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Palynology of samples from the Ballagan Formation of the Glenrothes Borehole, Fife

Internal Report IR/02/185

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INTERNAL REPORT IR/02/185

Palynology of samples from the Ballagan Formation of the Glenrothes Borehole, Fife

M H Stephenson

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Summary

This report records palynological analysis of 32 samples from the Glenrothes Borehole, Fife [NO 2561 0314] and includes data from a further 12 samples reported on by Turner (1995). The borehole was sampled in detail to investigate the potential for high precision correlation within the Ballagan Formation in the Midland Valley of Scotland, following detailed work at the Heads of Ayr section, Ayrshire (Stephenson et al. 2002; Stephenson, 2001).

Due to rather patchy recovery and poor preservation, correlations of the Ballagan Formation in the Glenrothes Borehole are necessarily tentative; however it seems likely that lower parts of the Ballagan Formation are present in the Glenrothes Borehole than in the section at the Heads of Ayr. The presence of *Pustulatisporites dolbii* (recorded only from the LL-PC Biozones, Higgs et al. 1988) and the absence of *Schopfites claviger* suggests that the sequence below 316.95 m depth may be assignable to the PC Biozone (Tn2b/c to Tn3a age, Higgs et al., 1988).

The age of the upper part of the Ballagan in Glenrothes is latest Tournaisian (CM Biozone Tn3c) since *Schopfites claviger* and *Auroraspora macra* are present and *Lycospora pusilla* is absent. The part of the Ballagan above 246.0 m depth may correspond to the upper parts of the Ballagan at the Heads of Ayr because *Acanthotriletes* cf. *macrogaletus* is present (but very rare) at this level and at 223.8 m depth, but other taxa characteristic of the upper parts of the Ballagan at the Heads of Ayr are not present. The age of the succeeding Pathead Beds is also uncertain due to very poor palynomorph preservation, but may be at least TC Biozone in age (late Holkerian – early Asbian) based on the presence of *L. pusilla* and possible specimens of *Schulzospora* sp.

Samples analysed in parallel for palynology and ostracods indicate that aquatic algal spores of the zygnemataceae indicate low salinity conditions. Correlation of autochthonous algal spore assemblages and ostracod faunas will be of further use in palaeoenvironmental determinations.

In previous work on the Ballagan Formation at the Heads of Ayr (Stephenson et al., 2002; Stephenson, 2001), it was suggested that assemblages dominated by algal forms may be indicative of impersistent low salinity lakes on low gradient coastal plains, and that the inverse relationship between terrestrially derived and autochthonous algal palynomorphs in these assemblages may be explained by local lacustrine drowning of terrestrial plant communities.

New lithofacies information presented here appears, however, to favour relatively shallow water conditions for algal spore assemblages since the latter are associated mainly with dessication-cracked sediments. It is now thought likely that they contain few terrestrially derived spores because of contemporaneous weathering, repeated wetting and drying and or alkaline dissolution in subaerial or near subaerial conditions. Algal spores may have been produced in small stagnant pools on the ground surface.

The lower part of Ballagan Formation in the Glenrothes Borehole, including the Mains of Errol Member, was deposited in shallow water and frequently sub aerial conditions while above about 280 m depth there is evidence of more persistent aquatic conditions because fish appear to be more common in this section, and facies indicative of sub aerial exposure or shallow water are fewer. At present it is not possible to be sure whether these more stable aquatic conditions were marine or freshwater since fish can occupy both, but the occurrence, at a number of horizons, of conchostracans and fresh-brackish water ostracods indicate that much of this section may have been deposited in low salinity conditions.

A summary of the biostratigraphy and palaeoenvironments of the Ballagan Formation in the Glenrothes Borehole is given in Fig. 1.

1 Introduction

This report records the results of palynological analysis of 32 samples from the Glenrothes Borehole, Fife National Grid Reference (NGR) [NO 2561 0314]. The borehole was sampled in detail to investigate the potential for high precision correlation within the Ballagan Formation in the Midland Valley of Scotland, following detailed work at the Heads of Ayr section, Ayrshire (Stephenson et al., 2002; Stephenson, 2001). In addition, the results of a palynological study of 12 different samples reported on by N Turner (1995) are included in the study. Attempts have been made to investigate palynological biostratigraphy and palynofacies variations through the section to allow correlation and palaeoenvironmental analysis. Ostracod data have also been used to analyse palaeoenvironments.

It is envisaged that a number of other boreholes penetrating the Ballagan Formation (for example the East Dron Borehole [NO 11 NW 24] will be the subjects of further reports.

2 Description of assemblages

2.1 SAMPLE MPA 50639

Sample depth 373.5 m.

The sample contained very little organic matter.

2.1.1 Interpretation

No age determination can be given.

2.2 SAMPLE MPA 50640

Sample depth 361.42 m.

The sample yielded a very sparse organic residue consisting mainly of black woody fragments and rare aquatic algae. The assemblage contains: *Leiosphaeridia* spp., *Discernisporites* sp., and Cf. *Peltacystia* sp. 1.

2.2.1 Interpretation

This assemblage is of the aquatic algal type (see later discussion). No age determination can be given.

2.3 SAMPLE MPA 50641

Sample depth 357.8 m.

The sample yielded a rich organic residue consisting mainly of dark brown to black woody fragments (many of which are elongate) with subordinate dark brown sheet cellular material, poorly preserved very light coloured palynomorphs and amorphous organic matter (AOM). The palynomorph assemblage is unusual in being dominated by abundant aquatic, mainly algal taxa of the genera *Botryococcus*, *Leiosphaeridia*, Cf. *Tetraporina* and Cf. *Peltacystia* and

Reduviasporonites. Spores of terrestrial origin are very rare and include *Spelaeotrilletes* sp., *Verrucosisporites nitidus*, and *Colatisporites* sp..

A number of new taxa are present. Short descriptions of these are given below:

‘Monolete spore’ of McLean & Neves (2001)

?Algal microfossil, large (approx. 100µm max dimension); outline oval, usually dark in colour. Discontinuous marginal fold (or thickening), 5-10 µm wide occurs close to, or coincident with, the margin. Exine approximately 1 µm thick; surface scabrate. A single split or dehiscence in the exine occurs parallel to the long axis, dehiscence as long or slightly longer than the diameter.

This rare, but very distinctive microfossil is closely similar in morphology to species of *Brazilea* Tiwari and Navale 1967, though it may be larger and more robust. Very similar specimens were recorded as a ‘monolete spore’ by McLean and Neves (2001) from the New Farm A Borehole, Perth and Kinross, in the upper Dron Member of the Ballagan Formation. I consider this form to be of probable zygenamatacean algal origin and its presence in an assemblage dominated by algal palynomorphs, tends to support this suggestion. The presence of the taxon in the lowest part of the Ballagan Formation, stratigraphically much lower than the Dron Member of the New Farm A Borehole, suggests that it is an opportunistic algal species of little regional correlation significance.

Ruduviasporonites spp.

The presence of this ?algal taxon (Foster et al. in prep.; Krassilov et al., 1999) is interesting partly because this may be one of earliest occurrences of the taxon and partly because this occurrence, amongst a largely algal assemblage, tends to support new interpretations of the palaeoenvironment of the organism (Foster et al. in prep).

Leiosphaeridia sp. D

?Algal microfossil; small (approximately 35 µm); outline oval or circular, usually dark in colour. Exine thin (<1 µm), possibly two layered. A split or dehiscence, with thickened edges resembling lips, occurs in a spiral pattern across the full length of the body.

2.3.1 Interpretation

In view of the lack of age diagnostic fossils, no age determination is possible, but some comment on palaeoenvironments is warranted.

A number of the taxa in the assemblage are likely to be of zygnematacean algal origin; this group of alga is associated with low salinity or freshwater as is another component of the assemblage, *Botryococcus*. Such an environment may be similar to those suggested for parts of the uppermost Ballagan at the Heads of Ayr foreshore (Stephenson, 2001).

The occurrence of the brackish or freshwater water ostracod *Shemonaella* cf. *scotoburdigalensis* in this sample (Williams, 2001) supports the palynological evidence for a low salinity or freshwater environment.

2.4 SAMPLE MPA 50642

Sample depth 356.22 m.

The sample yielded a very sparse organic residue consisting mainly of black woody fragments and AOM. The assemblage contains no identifiable palynomorphs.

2.4.1 Interpretation

No age determination can be given.

2.5 SAMPLE MPA 50643

Sample depth 345.1 m.

The sample contained very little organic matter.

2.5.1 Interpretation

No age determination can be given.

2.6 SAMPLE MPA 50644

Sample depth 344.44 m.

The sample yielded a very sparse organic residue consisting mainly of black woody fragments and poorly preserved spores and aquatic algae. The assemblage contains: *Leiosphaeridia* spp. and Cf. *Peltacystia* sp. 1.

2.6.1 Interpretation

This assemblage is of the aquatic algal type. No age determination can be given.

2.7 SAMPLE MPA 50645

Sample depth 341.0 m.

The sample yielded a very sparse organic residue consisting mainly of black woody fragments and poorly preserved spores and aquatic algae. The assemblage contains *Leiosphaeridia* spp..

2.7.1 Interpretation

This assemblage is of the aquatic algal type. No age determination can be given

2.8 SAMPLE MPA 50646

Sample depth 340.00 m.

The sample contained very little organic matter.

2.8.1 Interpretation

No age determination can be given.

2.9 SAMPLE MPA 50647

Sample depth 329.7 m.

The sample yielded a very sparse organic residue consisting mainly of dark brown to black equant woody fragments and AOM. No recognisable palynomorphs were recorded.

2.9.1 Interpretation

No age determination can be given.

2.10 SAMPLE MPA 50648

Sample depth 327.6 m.

The sample yielded a very sparse organic residue consisting mainly of black woody fragments, sheet cellular material and very rare, poorly preserved spores and aquatic algae. The assemblage contains: *Leiosphaeridia* spp. and *Retusotriletes* sp..

2.10.1 Interpretation

This assemblage is of the aquatic algal type. No age determination can be given

2.11 SAMPLE MPA 50649

Sample depth 325.0 m.

The sample yielded a sparse organic residue consisting mainly of black woody fragments, sheet cellular material and very rare poorly preserved spores and aquatic algae. The assemblage contains: *Leiosphaeridia* spp., *Retusotriletes* sp., Cf. *Leiosphaeridia* sp. A (see Stephenson et al., in prep.).

2.11.1 Interpretation

This assemblage is of the aquatic algal type and is closely similar to MPA 50650. No age determination can be given.

2.12 SAMPLE MPA 50650

Sample depth 319.00 m.

The sample yielded a sparse organic residue consisting mainly of black woody fragments and rare poorly preserved spores and aquatic algae. The assemblage contains: *Leiosphaeridia* sp., ?*Colatisporites* spp..

2.12.1 Interpretation

This assemblage is of the aquatic algal type. No age determination can be given

2.13 SAMPLE MPA 50651

Sample depth 316.95 m.

The sample yielded a rich organic residue consisting mainly of black woody fragments and moderately preserved dark brown to black spores with subordinate AOM and sheet cellular material. The assemblage contains:

Colatisporites denticulatus

Auroraspora cf. *macra*

Retusotriletes sp.

Colatisporites spp.

