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Cretaceous biozonation based on terrestrial palynomorphs from two wells in the offshore Orange Basin of South Africa

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The C-B1 and O-A1 petroleum exploration wells were drilled by SOEKOR Pty Ltd in 1988 and 1992, respectively, in the Orange Basin off the west coast of South Africa. A palynological analysis of the Cretaceous interval intersected by the two wells, for which the ages were adopted from foraminiferal studies, provides new information on the biostratigraphy and also on reconstructions of the Cretaceous palaeoflora and palaeoenvironment. The spores and pollen used in this study were extracted from over 500 samples of conventional cores, side-wall cores and ditch-cuttings. The identified terrestrial palynoflora includes 41 species of angiosperm and gymnosperm pollen, 85 species of fern and bryophyte spores, and two monolete spore taxa. Several of the pollen and spore taxa are possibly new species. Five palynological zones were established for each of the two wells, which are separated by a latitudinal distance of 300 km. Within the Early Cretaceous intervals of the two wells, there is a considerable degree of similarity in the palynological assemblages, which suggests that the terrestrial plant communities were relatively uniform. For the Late Cretaceous interval, however, there are marked differences suggesting that the plant communities had become more diverse and also that the palynomorphs were being supplied from separate geographical areas.

Keywords: South Atlantic, marine sediments, pollen, spores, Southern Hemisphere, Mesozoic.

INTRODUCTION

Onshore, Cretaceous sedimentary rocks in South Africa are preserved largely in the east within the Zululand and Algoa Basins and also within a series of smaller basins in the southern Cape between Worcester and Port Elizabeth. However, they are best represented in the thick successions of the sedimentary basins off the west, south and east coasts where they have been extensively drilled in the course of petroleum exploration since 1968. The focus of interest in the present publication is the offshore Orange Basin (Fig. 1), where 38 petroleum exploration wells have been drilled since 1976 by SOEKOR and other exploration companies. In addition, the DSDP 361 well was drilled in 1975 under the international Deep Sea Drilling Programme (Bolli *et al.* 1978).

Few palynological studies have been published on the spores and pollen of either the onshore or the offshore deposits. Publications relating to the onshore deposits include Martin (1960), Scott (1976), De Villiers & Cadman (1997, 2001), Oboh-Ikuenobe & de Villiers (2003) and Scholtz (1985), and for the offshore areas, Brown *et al.* (1995), McLachlan & Pieterse (1978), Zavada & Benson (1987) and Zavada (2004).

The fossil Cretaceous vegetation of South Africa is generally regarded as belonging to the southern Gondwanean floral province (Herngreen & Chlonova 1981). Studies of the spores and pollen led researchers (Scott 1976; McLachlan & Pieterse 1978; Sandersen 2007) to conclude that the Early Cretaceous assemblages from South Africa correspond well with forms described from elsewhere in the southern hemisphere (Dettmann 1963, 1981). However, with the breakup of East Gondwana (separation of South Africa from Antarctica, India, Australia, Madagascar about 150 million years ago) and of West Gondwana (separation of Africa from South America about 130 million years ago), South Africa became progressively distanced from the other continents (Dingle & Scrutton 1974). Correspondingly, the pollen assemblages presented by Scholtz (1985) and de Villiers & Cadman (1997, 2001) have clear southern African characteristics in the younger Cretaceous to Palaeogene palynofloras.

To further investigate these conclusions, a quantitative study was undertaken by Sandersen (2007) on samples from the Cretaceous sections of the C-B1 and O-A1 petroleum exploration wells which were drilled by the national petroleum exploration company, SOEKOR, in 1988 and 1992 respectively, in the Orange Basin, 50 to 100 km offshore from the present day coastline (Fig. 1). The ages assigned to the stratigraphic sections of the O-A1 and C-B1 wells were provided by the Petroleum Agency SA and are based on extensive and carefully calibrated foraminiferal studies carried out over several decades.

MATERIALS AND METHODS

The palynogical slides used in this study were kindly provided by the Petroleum Agency SA. They were originally prepared by SOEKOR from side-wall cores and ditch-cuttings. SOEKOR's standard palynological processing involved digestion of the sediment samples in hydrochloric and hydrofluoric acids, followed by a zinc chloride heavy liquid separation to remove mineral particles. A

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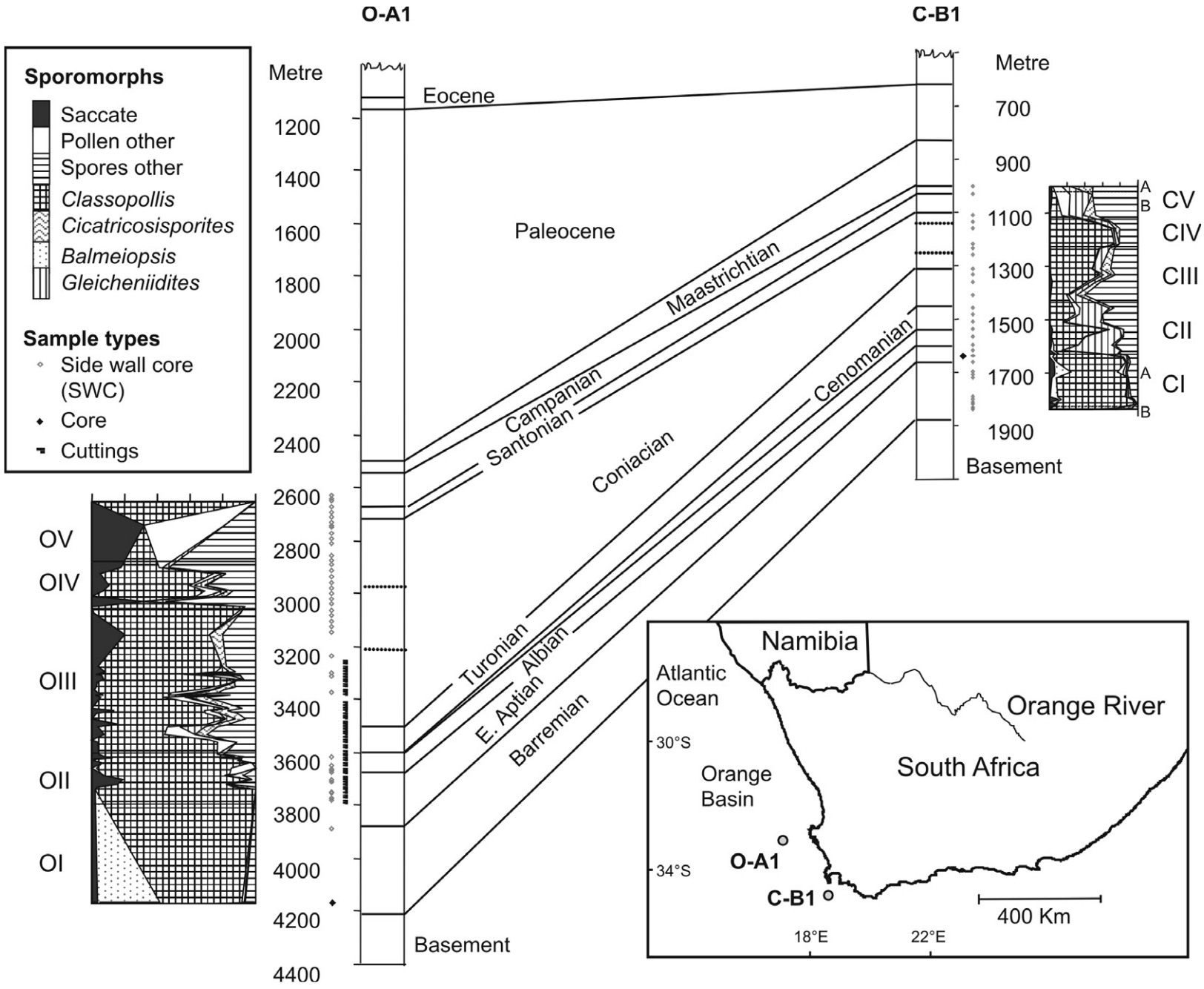


Figure 1. Locality map, idealized stratigraphic sequences and summary of pollen and spore groups for wells C-B1 and O-A1 (only the productive Cretaceous levels are indicated in the sporomorph diagram).

strew slide mounted in glycerine jelly was then prepared for petroleum source rock evaluation and a second slide for taxonomic study was made from a portion of the palynological residue, which had been subject to oxidation with dilute nitric acid, followed by staining with alizarine red.

