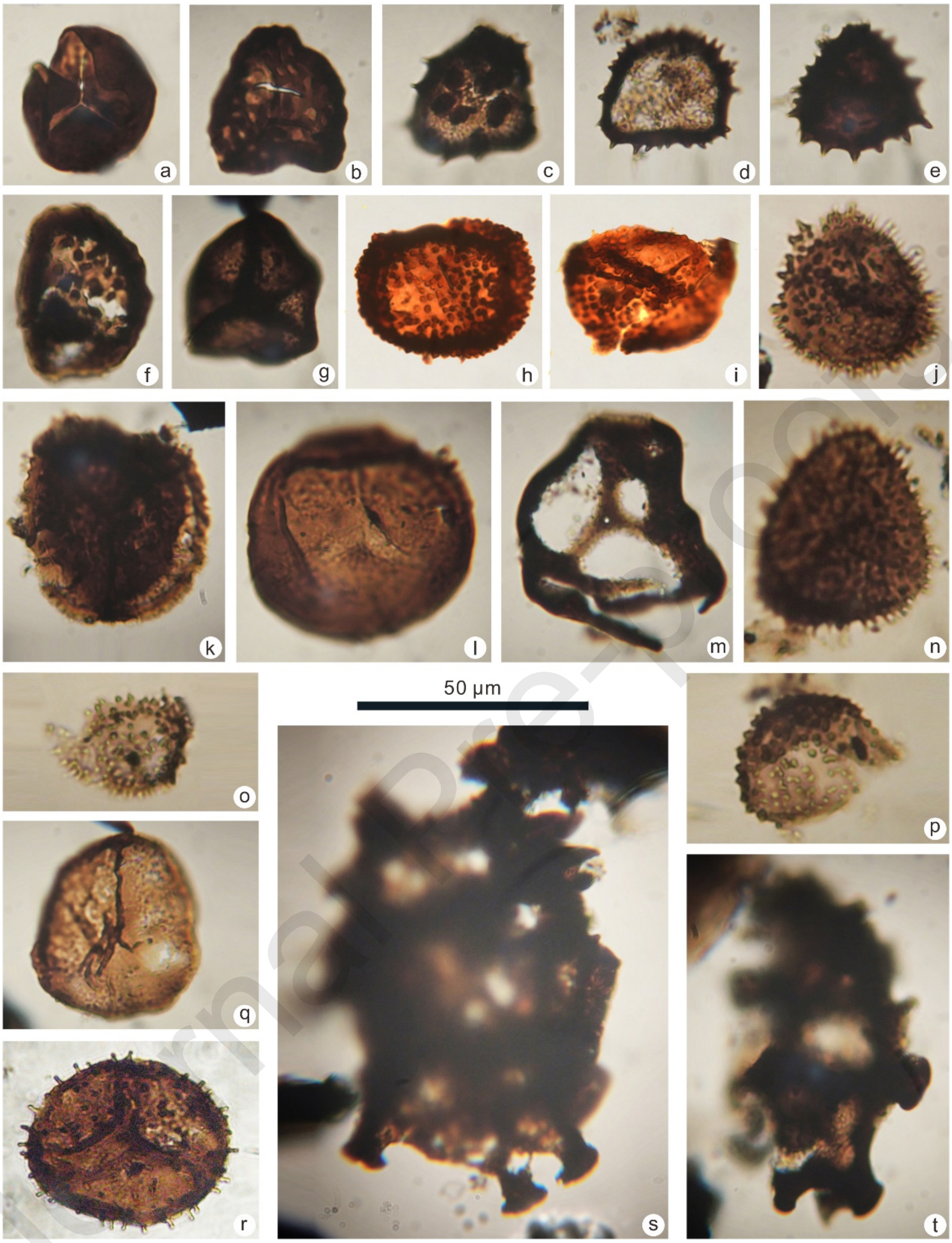
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