Auroraspora macra

Schopfites delicatus
Cf. Baculatisporites fusticulus
Schopfites claviger
Cyclogranisporites spp.
Rugospora polyptycha
Discernisporites crenulatus
Retusotriletes incohatus
Convolutispora spp.
Verrucosisporites nitidus
Latosporites sp.
Apiculiretusispora sp.
Corystisporites costatus
Spelaeotriletes tuberosus
Baculatisporites fusticulus
Stenozonotriletes spp.
Discernisporites micromanifestus
Verrucosisporites sp.

2.13.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspora macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977). The assemblage is most like those of the 'lower Ballagan' at the Heads of Ayr, Ayrshire (Stephenson et al., 2002). This assignment lowers the base of the CM Biozone in the Glenrothes Borehole from 283.0 m (as suggested by Turner, 1995), to 316.95 m depth.

2.14 SAMPLE MPA 60652

Sample depth 309.6 m.

The sample yielded a rich organic residue consisting mainly of light brown to grey, fluffy AOM with common black elongate woody fragments and relatively well-preserved yellow spores. The assemblage contains:

Colatisporites spp.
Auroraspora macra
Retusotriletes sp.
Colatisporites decorus
Rugospora minuta
Colatisporites denticulatus
Schopfites claviger
Convolutispora spp.
Knoxisporites spp.
Auroraspora cf. *macra*
Retusotriletes incohatus
Spelaeotriletes pretiosus
Verrucosisporites nitidus
Grandispora echinata
Stenozonotriletes spp.
Raistrickia corynoges
Convolutispora florida

2.14.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspora macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977).

2.15 SAMPLE MPA 60653

Sample depth 302.0 m.

The sample yielded a moderately rich organic residue consisting mainly of black equant woody fragments and light brown to grey fluffy AOM with very rare, poorly preserved palynomorphs. The assemblage is dominated by a palynomorph assignable to *Lophosphaeridium*, but a single specimen of *Colatisporites* was also recorded.

Lophosphaeridium sp. A

?Algal microfossil, without dehiscence structure or split, very small (approximate diameter 20 µm); outline circular. Exine approximately 1 µm thick, surface covered with very fine delicate spines or grana just resolvable under x100 objective; length of ornament elements approximately 0.5 µm; width at base approximately 0.5 µm, very densely and evenly distributed over the whole area of the vesicle (approximately 0.5 µm apart).

2.15.1 Interpretation

In view of the lack of age diagnostic fossils, no age determination is possible.

2.16 SAMPLE MPA 50654

Sample depth 294.55 m.

The sample yielded a sparse organic residue consisting mainly of black woody fragments and rare poorly preserved spores and aquatic algae. The assemblage contains: *Retusotriletes* spp., *Colatisporites* sp., *Leiosphaeridia* spp., *Lophosphaeridium* sp. A, Cf. *Peltacystia* sp. 1 and *Leiosphaeridia* sp. B.

2.16.1 Interpretation

This assemblage contains interesting aquatic algal taxa but no age-diagnostic spores. The presence of palynomorphs similar to *Peltacystia* may indicate freshwater conditions.

2.17 SAMPLE MPA 50655

Sample depth 287.35 m.

The sample yielded a sparse organic residue consisting mainly of black woody fragments and rare poorly preserved spores and aquatic algae. The assemblage contains *Leiosphaeridia* spp. and Cf. *Palambages* sp..

2.17.1 Interpretation

This assemblage is of the aquatic algal type. No age determination can be given.

2.18 SAMPLE MPA 50656

Sample depth 277.03 m.

The sample yielded a rich organic residue consisting mainly of black elongate woody fragments with subordinate relatively well-preserved yellow spores and sheet cellular material. The assemblage contains:

Colatisporites spp.

Knoxisporites spp.

Schopfites claviger
Aurororaspota cf. *macra*
Apiculisretusispota spp.
Stenozonotriletes spp.
Retusotriletes sp.
Verrucosisporites cf. *nitidus*
Schopfites delicatus
Murospota sp.
Colatisporites denticulatus
Convolutispota spp.
Prolycospota claytonii
Verrucosisporites spp.
Verrucosisporites nitidus
Calamospota spp.
Rugospota polyptycha
Knoxisporites literatus
Plicatispota scoleophora
Laevigatosporites sp.
Discernisporites micromanifestus
 Cf. *Corystisporites costatus*
Grandispota echinata
Corystisporites costatus
Dictyotriletes sp.
Spelaeotriletes sp.
Grandispota cf. *echinata*

2.18.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspota macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977). The assemblage is most like those of the ‘lower Ballagan’ at the Heads of Ayr, Ayrshire (Stephenson et al., 2002).

2.19 SAMPLE MPA 50657

Sample depth 268.05 m.

The sample yielded a very sparse organic residue consisting mainly of dark brown to black equant woody fragments. Palynomorphs are relatively rare; spores of terrestrial origin are poorly preserved so that neither species nor genera can be recognised. Algal palynomorphs are slightly better preserved and these include: *Chomotriletes* sp., Cf. *Palambages* sp. *Leiosphaeridia* sp. and Cf. *Tetraporina* sp..

2.19.1 Interpretation

No age determination is possible. The occurrence of zygospores of probable zynemataceean origin (e.g. *Chomotriletes* sp. and Cf. *Tetraporina* sp.) suggests a freshwater or reduced salinity environment.

2.20 SAMPLE MPA 50658

Sample depth 264.2 m.

The sample yielded a moderately rich organic residue consisting mainly of black woody fragments and rare, very poorly preserved dark brown to black spores. The assemblage contains: *Schopfites claviger*, *Colatisporites denticulatus*, *Colatisporites* spp., *Latosporites* sp., *Leiosphaeridia* spp., ?*Cirratiradites* sp. and *Retusotriletes* sp..

2.20.1 Interpretation

The presence of *Schopfites claviger* alone suggests that this sample can be assigned to the latest Tournaisian – earliest Viséan CM to Pu biozones of Clayton et al. (1977), though the presence of *Colatisporites denticulatus*, *Colatisporites* spp. and the stratigraphic context of the sample suggests a CM Biozone age.

2.21 SAMPLE MPA 50659

Sample depth 254.45 m.

The sample yielded a rich organic residue consisting mainly of black woody fragments and poorly preserved dark brown to black spores. The assemblage contains:

Colatisporites spp.
Schopfites claviger
Retusotriletes sp.
Auroraspora macra
Leiosphaeridia spp.
Plicatispora scolecophora
Cf. *Palambages* sp.
Lophosphaeridium sp. A
Discernisporites micromanifestus
Auroraspora sp.
Chomotriletes sp.
Knoxisporites spp.
Grandispora echinata
Grandispora cf. *echinata*
Auroraspora cf. *macra*

2.21.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspora macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977). The assemblage is most like those of the ‘lower Ballagan’ at the Heads of Ayr, Ayrshire (Stephenson et al., 2002).

2.22 SAMPLE MPA 50660

Sample depth 246.00 m.

The sample yielded a rich organic residue consisting mainly of black woody fragments and poorly preserved dark brown to black spores with subordinate sheet cellular material. The assemblage contains:

Colatisporites spp.
Schopfites claviger
Colatisporites denticulatus
Retusotriletes spp.
Apiculiretusispora sp.
Auroraspora macra

Rugospora minuta
Convolutispora spp.
Biannulatisporites simplex
Plicatispora scolecophora
 Cf. *Spelaeotriletes* sp.
Auroraspora cf. *macra*
Reduviasporonites cf. *catenulatus*
Crassispora cf. *maculosa*
Anaplanisporites baccatus
Raistrickia cf. *corynoges*
Rugospora polyptycha
 Monolete spore of McLean (2001)
Discernisporites micromanifestus
Acanthotriletes cf. *macrogaleatus*
Punctatisporites sp.
Cyclogranisporites sp.
Spelaeotriletes microspinosus
Verrucosisporites nitidus
Spelaeotriletes spp.
Dibolisporites distinctus
Dictyotriletes spp.
Spelaeotriletes pretiosus
Grandispora echinata
Baculatisporites fusticulus
 Cf. *Aratrisporites* sp.
Spelaeotriletes cf. *tuberosus*
Vallatisporites sp.
Brevitriletes cf. *hennellyi*

2.22.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspora macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977). The presence of *Acanthotriletes* cf. *macrogaleatus*, *Spelaeotriletes microspinosus* and lycopsid spores of *Vallatisporites* sp. suggests similarities with the ‘upper Ballagan’ at the Heads of Ayr, Ayrshire (Stephenson et al., 2002), though *Radiizonates mirabilis*, an important marker of the latter section, is absent from the sample.

2.23 SAMPLE MPA 50661

Sample depth 240.20 m.

The sample contained very little organic matter.

2.23.1 Interpretation

No age determination can be given

2.24 SAMPLE MPA 50662

Sample depth 232.45 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and moderately preserved dark brown palynomorphs in equal measure. The assemblage contained:

Colatisporites spp.
Schopfites claviger
Colatisporites decorus
Colatisporites denticulatus
Auroraspora cf. *macra*
Retusotriletes sp.
Plicatispora scolecophora
Dibolisporites distinctus
Discernisporites micromanifestus
Spelaeotriletes sp.
Grandispora echinata
Auroraspora macra

2.24.1 Interpretation

The presence of *Schopfites claviger* and *Auroraspora macra* suggests that this sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977).

2.25 SAMPLE MPA 50663

Sample depth 223.8 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and AOM but also contained rare very poorly preserved black/opaque palynomorphs including: *Retusotriletes* spp., *Acanthotriletes* cf. *macrogaleatus* *Spelaeotriletes pretiosus* and *Anaplanisporites baccatus*.

2.25.1 Interpretation

Although *Schopfites claviger* and *Auroraspora macra* were not identified in the assemblage, the presence of *Acanthotriletes* cf. *macrogaleatus* suggests a possible correlation with the 'upper Ballagan' at the Heads of Ayr. This correlation must be considered very tentative given the poor preservation of the assemblages.

2.26 SAMPLE MPA 50664

Sample depth 217.8 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments, moderately preserved aquatic algal palynomorphs and AOM. The assemblage contained: *Leiosphaeridia* spp., *Lophosphaeridium* sp. A, *Chomotriletes* spp., ?Algal palynomorph sp. A and cf. *Chomotriletes* sp.

2.26.1 Interpretation

No age determination is possible.

Some of the taxa in the assemblage are likely to be of zygnematacean algal origin; this group of alga is associated with low salinity or freshwater. The significance of abundant large specimens of *Leiosphaeridia* is not known though in a number of Ballagan environments they seem to suggest low salinity or freshwater conditions (Stephenson et al., 2002).

2.27 SAMPLE MPA 50665

Sample depth 210.0 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments, very poorly preserved black/opaque palynomorphs, AOM and rare sheet cellular material. The assemblage contained: *Colatisporites denticulatus*, *Colatisporites decorus*, *Anaplanisporites baccatus*, *Auroraspora* cf. *macra*, *Retusotriletes* spp., *Schopfites claviger* and *Discernisporites micromanifestus*.

2.27.1 Interpretation

This sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977).

2.28 SAMPLE MPA 50666

Sample depth 209.8 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and very poorly preserved black/opaque palynomorphs and AOM. The assemblage contained: *Colatisporites* spp., *Colatisporites denticulatus*, *Auroraspora macra*, *Retusotriletes* spp., *Schopfites claviger*, *Lophosphaeridium* sp. A and *Spelaeotriletes* cf. *pretiosus*.