It is important to note however, that a certain amount of down-hole contamination of palynomorphs can be expected in the slides derived from ditch-cuttings, as it is not possible to remove all traces of drilling mud and contaminating rock chips prior to palynological processing. The net effect of this is that palynomorphs from younger, stratigraphically higher formations can be expected in palynological slides prepared from older, lower formations. To counter this problem, during drilling, SOEKOR acquired a large number of side-wall cores which were carefully cleaned of contaminating drilling mud before palynological processing was started (Fig. 1). The samples prepared from the carefully cleaned conventional cores also provide control on down-hole contamination.

The palynological study was carried out under oil immersion using a ×100 objective lens on a Zeiss Axioskop Petrographic microscope at the Bernard Price Institute for Palaeontological Research, University of the Witwatersrand. The number of palynomorphs counted depended on their richness, with the ideal number of 500 only achieved in the slides containing the Late Cretaceous organic residue. Data presentation and zonation were done by means of the Tilia*Graph and CONISS programs (Grimm 1987).

The palynomorphs identified from offshore wells C-B1 and O-A1 are not formally described here. They were classified by Sandersen (2007) in a modified 'turma' system based on the methods of classification of form genera adopted by several authors, including van der Hammen (1956), Potonié (1956), Dettmann (1963) and Burger (1966), but here they are only listed according to their broad plant taxonomic affinities (Appendix 1).

GEOLOGICAL DETAILS

The Orange Basin constitutes the quintessential passive margin that formed during the break up of West Gondwana and the associated rifting and opening of the South Atlantic Ocean. The Late Jurassic to Early Cretaceous syn-rift portion of the basin is characterized by a series of grabens and half-grabens that trend approximately parallel to the present day coastline. The sedimentary fill comprises predominantly siliciclastic marine and lacustrine beds as well as volcanic rocks (Paton *et al.* 2007). Most of the syn-rift sequences were deposited immediately to the east of the marginal ridge, and within isolated half-grabens on the middle and inner shelf. Sediment at this time was transported into the Orange Basin by the palaeo-Orange and -Olifants Rivers which were fed by large drainage basins (Emery *et al.* 1975; Bolli *et al.* 1978a,b; Gerrard & Smith 1980; Dingle *et al.* 1983; Dingle & Hendey 1984; Broad *et al.* 2006).

The post-rift Barremian/early Aptian sequence corresponds to a transitional phase between the syn-rift and drift successions (Paton *et al.* 2007), during which time the best quality petroleum source rock was deposited. This sequence is overlain by more than 5500 m of Late Cretaceous shales and claystones. Paton *et al.* (2007) recognized eight sequence stratigraphic units within the Cretaceous Orange Basin. In this model the syn-rift successions (Berriasian, Valanganian and early Hauterivian age) are unconformably overlain by transitional systems (late Hauterivian to late Barremian age), which in turn are unconformably overlain by drift sequences (Aptian to Maastrichtian age). The contact between the Barremian and lower Aptian successions therefore constitutes the drift-onset unconformity. Several of these unconformities occur within the time spans covered in boreholes O-A1 and C-B1 (Paton *et al.* 2007).

RESULTS

A summary of the most prevalent groups found in the pollen assemblages is shown in Fig. 1. Detailed pollen diagrams are presented in Figs 2 and 3. All recorded palynomorph taxa are documented in Figs 4–14 and in Appendix 1.

The palynomorph yield of the processed samples ranged from barren to highly productive. Some major information gaps due to low sampling resolution and poor palynomorph yield occur in the Early Cretaceous part of well O-A1 (Fig. 1). Overall, the study wells O-A1 and C-B1 (Figs 2 and 3, respectively) yielded 133 distinct sporomorph types that included 41 species of pollen, 85 species of trilete spores, two species of monolete spores, four types of algal structures and one type of fungal spore. The pollen diagram for well O-A1 (Fig. 2) and C-B1 (Fig. 3) were divided into five zones each (OI, OII, OIII, OIV, OV and CI, CII, CIII, CIV, CV) with sub-zones only in C-B1 (CI-A and -B, CV-A and -B). The palynological zones and subzones described are believed to reflect the main changes in vegetation in the hinterland.

The gymnospermous cheirolepidacean pollen *Classopollis,* shows strong variation in relative abundance and is generally the most prominent pollen type in both the Early and Late Cretaceous intervals at both well sites. A variety of spores of non-vascular and vascular plants are also prominent along with a fair quantity of saccate and other gymnosperm pollen. Although appearing in the Early Cretaceous interval of both wells, tricolpate angiosperm pollen grains are more noticeable in the upper parts.

EARLY CRETACEOUS PERIOD (BARREMIAN TO ALBIAN STAGES)

Zones CI and OI

The most prolific pollen taxon of the Barremian in both these zones is *Classopollis torosus.* This cheirolepidacean conifer probably formed dense woodlands (Srivastava 1976, 1978; Sandersen 2007) along the coastline of this early rift valley (Pocock & Jansonius 1961, Ryere 1970). In the high altitude regions, gymnosperm-rich forests probably flourished which included inaperturate types such as *Zonalapollenites, Balmeiopsis* and *Excessipollenites.* In both the low-lying and high-lying regions of this early