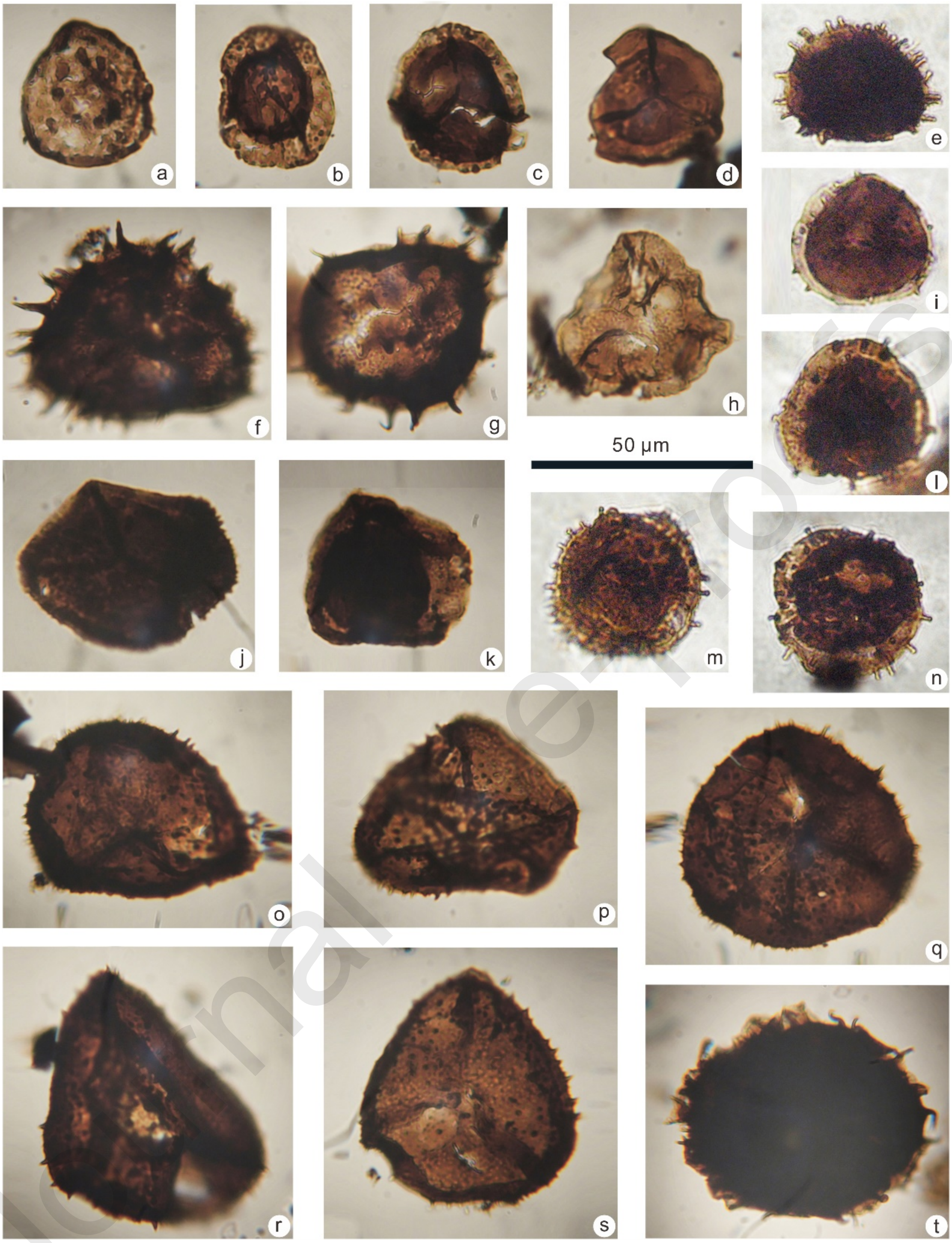
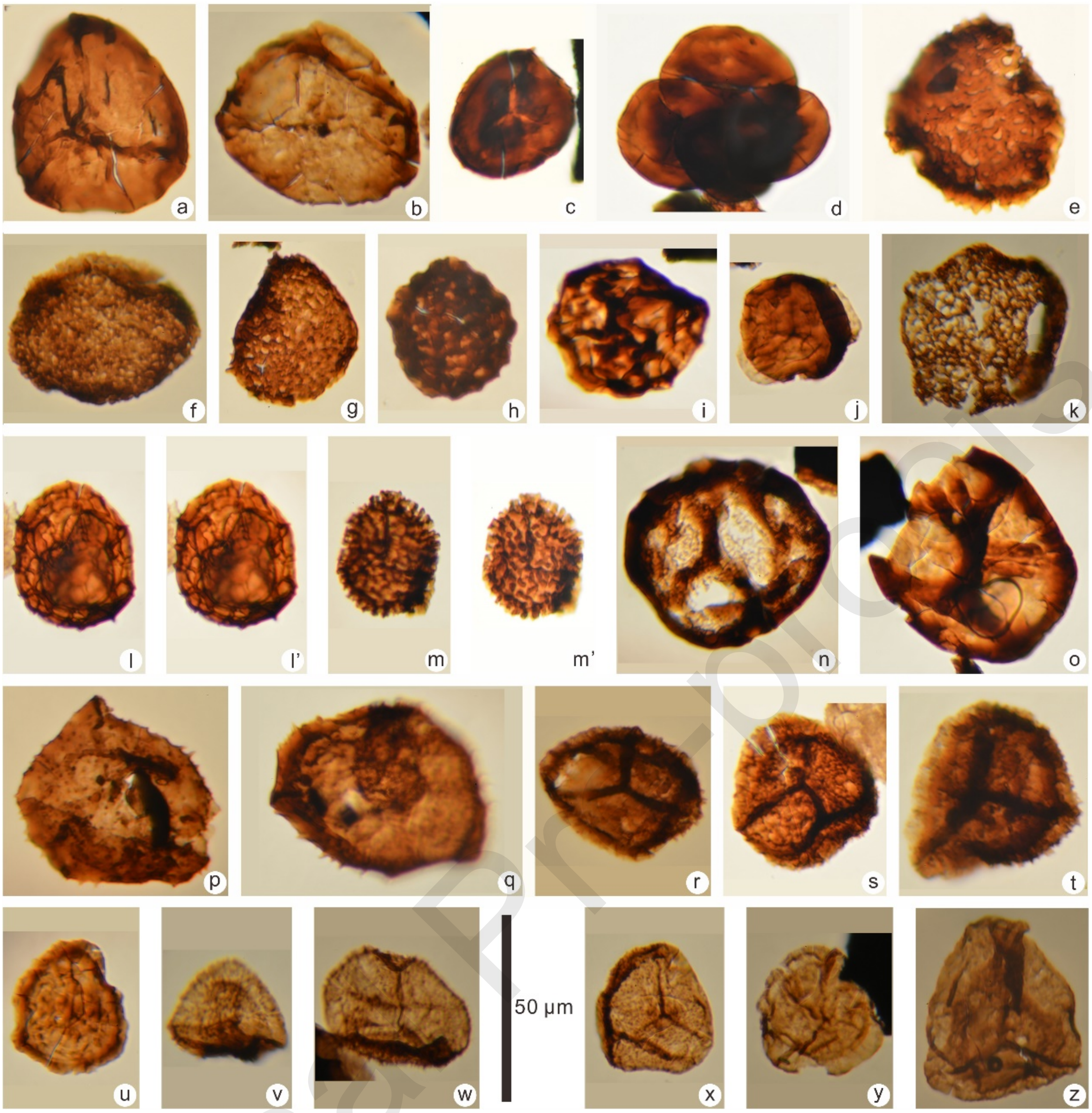