2.28.1 Interpretation

This sample can be assigned to the Tn3c (latest Tournaisian) CM Biozone of Clayton et al. (1977).

2.29 SAMPLE MPA 50667

Sample depth 205.75 m.

The sample yielded a sparse organic residue consisting mainly of black equant woody fragments and very poorly preserved black/opaque palynomorphs in equal measure. The assemblage contained: ?*Colatisporites* sp., *Schopfites claviger* and *Rugospora polyptycha*.

2.29.1 Interpretation

The poor preservation of taxa in the assemblage makes age determination difficult; however the assemblage seems to be closely similar to MPA 50662 (232.45 m depth) and probably belongs to the same biozone.

2.30 SAMPLE MPA 50668

Sample 198.70 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and very poorly preserved black/opaque palynomorphs in equal measure. The assemblage contained no spores identifiable to species or genus level.

2.30.1 Interpretation

No age determination can be given.

2.31 SAMPLE MPA 50669

Sample depth 195.21 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and very poorly preserved black/opaque palynomorphs in equal measure; also occurring are common sheet cellular material and AOM. The assemblage contained *Lycospora pusilla* and ?*Dictyotriletes* sp..

2.31.1 Interpretation

The poor preservation of taxa makes age determination difficult; however the assemblage is likely to be at least of Pu Biozone (earliest Viséan) age (Clayton et al., 1977).

2.32 SAMPLE MPA 50670

Sample depth 184 m.

The sample yielded a rich organic residue consisting mainly of black equant woody fragments and very poorly preserved black/opaque palynomorphs in equal measure; also occurring are common sheet cellular material and AOM. The assemblage contained: *Lycospora pusilla*, ?*Dictyotriletes* sp. and ?*Schulzospora* sp..

2.32.1 Interpretation

The assemblage is likely to be at least TC Biozone in age if *Schulzospora* is present (Clayton et al., 1977).

Note:

Samples reported on by Turner (1995) were also included in this study (see Figure 1). Taxa recorded by Turner (1995) were also recorded by the present author, however *Pustulatisporites dolbii* (indicative of the LL-PC Biozones, Higgs et al., 1988), not recorded by Turner, was noted in Sample MPA 30030, (320.17 m depth).

3 Palynofacies

The organic residue of the samples was classified into: amorphous organic matter (AOM), woody material, algal aquatic material, spores and cuticle/sheet cellular material. The palynofacies composition of Ballagan samples is shown in Figure 2.

4 Palaeoenvironmental analysis

In order to understand the development of the palaeoenvironments of the Ballagan Formation in the Glenrothes Borehole, an attempt has been made to integrate wireline logs, sedimentology, palynology, ostracods and palynofacies.

4.1 PALYNOFACIES

The assemblages of the Glenrothes Borehole, and to a large extent of the sequence at the Heads of Ayr can be split into two types:

4.1.1 Type 1 Aquatic algal

Woody material (usually equant black fragments) is the most common type of organic matter in these assemblages but the palynomorph component of the assemblages is dominated by aquatic algal bodies (filaments, spores and ?cysts), mainly *Leiosphaeridia* spp., *Chomotriletes* spp., *Botryococcus* spp., Cf. *Tetraporina* spp., Cf. *Peltacystia* sp., *Lophosphaeridium* sp. A and *Reduviasporonites* spp.. Such assemblages contain terrestrially-derived spores, but these are usually rare and poorly preserved.

4.1.2 Type 2 Terrestrially-derived

These assemblages contain approximately equal amounts of woody fragments and well preserved terrestrially derived spores; also present are AOM and sheet cellular material. Aquatic algal bodies are usually not present. Woody fragments in these assemblages are, as in type 1 assemblages, dominated by small equant black fragments, but elongate fragments and fragments plainly derived from lignin of vascular plants also occur.

4.2 LITHOFACIES (S JONES)

The strong distinction in palynofacies is to some extent reflected in lithology. Type 1 assemblages are almost exclusively associated with grey to light gray calcareous siltstones that are pervasively desiccation-cracked or show other evidence of near subaerial exposure, for example, palaeosols (Plate 20). In these samples, lamination is poorly defined or deformed by desiccation.

Type 2 assemblages are recovered from dark, rather less calcareous siltstone, that shows no evidence of desiccation cracks and in which lamination is well defined (Plate 21).

4.3 WIRELINE LOGS (S JONES)

The gamma trace for the Ballagan Formation between 230 m and 380 m depth in the Glenrothes Borehole (Figure 3) illustrates a number of very marked troughs that correspond with:

probable anhydrite/gypsum horizons;

probable carbonate rich laminated sediments (cementstones);

probable carbonate rich, pervasively desiccation-cracked sediments;

probable carbonate rich red-brown palaeosols.

The gamma lows therefore probably indicate 'shallowing' events. The darker, well-laminated, less carbonate-rich siltstones appear to be associated with gamma highs and the fact that fish fossils are found in these intervals (Figure 3), may suggest that they indicate deeper water conditions of sufficient persistence to allow fish to develop.

Overall, wireline logs suggest that between 230 and 360 m depth in the Glenrothes Borehole the Ballagan Formation can be divided into a lower sequence deposited in shallow water and frequently sub aerial conditions (partly conforming with the Mains of Errol Member), and an upper section in which more persistent aquatic conditions occur. This appears to be supported by the greater occurrence of fish fossils in this upper part.

4.4 OSTRACODS

The distribution of ostracods in the Glenrothes Borehole in relation to palynology is summarised in Figure 1. Ostracods of the Glenrothes borehole are described more fully by Williams (2001). The absence of *Sulcella* cf. *affiliata* in the Glenrothes Borehole may indicate that the ‘uppermost Ballagan’ (*sensu* Heads of Ayr) may not be present, though another interpretation of the evidence is that this absence, and the overall scarcity of ostracods in the upper part of the Ballagan may suggest freshwater-brackish rather than marine conditions.

Samples analysed in parallel for palynology and ostracods indicate that aquatic algal spores of the zygnemataceae indicate low salinity conditions. At 357.80 m depth in the Glenrothes Borehole a sample dominated by the zygnemataceae contains the fresh/brackish water ostracod *Shemonaella* cf. *scotoburdigalensis*. Correlation of autochthonous algal assemblages and ostracod faunas will be of further use in palaeoenvironmental determinations.

4.5 SYNTHESIS

In previous work at the Heads of Ayr (Stephenson et al. 2002; Stephenson, 2001), it was suggested that assemblages dominated by algal spores (i.e. Type 1 assemblages) may be indicative of impersistent low salinity lakes on low gradient coastal plains, and that the inverse relationship between terrestrially derived and autochthonous algal palynomorphs may be explained by local lacustrine drowning of terrestrial plant communities.

The sedimentological and facies evidence presented here appears however to favour relatively shallow water conditions for Type 1 assemblages since the latter are associated mainly with dessication cracked sediments near anhydrite/gypsum and carbonate rich horizons. Zygnematacean algae are today most associated with freshwater or low salinity lakes or small stagnant ponds (Van Geel and Grenfell, 1996) and their spores allow the algae to overcome unfavourable conditions (e.g. drying of temporary pools).

It is now thought likely that Type 1 assemblages contain few spores possibly because of contemporaneous weathering, repeated wetting and drying and or alkaline dissolution (Playford and Dettmann, 1996; Traverse, 1988). The dominance of simple black fragments in the palynofacies of these samples, as opposed to more variable delicate palynofacies types, tends to support this suggestion. Lithologies that show very strong dessication cracking and gypsum/anhydrite development are generally barren.

The occurrence in such conditions of moderately well preserved algal bodies, including algal spores, is difficult to explain unless they were released in small stagnant pools on the ground surface and were fortuitously preserved due to later burial. Such pools may have developed due to local shortlived rises in water table. Similar colonisation by zygnematacean algae (Van Geel, 1978) due to water table rise has been recorded from Holocene sediments.

In Ayrshire, distinctive algal palynomorph assemblages containing *Leiosphaeridia* sp. A (Stephenson et al., 2002) allowed correlation between the Ballagan at the coast and inland at Straiton. Similar very distinctive algal assemblages occur in the Glenrothes Borehole and may be useful in local correlation.

5 Correlation

In view of the few samples so far analysed and the so-far patchy recovery, correlations of the Ballagan Formation in the Glenrothes Borehole are necessarily tentative; however it seems likely that lower parts of the Ballagan Formation are present in the Glenrothes Borehole than in the

section at the Heads of Ayr. The presence of *Pustulatisporites dolbii* (recorded only from the LL-PC Biozones, Higgs et al., 1988) and the absence of *Schopfites claviger* suggests that the sequence below 309.6 m depth may be assignable to the PC Biozone (Tn2b/c to Tn3a age, Higgs et al., 1988).

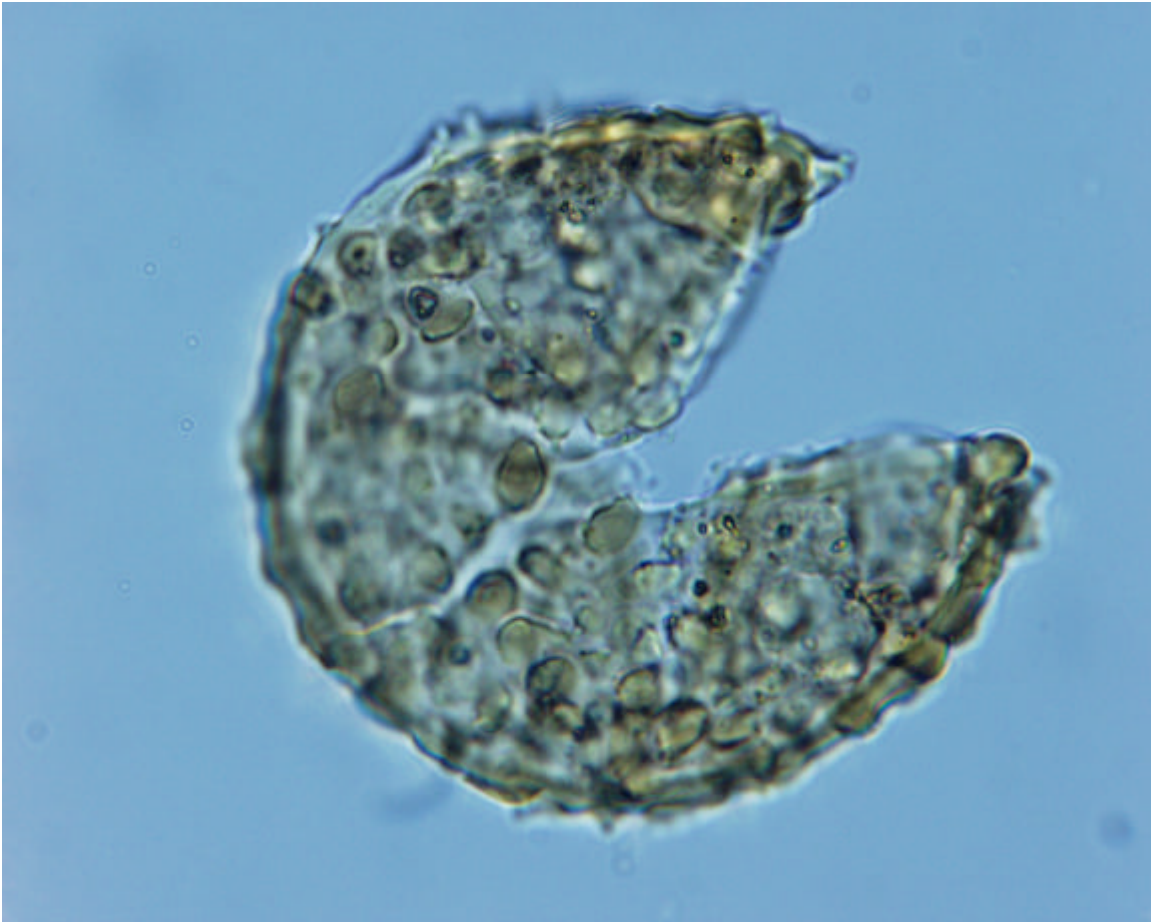
The upper parts of the Ballagan Formation in the Glenrothes Borehole are difficult to relate to other sequences due to the poor preservation above approximately 250 m depth due to high maturation. Only the sample from 246.0 m depth (MPA 50660) yielded an assemblage comparable to those of the 'upper Ballagan' at the Heads of Ayr, since *Spelaeotriletes microspinosus* and *Acanthotriletes* cf. *macrogleatus* are present.