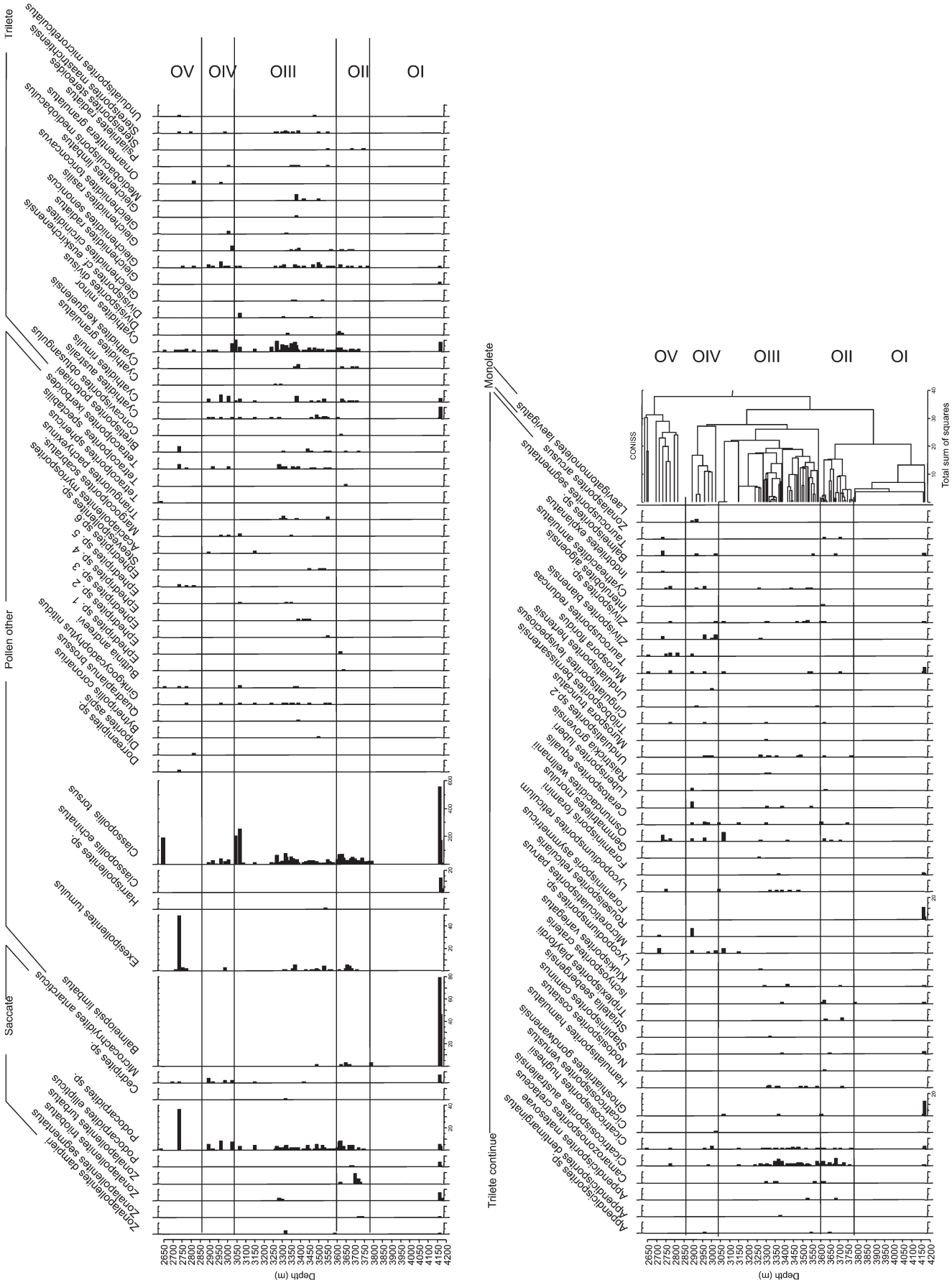


Figure 2. Pollen diagram representing pollen and spore distribution for offshore site O-A1.

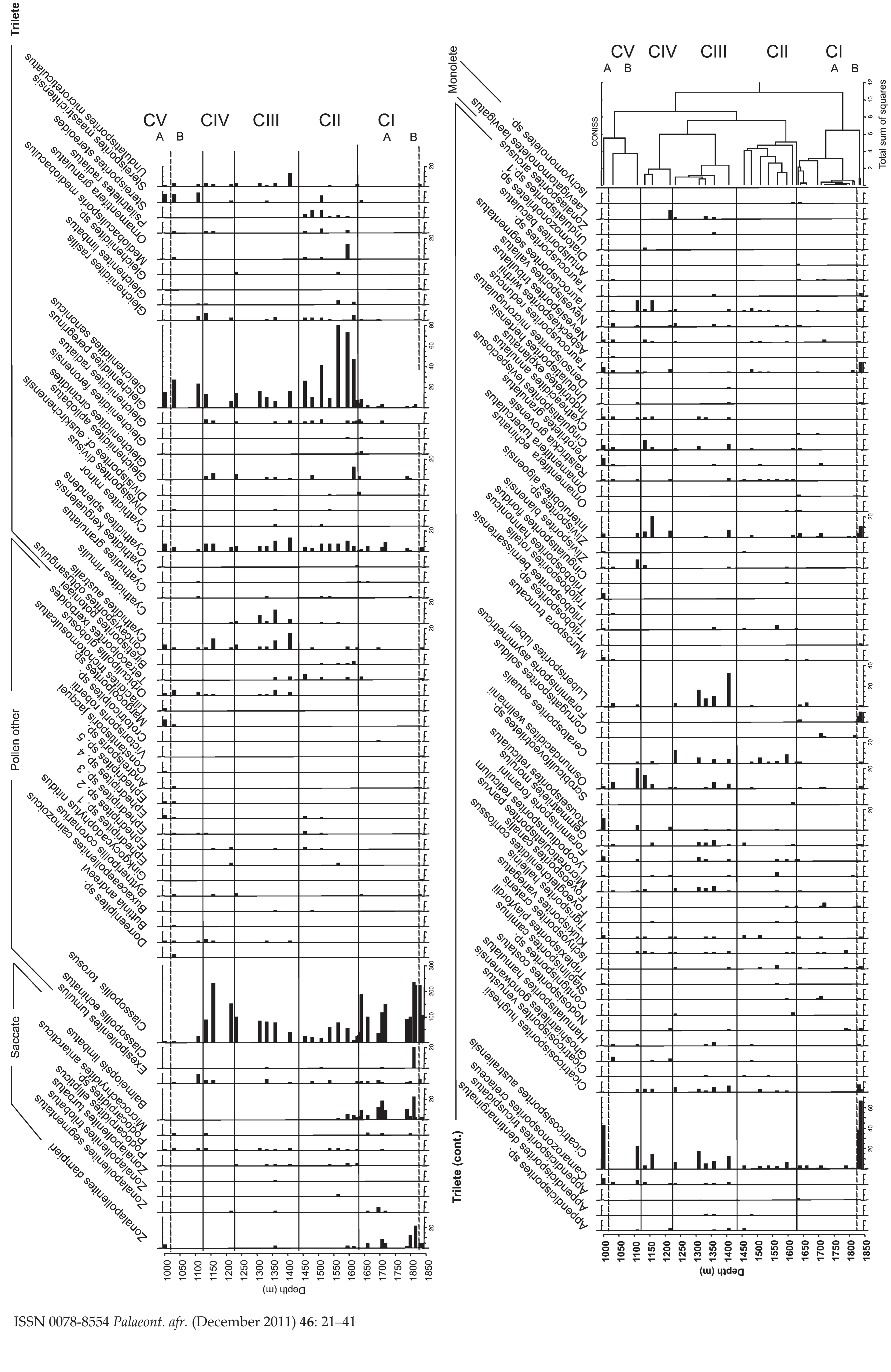


Figure 3. Pollen diagram representing pollen and spore distribution for offshore site C-B1.

rift valley, ferns (*Cicatricosisporites, Gleicheniidites* and *Cyathidities*) and mosses (*Foraminisporis*) probably dominated the ground cover especially around river systems. Both zones contain palynological elements that are typical of Herngreen & Chlonova's (1981) Southern Gondwana province.