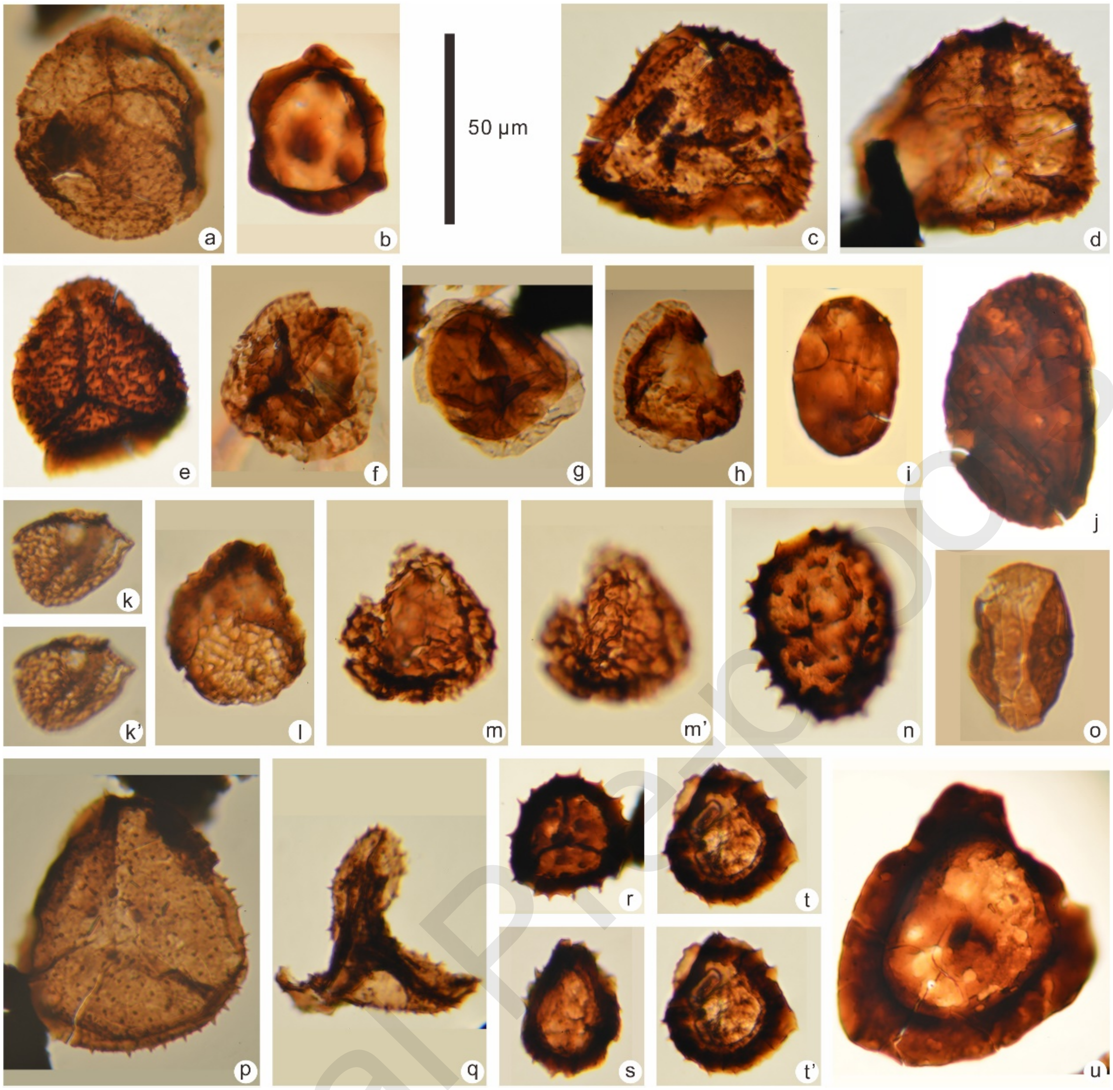

a
b
c
d
e
f
g
h
i
50 μm
l
j
k
m
n
o
p
q
r
s
t


a
b
c
d
e
f
g
h
i
j
k
l
l'
m
m'
n
o
p
q
r
s
t
u
v
w
50 µm
x
y
z


50 µm
a
b
c
d
e
f
g
h
i
j
k
k'
l
m
m'
n
o
p
q
r
s
t
t'
u