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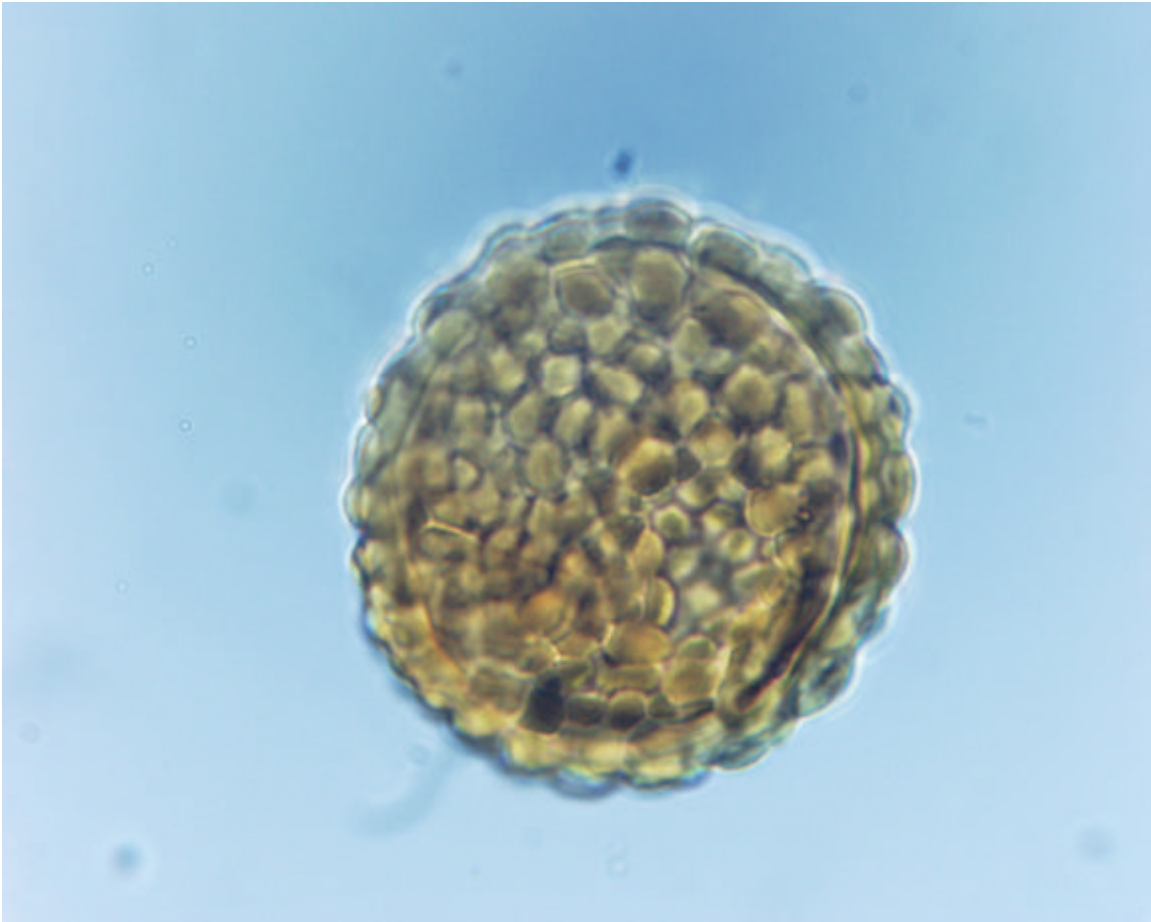
Pustulatisporites dolbii, G22/1, 30030