SOEKOR assigned a Barremian to Aptian age-range to Zones CI (includes subzones CI-A and CI-B) and OI. Only one pollen grain with columellate semi-tectate sculpture (*Crototricolpites* sp.) which is recorded at the base of Zone CI (subzone CI-A), is typical of the Barremian Stage (Doyle *et al.* 1977; Hickey & Doyle 1977; Hughes *et al.* 1979; Brenner 1984). The second part of Zone CI (subzone CI-B) contains sporomorphs typical in Barremian to Aptian age ranges elsewhere. These include a single, mostly psilate tricolporate pollen grain (*Margotricolporites* sp.), two species of *Gleicheniidites* namely *G. radiatus* and *G. rasilis* that are known to make their first appearances during the Aptian Stage (Krutzsch 1959) and *Foraminisporis asymetricus,* an Early Cretaceous species that according to Krutzsch (1959) and Dettmann (1963) makes its last appearance during the Aptian Stage. None of the 25 palynomorphs identified in Zone OI can be used to support the Barremian age interpreted by SOEKOR based on foraminifera studies because only long ranging taxa were found. However, the Aptian age is supported by the presence of *Gleicheniidites radiatus* and *Foraminisporis asymetricus.* Zones CI and OI therefore represent transitional syn-rift to drift fills of a Barremian to Aptian age.

Zone CII and OII

Zones CII and OII represent deposition during the close of the early rift/late rift and early drift phases, with Africa and South America effectively separated from each other by the end of the Cenomanian Stage.

Coastal-dominated woodlands of cheirolepidacean conifers (*Classopollis*) (Pocock & Jansonius 1961) declined in abundance but still maintained a strong presence in both zones. Terrestrial ferns (*Cyathidities, Gleicheniidites* and *Cicatricosisporites* families) and mosses continued to flourish and were becoming increasingly more diverse. *Gleicheniidites senonicus* was the most dominant of the ferns in Zone CII. The vegetation was slowly becoming more depleted in species such as *Microcachryidites antarcticus* and *Balmeiopsis limbatus,* which were possibly from higher altitudes than the presumed coastal habitat characterized by *Classopollis* (Pocock & Jansonius 1961), and became richer in *Podocarpites* and *Zonalapollenites* pollen. Sedimentation under regressive marine conditions occurred at both sites during the Aptian to Cenomanian stages (Haq *et al.* 1987).

Zone CII is an Early Cretaceous/Late Cretaceous transition zone dated by SOEKOR as Aptian to Turonian in age and Zone OII is dated as Aptian to Albian. The assemblages in both zones are interpreted as Early Cretaceous based on the presence of *Gleicheniidites radiatus,* a species common only to the Aptian. Several palynomorphs also occur in a Late Cretaceous to younger age range such as *Bytneripollis coronaries, Divisisporites divisus, D. euskirchenensis* and *Stereisporites electoides* to name a few.

LATE CRETACEOUS PERIOD (CENOMANIAN TO CAMPANIAN STAGES)

Zones CIII and OIII

The sediments comprising the assemblages of Zones CIII and OIII accumulated during the middle part of the continental drift phase. In comparison to Zones CII and OII, the Cheirolepidacean woodlands gradually repopulated the coastal regions. The higher altitudes were probably covered in dense, evergreen forests of Gymnosperms that produced the pollen species *Excesipollenites* and *Podocapidites* (Srivastava 1976, 1978). Ferns (*Cyathidites, Gleicheniidites* and *Cicatricosisporites* families) and mosses formed the ground cover in the sheltered understories of the forests and woodland regions. A diversity of pteridophyte spores, particularly the presence of *Cyathidites* (Aboula Ela & Mabrouk 1978), and the more abundant *Gleichenia*-like spores and more diverse schizaeaceous derivatives would seem to indicate warmer climatic conditions (Dettmann 1981). Haq *et al.* 1987 indicate that a regression occurred during the Turonian Stage of this zone.

Several angiosperm pollen species, all of them also extending into the Palaeogene, appeared at intervals throughout Zones CIII and OIII. Especially in the case of C–B1 some of these forms have been found in side wall cores, which suggest that this is not simply a case of down-hole contamination. SOEKOR's microfaunal datings indicate a Turonian to middle Coniacian age for both Zones CIII and OIII. However, *Buttinia andreevii,* often found in the Maastrichtian, has been reported by several authors from western Africa and northern South America (Herngreen 1975; Vajda-Santivanez 1999; Vajda & McLoughlin 2005). It does appear for the first time in side-wall cores of Zones OIII and CIII generally supporting a Late Cretaceous age, therefore possibly occurring earlier here than in other records where it is usually found.

Zones CIV and OIV

The sediments representing Zones CIV and OIV accumulated during the middle of the continuing drift phase of continental separation. The presumed high and low altitude palynomorph flora of the previous zones appears to have changed character as a result of shifting vegetation belts. The sea level was high (Haq *et al.* 1987) and stable during this period.

The conifer-dominated woodlands changed noticeably during the deposition of sediments of Zones CIV and OIV. In Zone CIV *Classopollis torosus* sharply increased in relative abundance and peaks at percentages similar to those suggested for Zone CI (Barremian Stage). In comparison the same species of *Classopollis* sharply declined in abundance within Zone OIV. Ferns and mosses, however, continued to dominate the palaeoflora with the most prevalent members continuing to include the long-ranging *Gleicheniidites, Cicatricosisporites* and *Cyathidites* groups. The presence of *Cyathidities* (Aboula Ela & Mabrouk 1978), *Gleicheniidites* and the more diverse schizaeaceous spores supports warm, humid climatic conditions in the lower

altitudes (Dettmann 1981). *Buttinia andreevii* and *Tetracolporites ixerboides* represent an established long-ranging angiosperm flora. Palynomorphs in Zone OIV, suggests the higher altitudes continue to be covered in dense, evergreen forests including *Podocarpidites, Microcachryidites* as well as *Exesipollenites*-producing conifers.

A middle to late Coniacian age range has been suggested for Zones CIV and OIV. As with the previous zones, the palynomorph flora gives very little indication as to the specific age of these zones.

Zones CV and OV

Zone CV (includes subzones CV-A and CV-B) and OV are Late Cretaceous in age and both reflect a shift in sporomorph composition that may in part be a result of selection due to longer transport as the distance from the shore increased. By the late drift phase, the South Atlantic had expanded considerably and deepened to more than 4 km (Thierde & van Andel 1977). Seas were transgressive, up to 200 m higher than today during this Late Cretaceous Period (Haq *et al.* 1987). Zones CV and OV are characterized by a high diversity of angiosperm as well as tropical African palm pollen which signalled a climatic shift from hot and semi-arid to a mixed warm, temperate and humid climate. This setting is reminiscent of the Palmae Province of Herngreen & Chlonova (1981).

Only remnants of the once dense cheirolepidacean woodlands of Zone CI to CIV and OI to OIV remained in both Zones CV and OV. This sudden change may be a result of very high sea levels inundating the low-lying coastal regions thereby terminating once flourishing plant communities.

In Zone CV, the continued diversity and abundance of the pteridophyte spores, particularly the presence of *Cyathidites,* more diverse schizaeaceous spores (*Cicatricosisporites*) and pollen, (*Dorreenipites* sp., *Andreisporis mariae* and *Constantisporis jacquei*) that appear for the first time at the close of this zone, indicates an adaptation to ever changing conditions. Only a few podocarp species remain of the previous diverse high altitude flora. In comparison to Zone CV, the palynomorph flora of Zone OV exhibits a sudden decrease in the diversity of ferns and mosses along with a change in the composition of forests. This change as mentioned earlier could be a result of an advancing sea. The *Gleicheniidites, Cicatricosisporites* and *Cyathidites* species are still present but low in abundance. *Dorreenipites* sp. is the only palm pollen present in this zone unlike Zone CV where numerous members of the palm families are present. The forests, however, continue to support species that include *Exesipollenites, Podocarpidites* and *Microcachryidites.*

Both Zones CV (including subzones CV-A and CV-B) and OV are late Coniacian to Campanian in age. None of the palynomorphs identified in either zone could confirm this age assignment since there are no certain indicator species present.