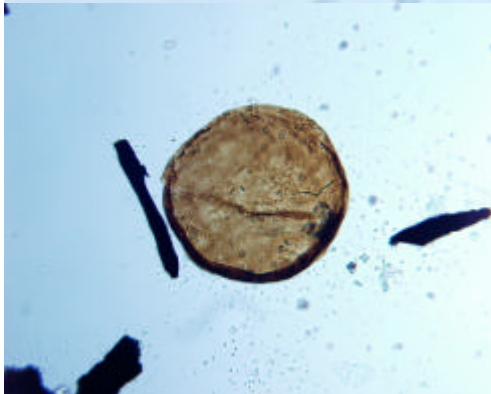
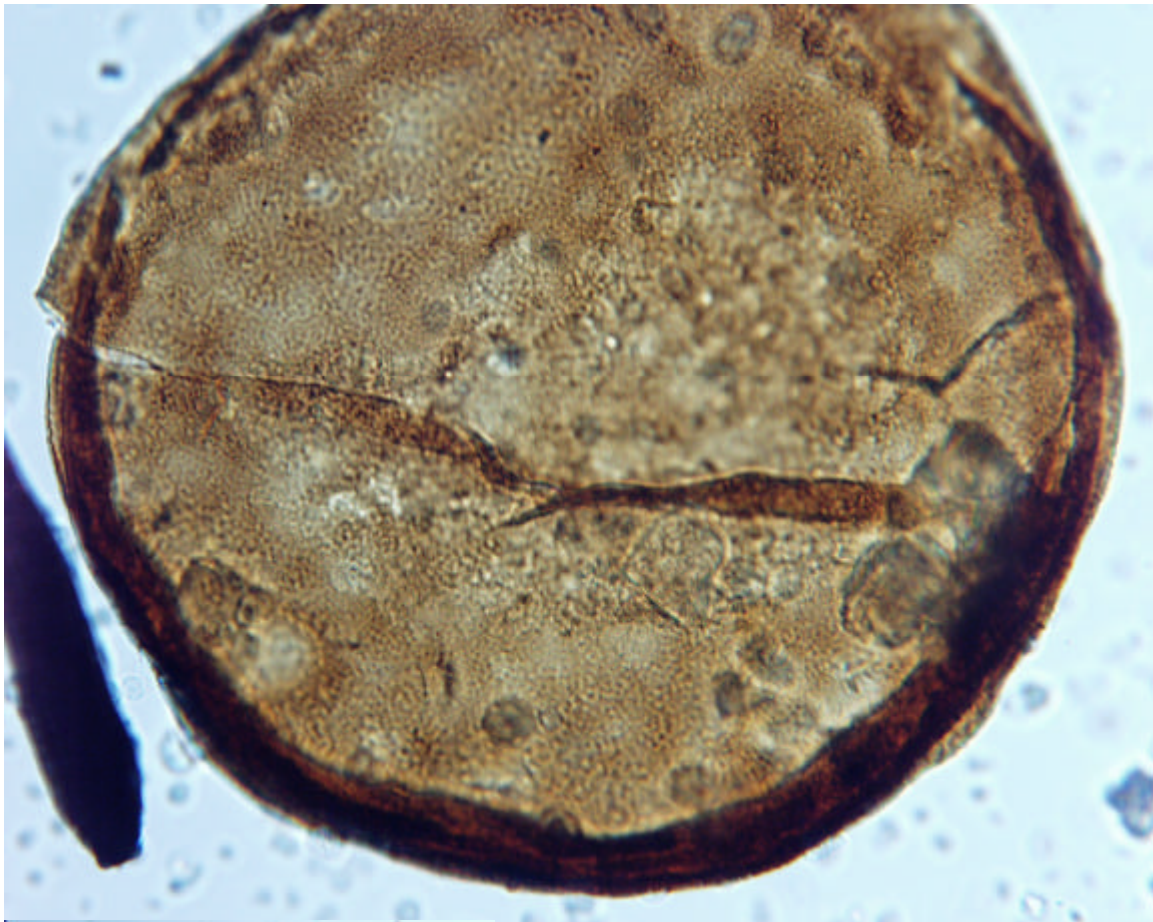
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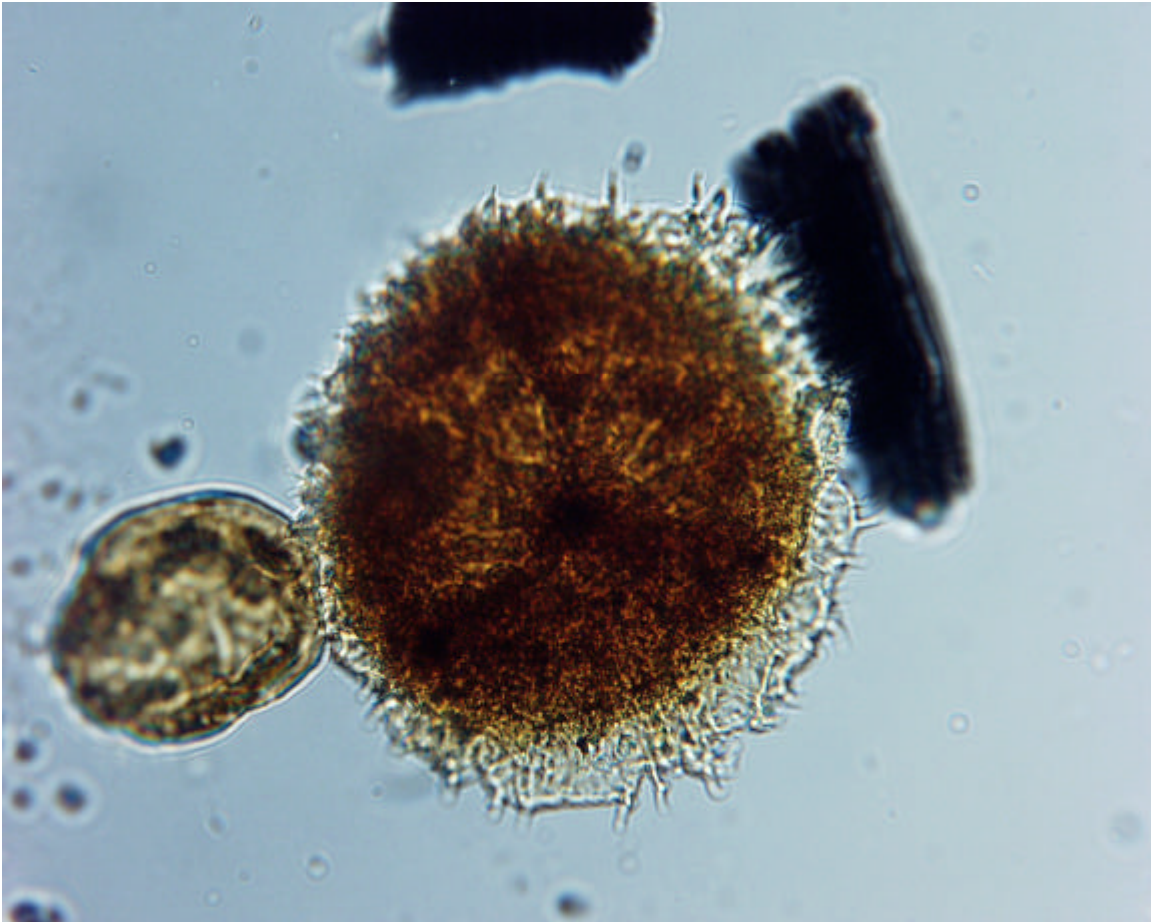
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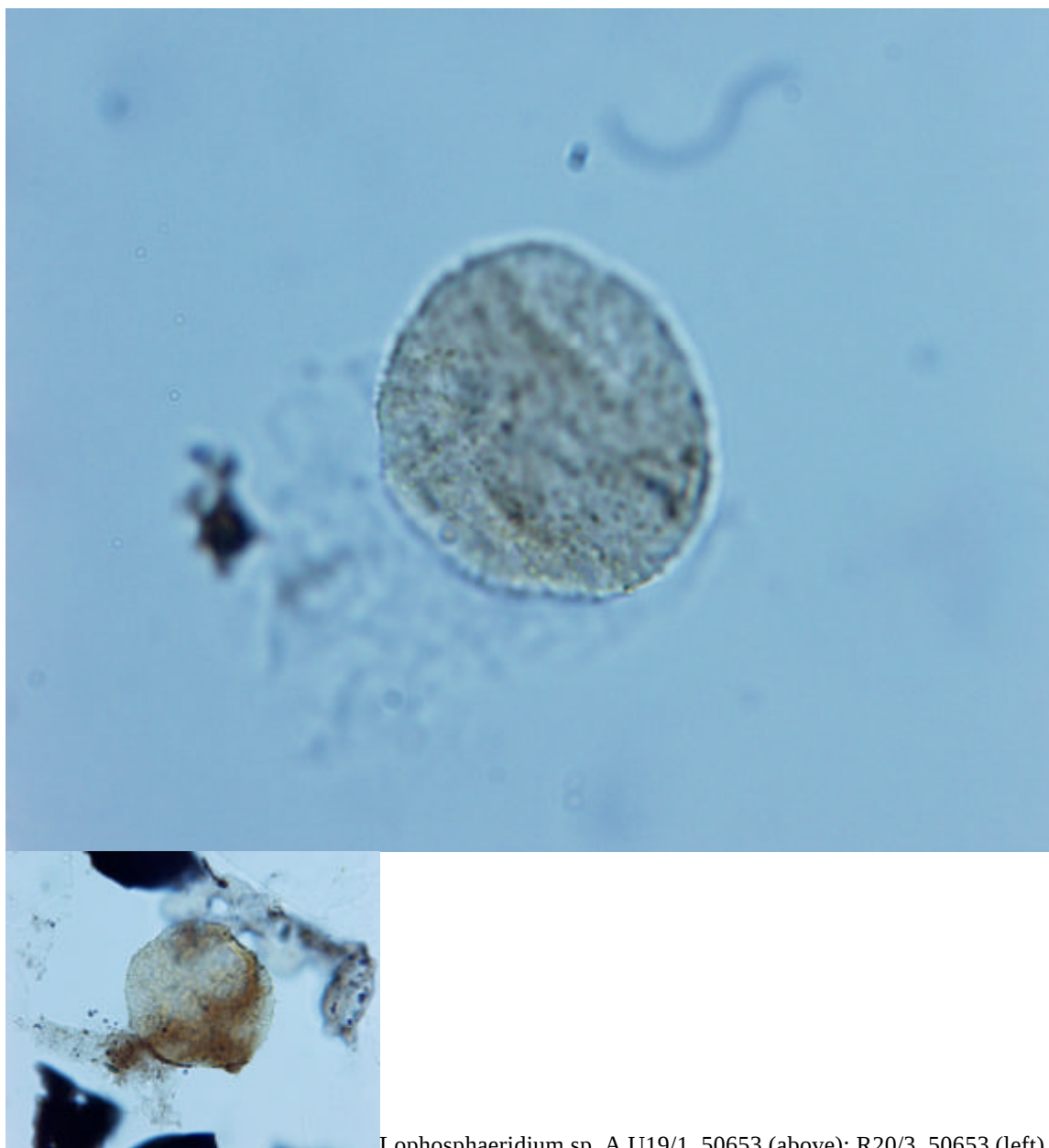
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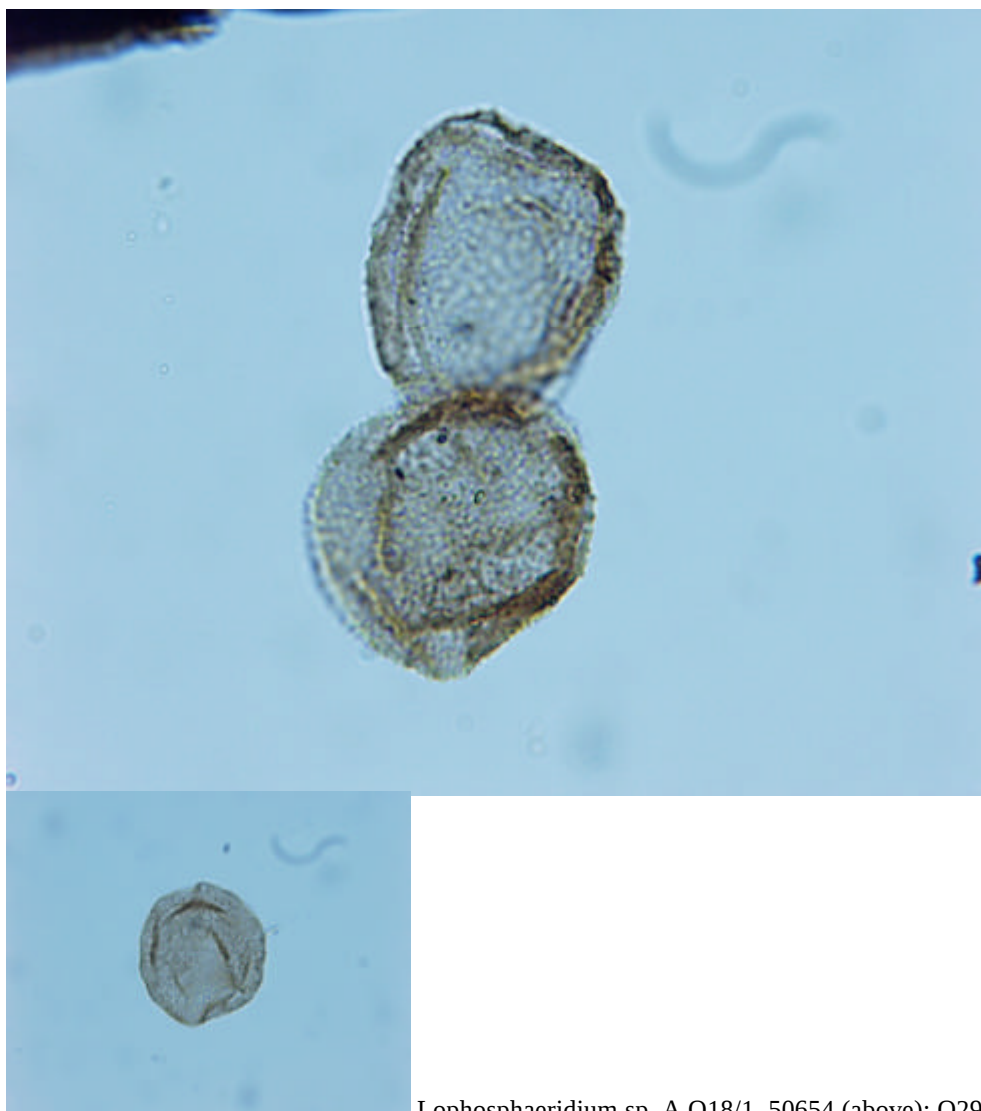
'Monolete spore' of McLean & Neves (2001)