DISCUSSION AND CONCLUSION

Five palynological zones each, have been defined within the Cretaceous intervals of the two wells studied. Gymnosperms are represented at both well sites by the pollen genera *Classopollis, Podocarpaceae, Zonalapollenites, Balmeiopsis* and *Exesipollenites.* Spores of *Cyathidites, Gleicheniidites* and other schizeaceous types dominated the spore population.

The pollen and spore assemblages of the Early Cretaceous part of the studied well sections are both dominated by gymnosperm pollen (mainly *Classopollis* with fewer saccates) and fern spores, despite their 300 km wide geographic separation, suggesting that the vegetation of the provenance areas from which the spores and pollen derived were relatively homogeneous.

However, during the Late Cretaceous, the spore and pollen assemblages at the two well sites show significant differences but at both locations, angiosperm pollen (including characteristic marker species such as *Buttinia andreevii* and *Bytneripollis coronaries*) is more abundant and diverse. Within the Campanian interval, the angiosperm palynoflora shares many of the characteristics of the Paleogene assemblages (Scholtz 1985).

Our tentative reconstruction of the palaeoflora has been based on the known botanical affinities of the palynomorphs. Considering the current montane habitat of podocarp forests, we may speculate that the Cretaceous forests, which included *Podocarpaceae, Microcachryidites* and *Exesipollenites,* occurred at cooler higher-lying regions on the edges of the newly developing rift valley than the warmer coastal areas that were more typically associated with *Classopollis* (Pocock & Jansonius 1961). The undergrowth included varieties of ferns (*Cyathidites* and other shizeaceous plants) and mosses.

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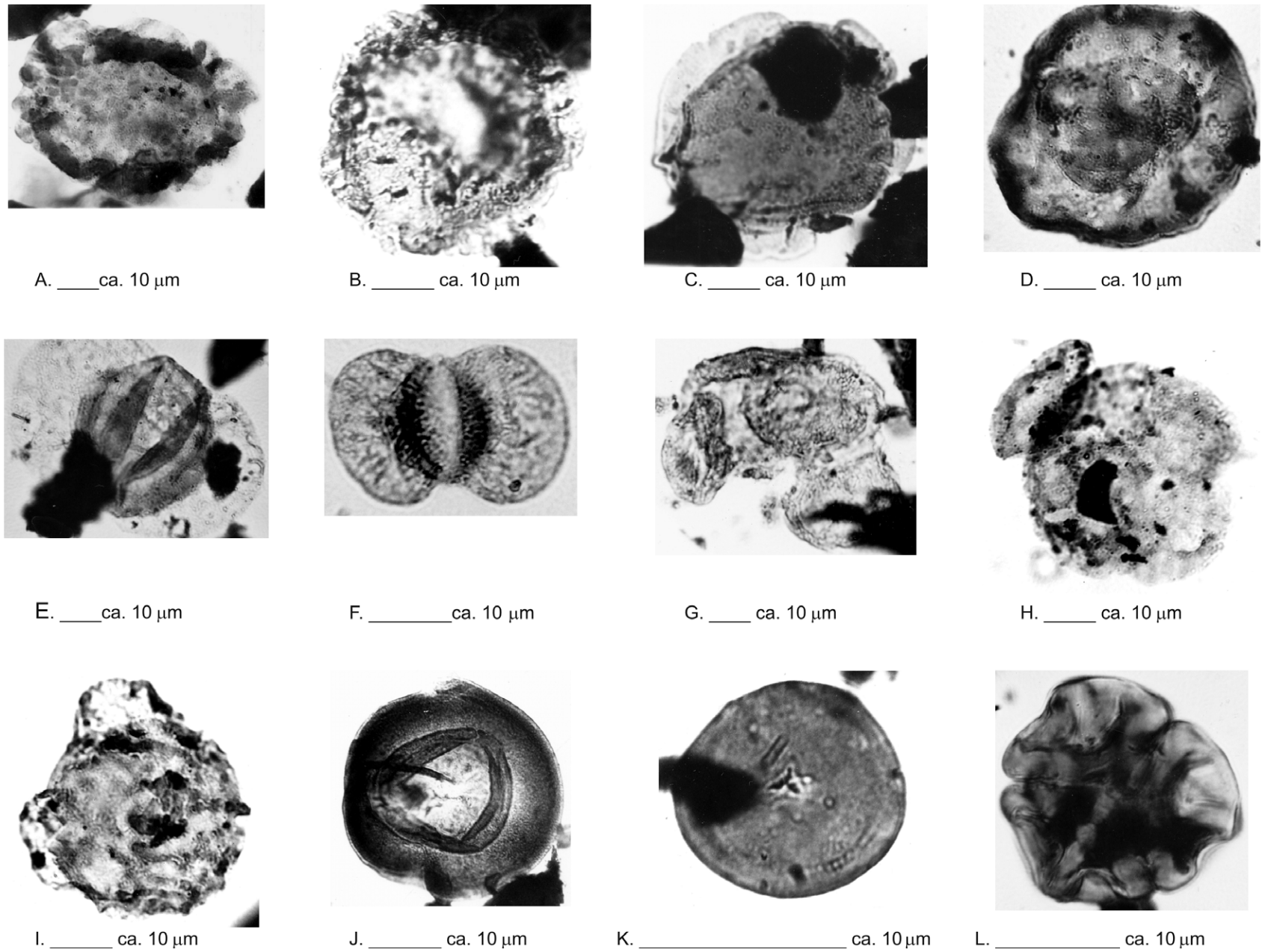


Figure 4. **A**, *Zonalapollenites dampieri* Balme, 1957. **B**, *Zonalapollenites segmentatus* Balme, 1957. **C**, *Zonalapollenites trilobatus* Balme, 1957. **D**, *Zonalapollenites turbatus* Balme, 1957. **E**, *Podocarpidites ellipticus* Cookson, 1947. **F**, *Podocarpidities* sp. **G**, *Cedriptes* sp. **H**, *Lactoripollenites* cf. *L. africanus* Zavada & Benson, 1987. **I**, *Microcachryidites antarcticus* (Cookson) Couper, 1953. **J**, *Balmeiopsis limbatus* (Balme) Archangelsky, 1977 emend. Norvick & Burger, 1976. **K**, *Exesipollenites tumulus* Balme, 1957. **L**, *Harrisipollenites* sp.