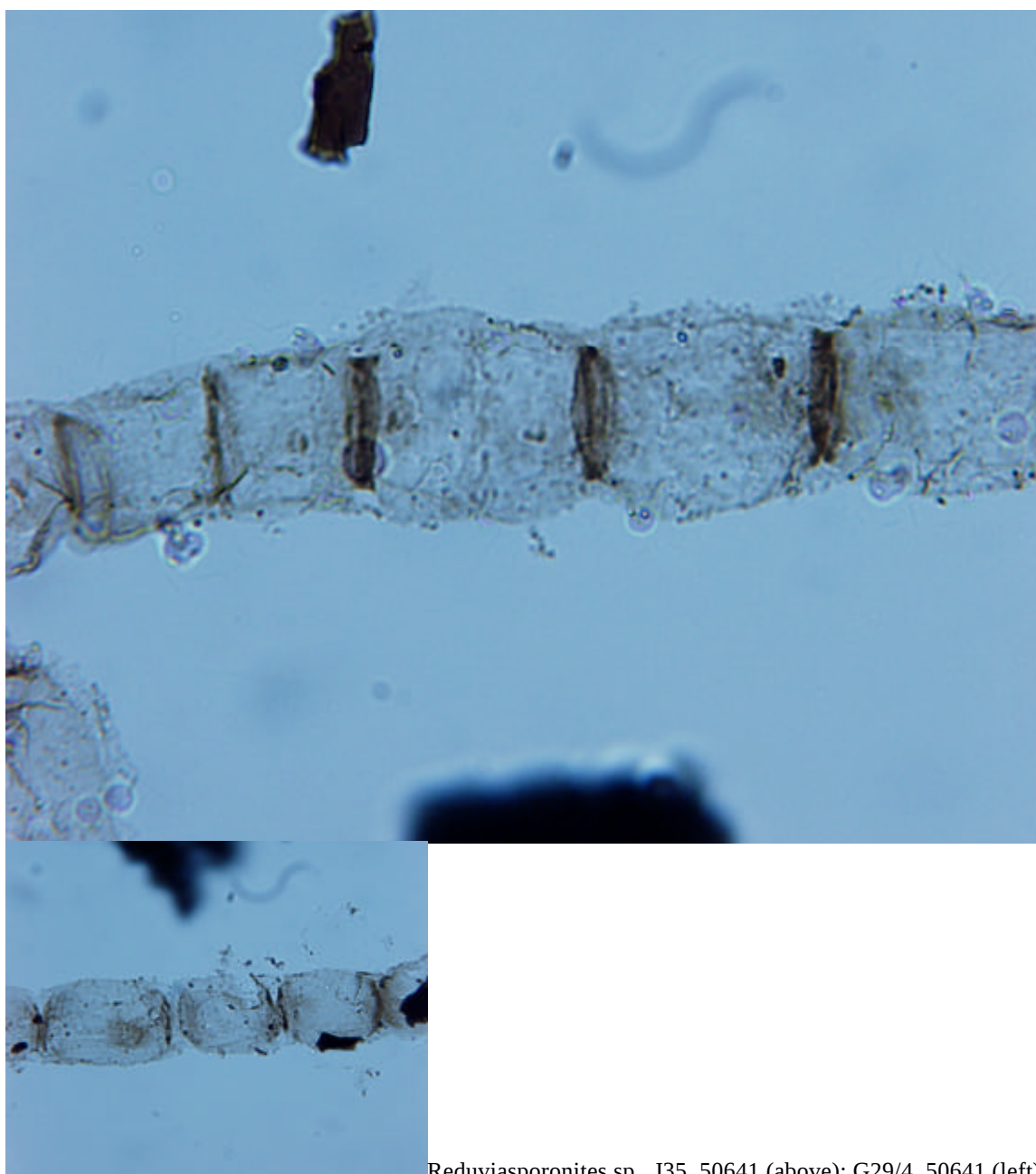
Corystisporites costatus, Q7, 30030



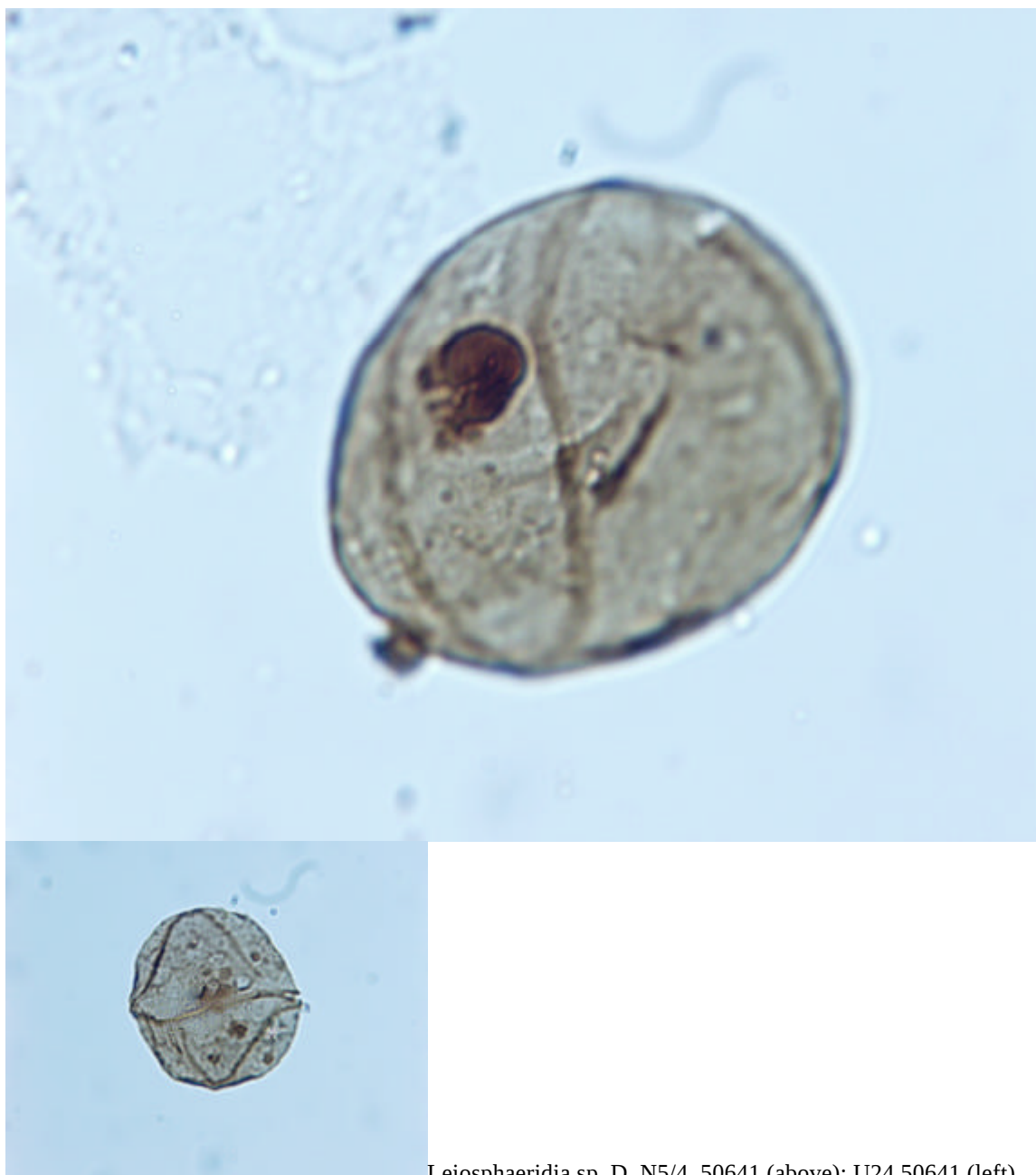
Lophosphaeridium sp. A U19/1, 50653 (above); R20/3, 50653 (left)



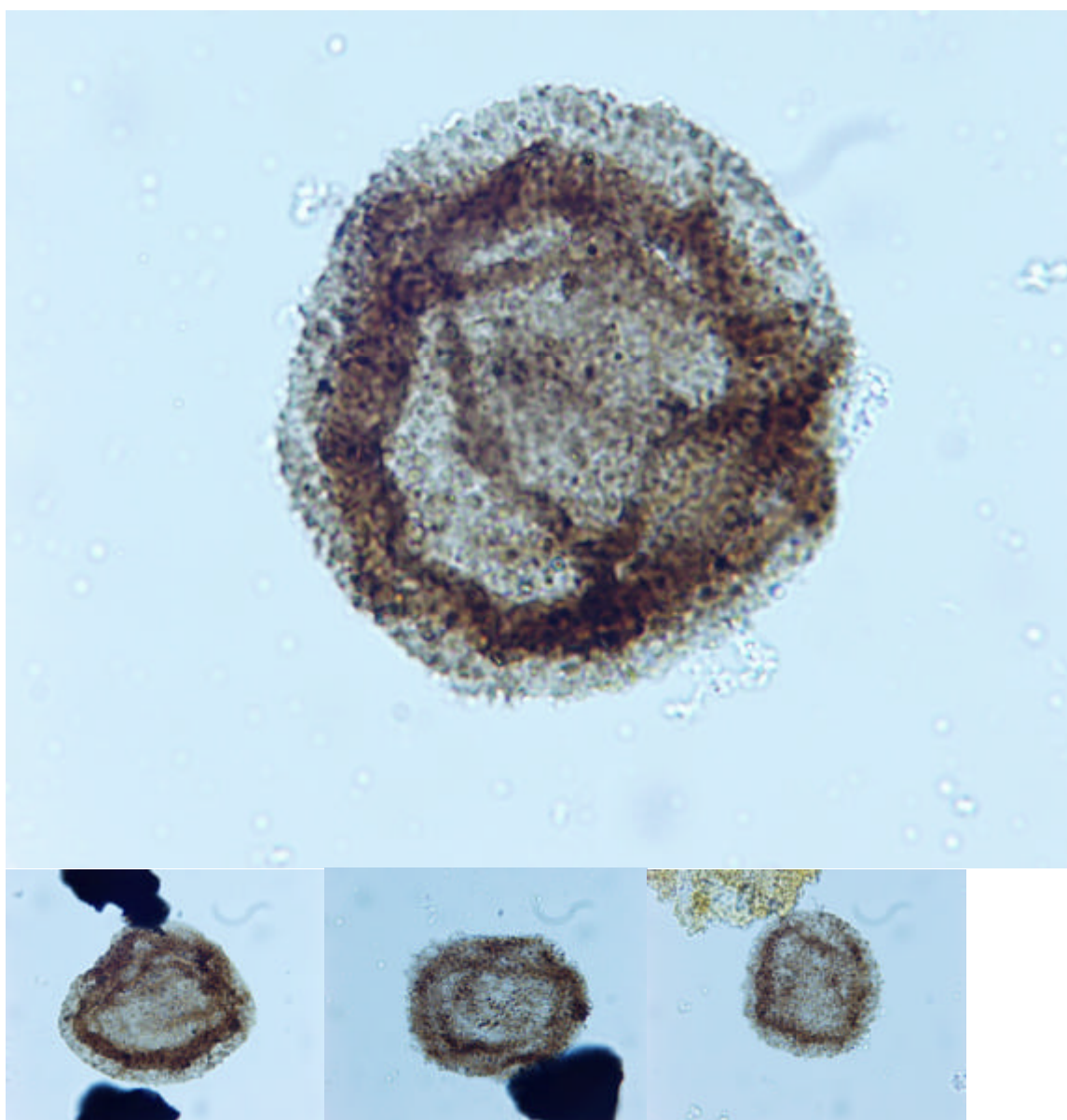
Lophosphaeridium sp. A Q18/1, 50654 (above); Q29/3, 50654 (left)



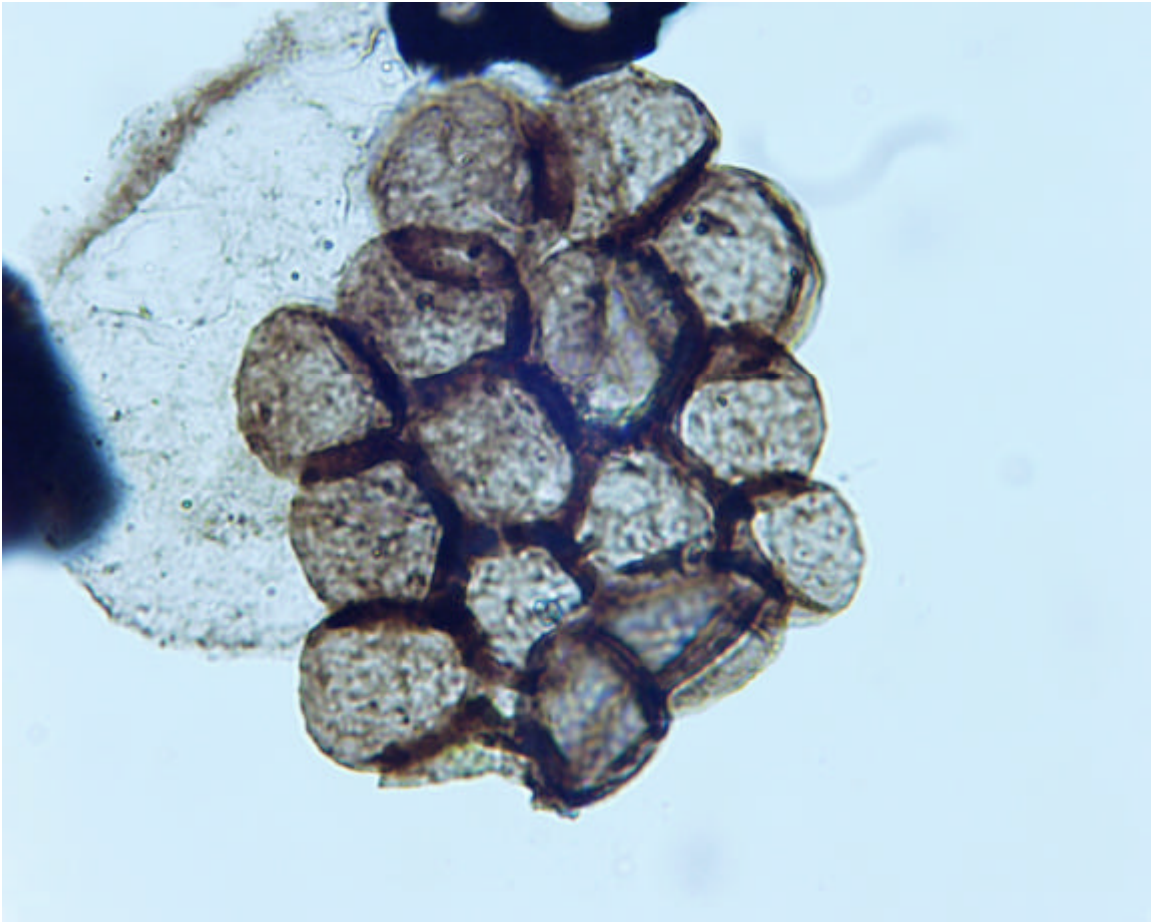
Reduviasporonites sp., J35, 50641 (above); G29/4, 50641 (left)