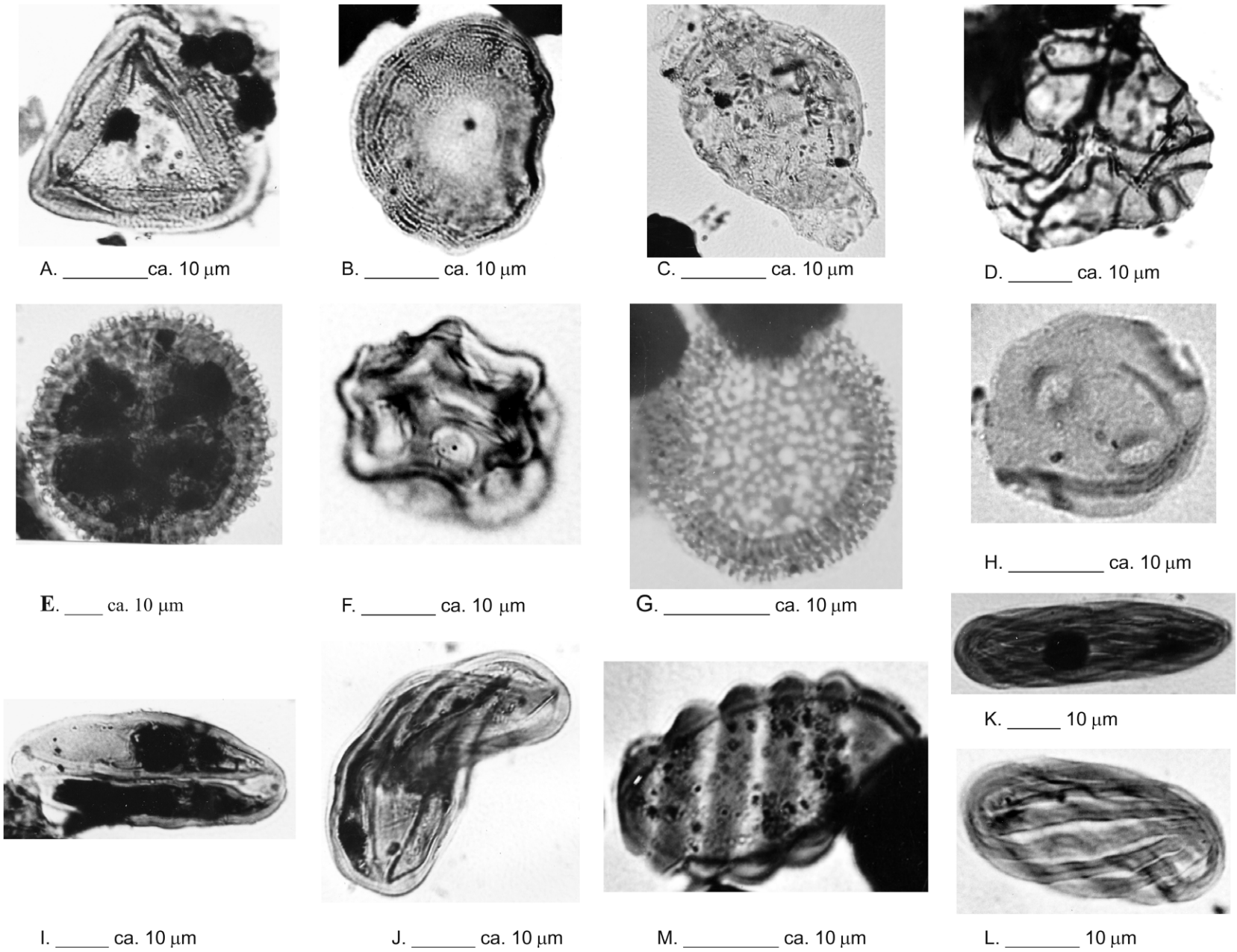


Figure 5. **A**, *Classopollis* cf. *C. echinatus* Burger, 1965. **B**, *Classopollis torosus* (Reissinger, 1950; Balme, 1957) Couper, 1958 emend. Burger, 1965. **C**, *Diporites aspis* Pocknall & Mildenhall, 1984. **D**, *Lycopodiumsporites* sp. **E**, *Quadraplanus brossus* Stover, 1973. **F**, *Buttinia andreevii* Boltenhagen, 1967. **G**, *Buxaceaepollenites cainozoicus* Sah, 1967. **H**, *Bytneripollis coronarius* Konzalová, 1976. **I**, *Ginkocycadophytus nitidus* (Balme) De Jersey, 1962. **J**, *Ephedripites* sp. 1. **K**, *Ephedripites* sp. 2. **L**, *Ephedripites* sp. 3. **M**, Ephedripites sp. 4.

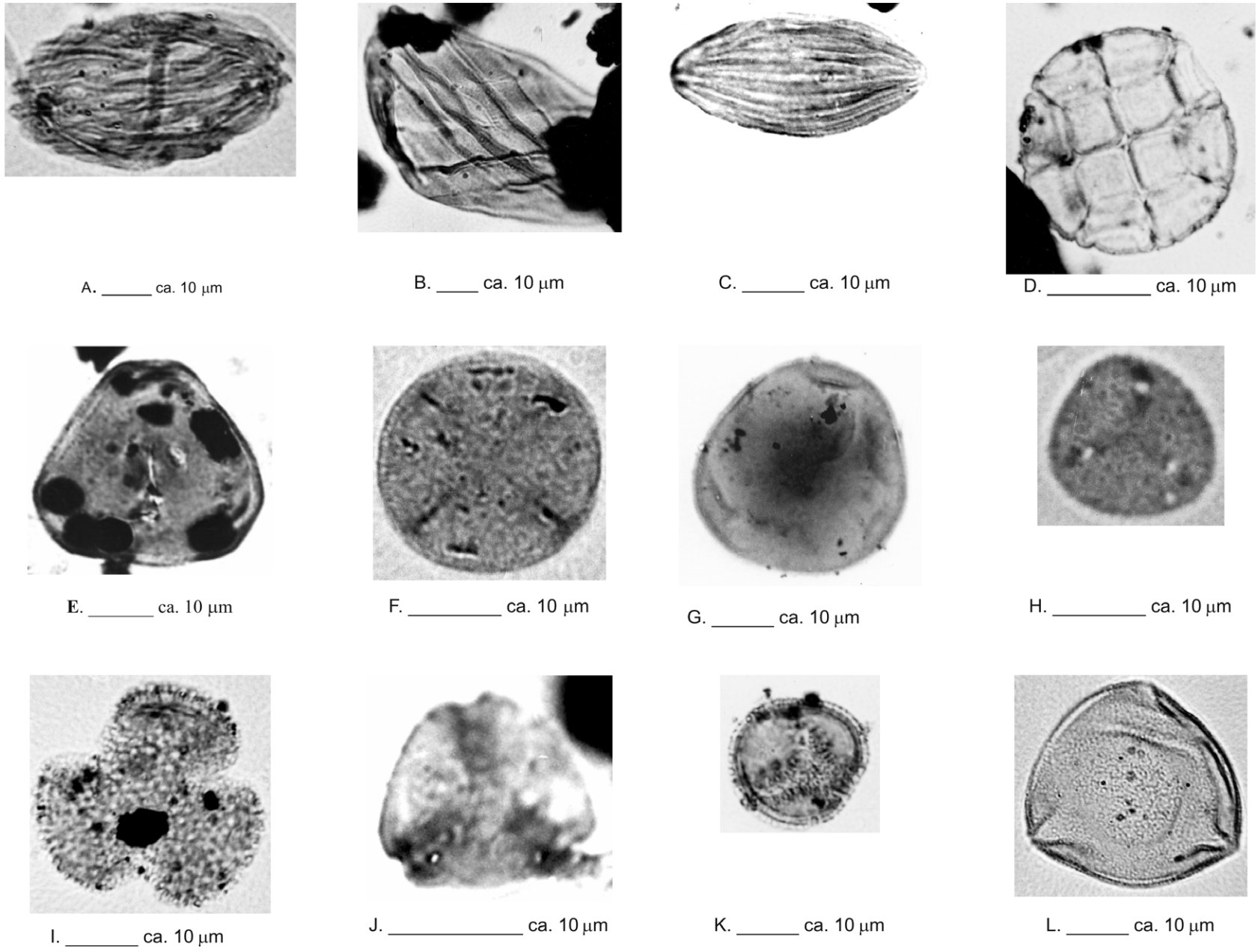


Figure 6. **A**, *Ephedripites* sp. 5. **B**, *Ephedripites* sp. 6. **C**, *Steevipollenites* sp. **D**, *Acaciapollenites myriosporites* (Cookson) Mildenhall, 1972 ex Jansonius & Hills, 1976. **E**, *Andreisporis* cf. *A. mariae* Belsky, Boltenhagen & Potonié, 1965. **F**, *Constantinisporis jacquei* Belsky, Boltenhagen & Potonié, 1965. **G**, *Dorreenipites* sp. **H**, *Victorisporis robertii* Belsky, Boltenhagen & Potonié, 1965. **I**, *Crototricolpites* sp. **J**, *Margocolporites* sp. **K**, *Liliacidites trichotomosulcatus* Singh, 1971. **L**, *Orbiculapollis globosus* Chlonova, 1961.