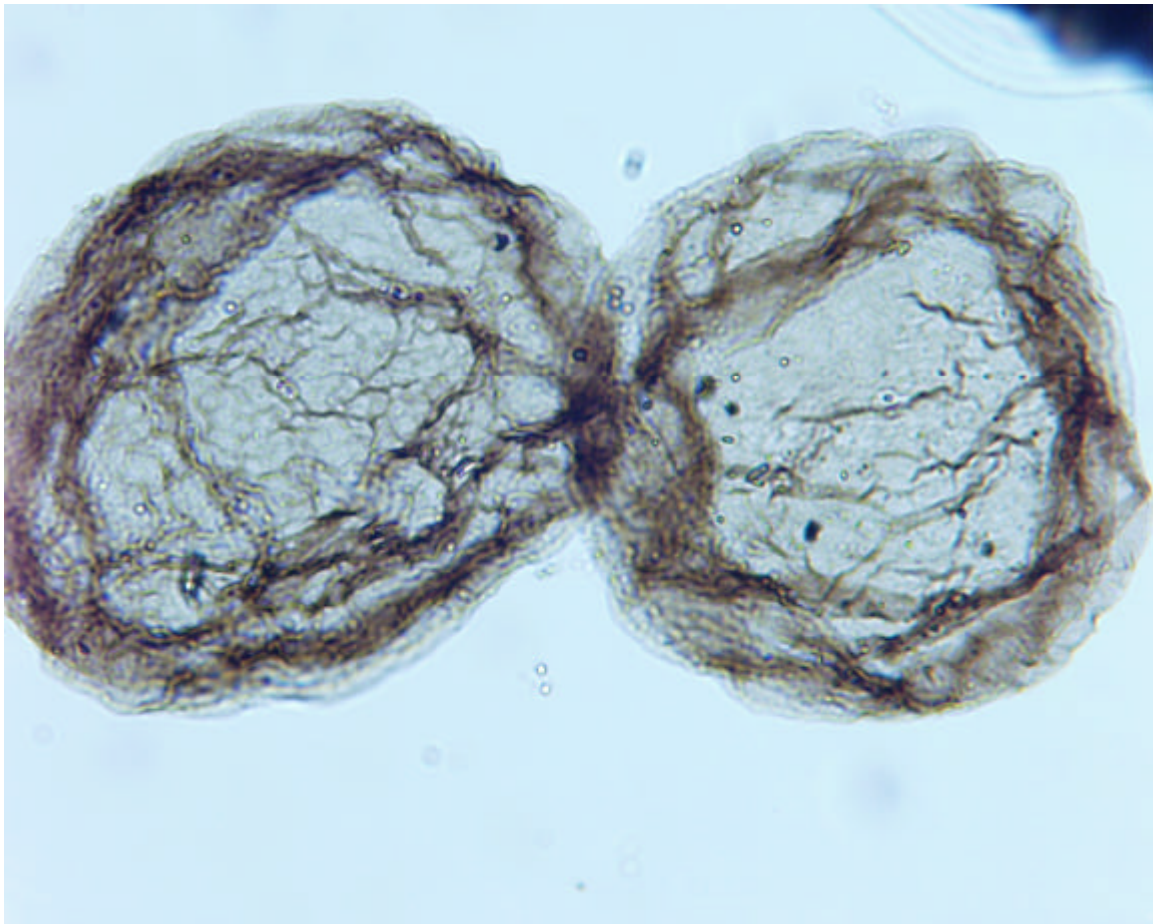
Leiosphaeridia sp. D, N5/4, 50641 (above); U24 50641 (left)



Cf. *Peltacystia* sp. 1 V9/4, 50654 (top); U29/1, 50654 (above left); W18/3, 50654 (above centre); T9 50654 (above right).