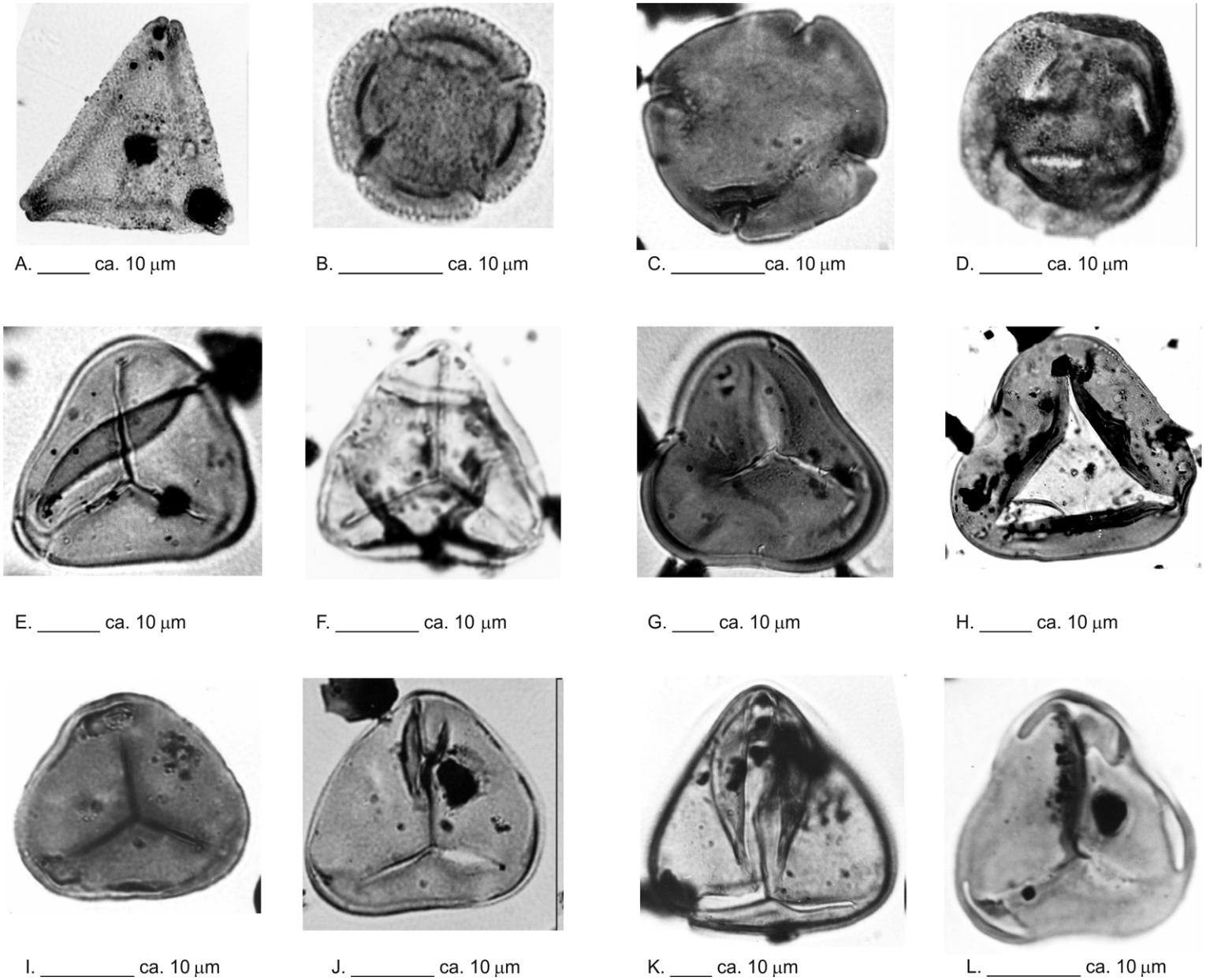


Figure 7. **A**, *Triangulorites pachyexinus* Kar & Kumar, 1986. **B**, *Tetracolporites* ixerboides Pocknall & Mildenhall, 1984. **C**, *Tetracolporites spectabilis* Pocknall & Mildenhall, 1984. **D**, *Tetracolporites sphericus* Couper, 1960 emend. Pocknall & Mildenhall, 1984. **E**, *Biretisporities potoniaei* Delcourt & Sprumont, 1955 & 1959. **F**, *Concavisporites obtusangulus* (Potonié) Krutzsch, 1959. **G**, *Cyathidites australis* Couper, 1953. **H**, *Cyathidites australis rimulis* Balme, 1957. **I**, *Cyathidites punctatus* (Delcourt & Sprumont) Delcourt, Dettmann & Hughes, 1963. **J**, *Cyathidites kerguelensis* Cookson, 1947. **K**, *Cyathidites major splendens* Harris, 1965. **L**, *Cyathidites minor* Couper, 1953.