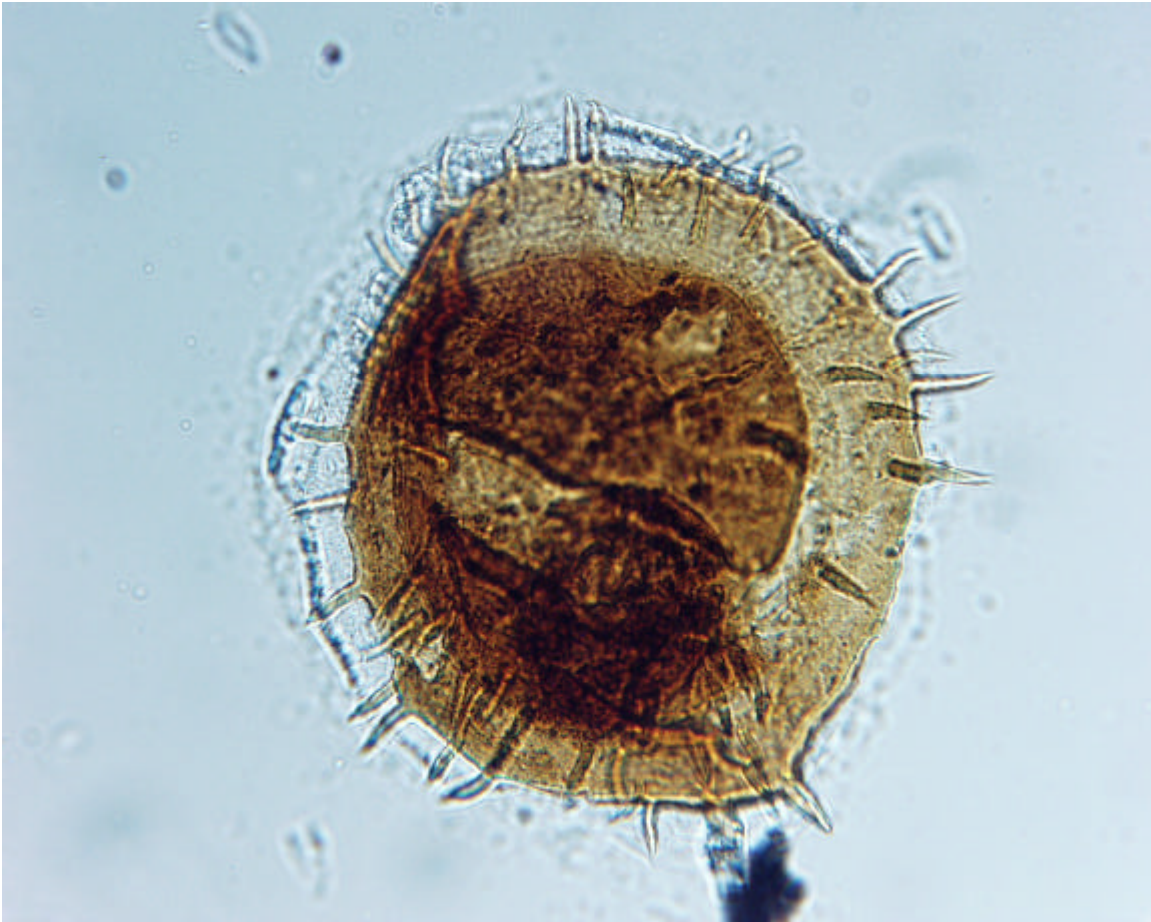
Cf. Palambages sp. M28/2, 50657



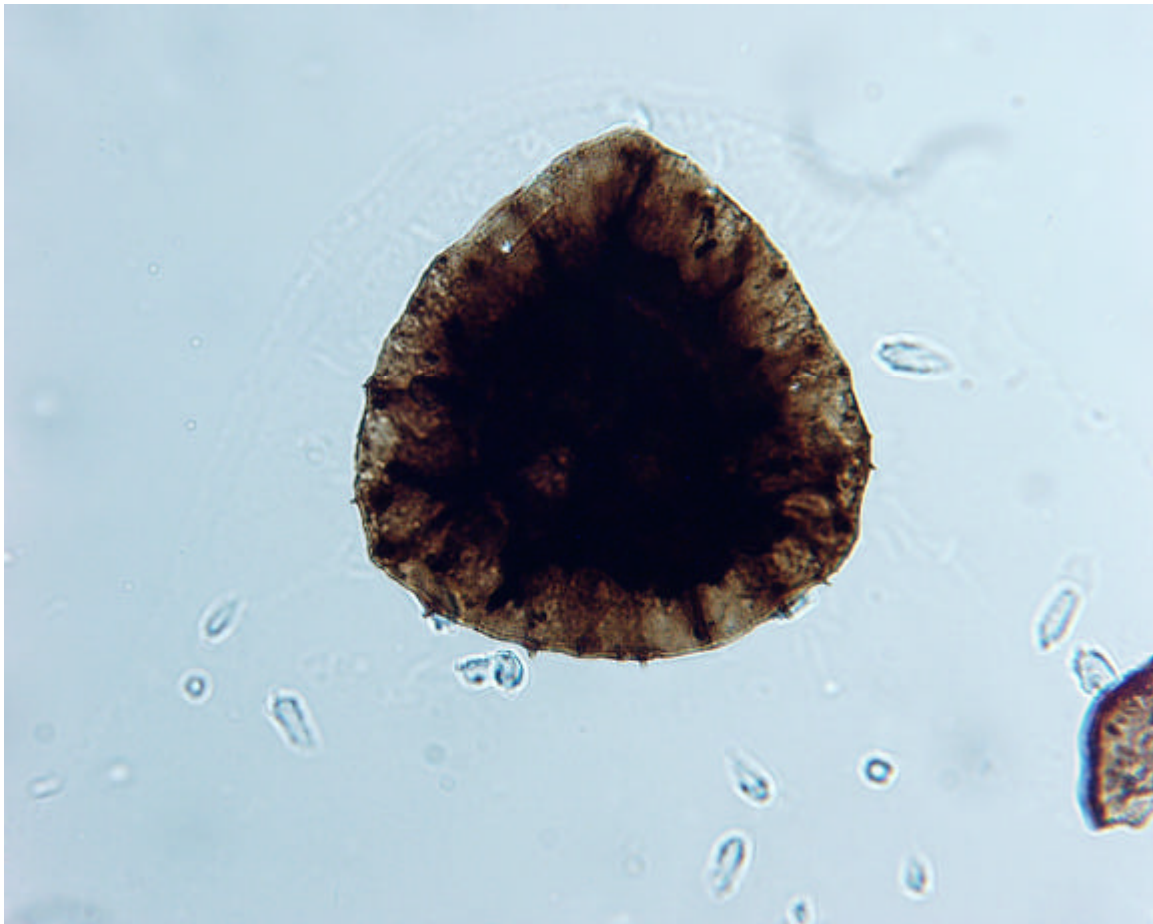
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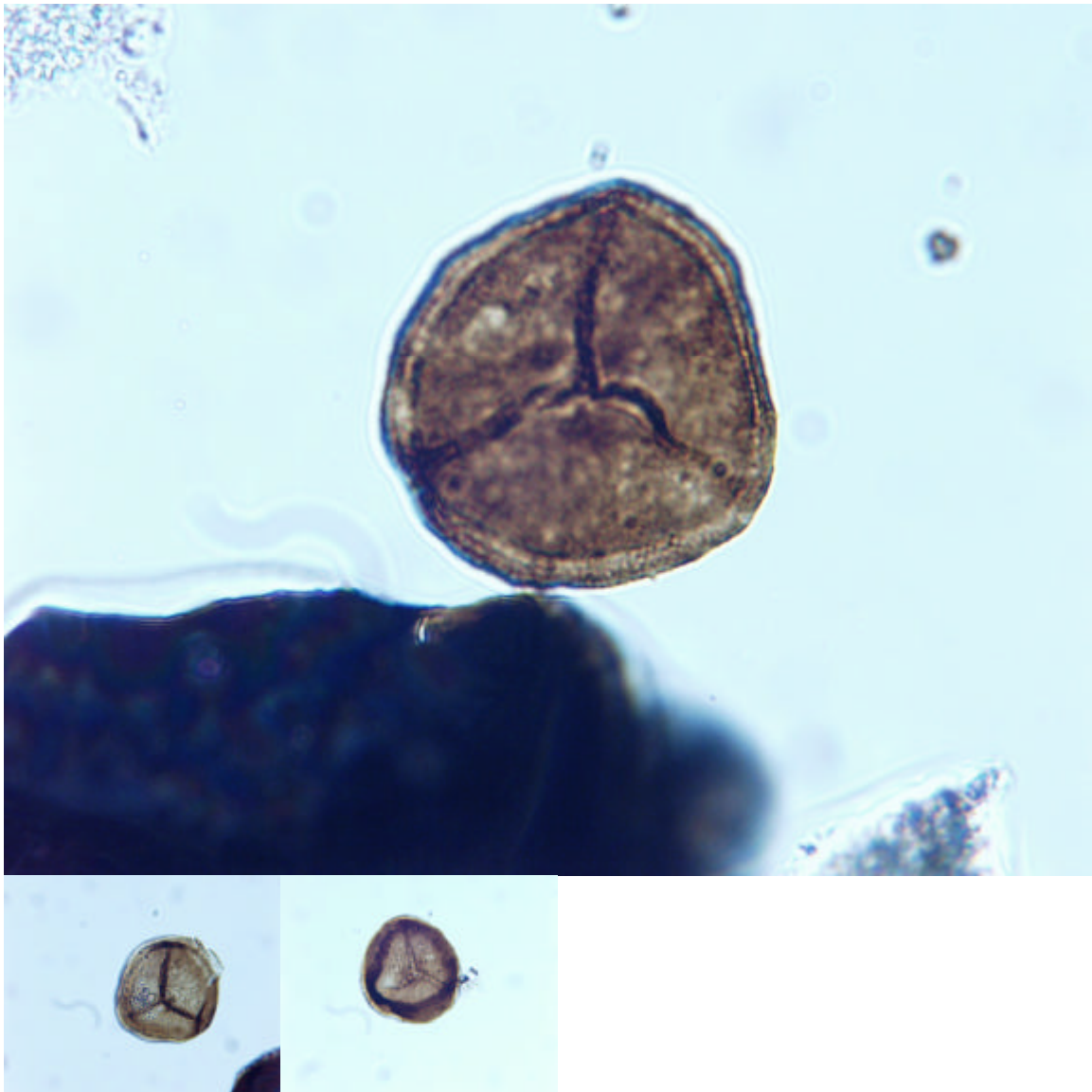
Prolycospora claytonii F18/2, 50656



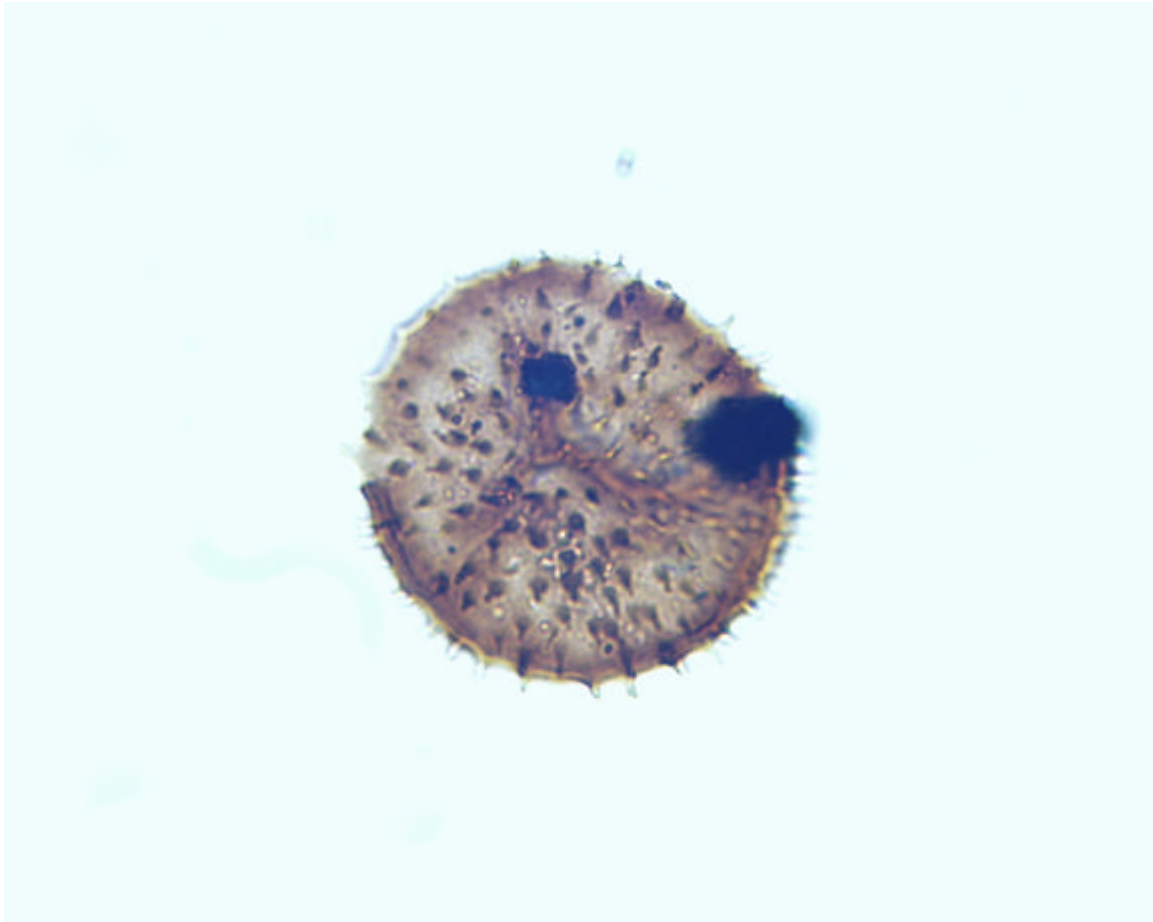
Spinozonotriletes uncatus P12/2, 30025



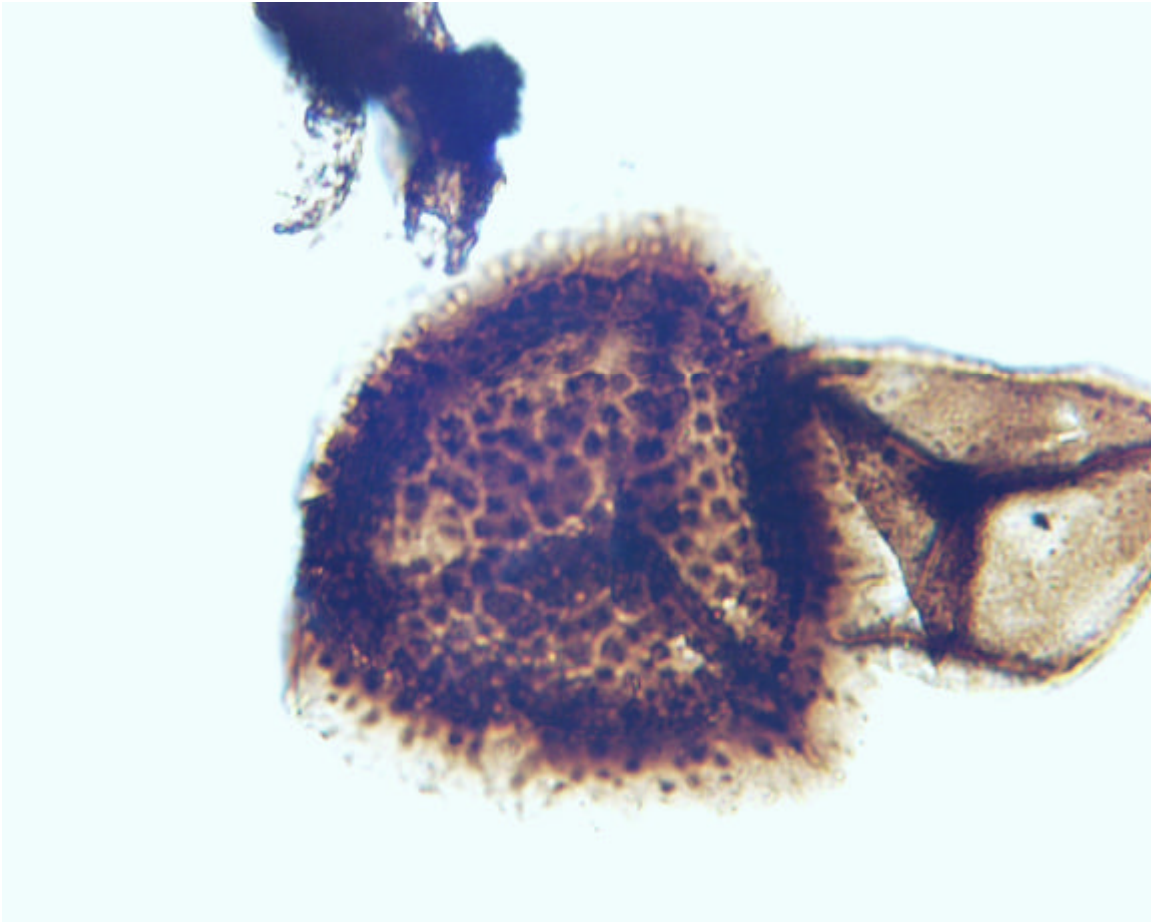
Cristatisporites bellus O18/4, 30025



Cf. *Spelaetriletes* sp. O23, 50660(2) (top); P27, 50660(2) (above left); P7, 50660 (above right).



Brevitriletes cf. *hennellyi* P14/3, 50660(2)



Vallatisporites sp. R12, 50660(2)



Lithofacies: Type 1 Aquatic algal; 357.80m



Lithofacies: Type 1 Aquatic algal; 327.0m



Lithofacies: Type 2 Terrestrially-derived palynomorphs 277.03m



Lithofacies: Type 2 Terrestrially-derived palynomorphs 246.0m