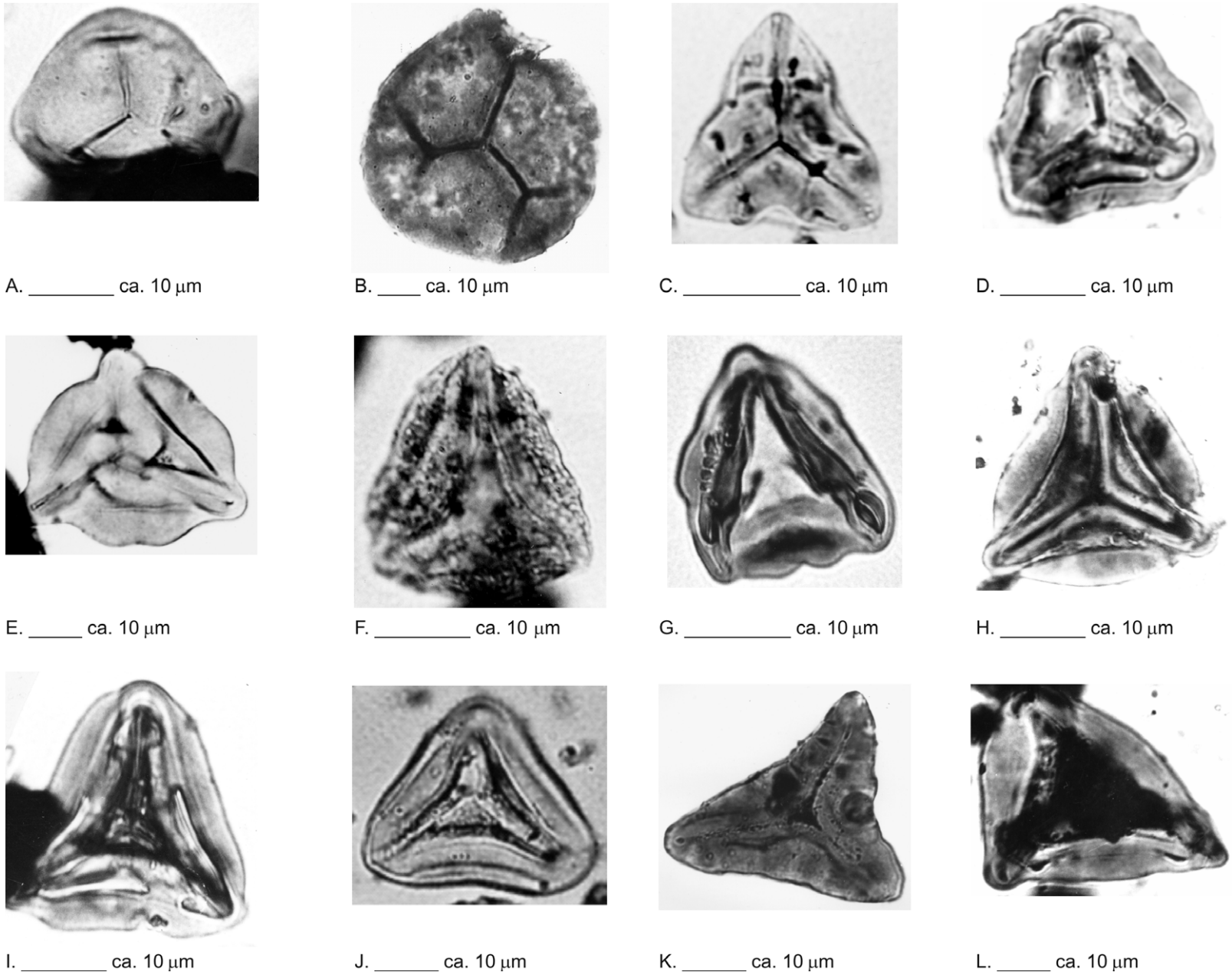


Figure 8. **A**, *Divisisporites divisus* Pflug, 1953. **B**, *Divisisporites euskirchenensis* (Thompson) Thompson & Pflug, 1953. **C**, *Gleicheniidites apilobatus* Brenner, 1963. **D**, *Gleicheniidites circindites* (Cookson) Dettmann, 1963. **E**, *Gleicheniidites feronensis* (Delcourt & Sprumont) Delcourt & Sprumont, 1959. **F**, *Gleicheniidites peregrinus* Krutzsch, 1959. **G**, *Gleicheniidites radiatus* (Bolkhovitina) Krutzsch, 1959. **H**, *Gleicheniidites rasilis* (Bolkhovitina) Krutzsch, 1959 **I**, *Gleicheniidites senonicus* Ross, 1949. **J**, *Gleicheniidites toriconcavus* Krutzsch, 1959. **K**, *Gleicheniidites* sp. **L**, *Gleichenites limbatus* Agranovskaja, 1960.

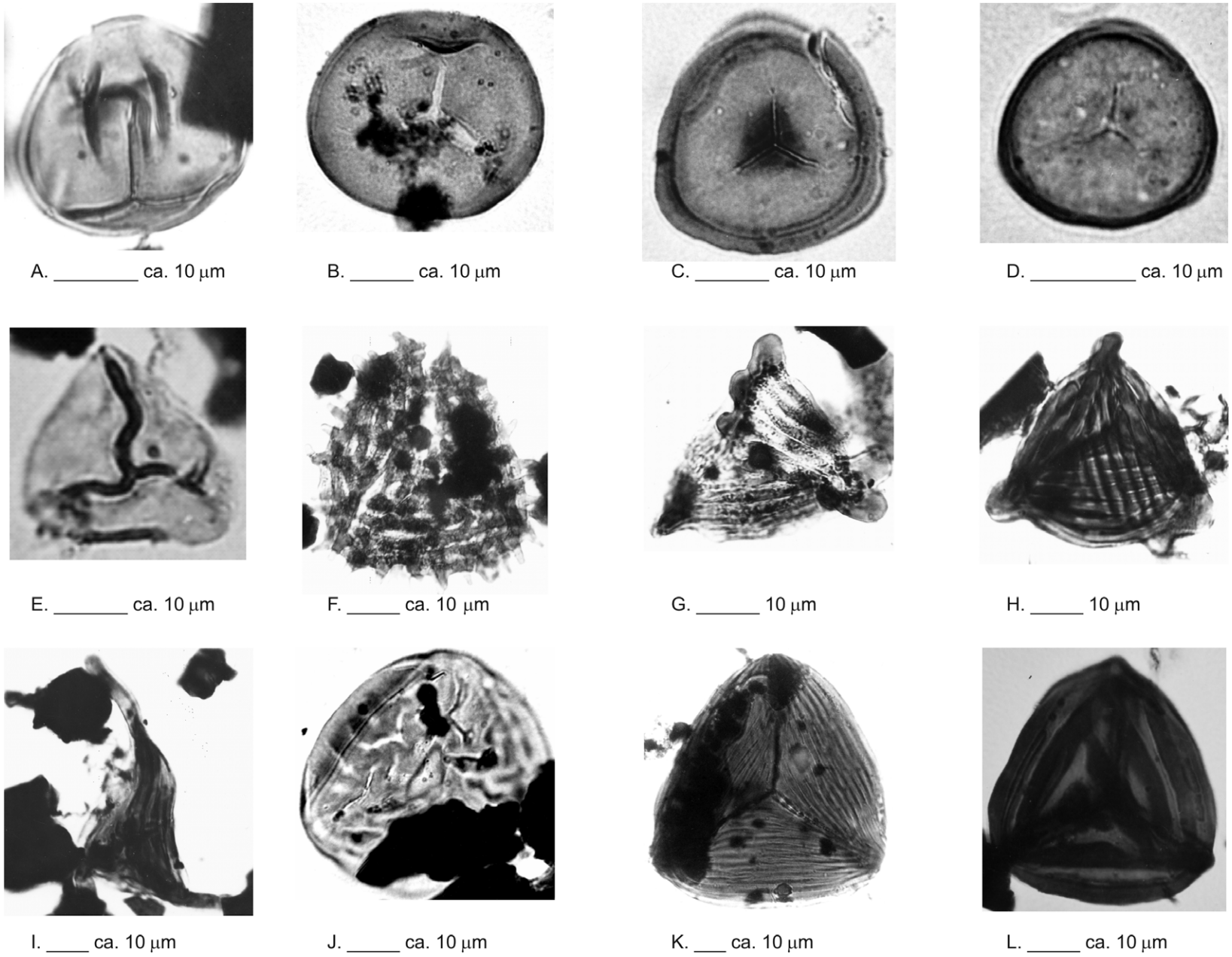


Figure 9. **A**, *Mediobaculisporis mediobaculatus* Krutzsch, 1959. **B**, *Psilatriletes radiatus* Brenner, 1963. **C**, *Stereisporites electoides* Krutzsch, 1963. **D**, *Stereisporites stereoides* (Potonié & Venitz) Pflug, 1953. **E**, *Undulatisporites microcutis* Pflug, 1953. **F**, *Appendicisporites dentimarginatus* Brenner, 1963. **G**, *Appendicisporites matesovae* (Bolkhovitina) Norris, 1967. **H**, *Appendicisporites tricorinatatus* Weyland & Greifeld, 1953. **I**, *Appendicisporites tricuspidatus* Weyland & Greifeld, 1953. **J**, *Camarozonosporites cretaceus* (Weyland & Krieger) Potonié 1956. **K**, *Cicatricosisporites australiensis* (Cookson) Potonié, 1956. **L**, *Cicatricosisporites hughesii* Dettmann, 1963.

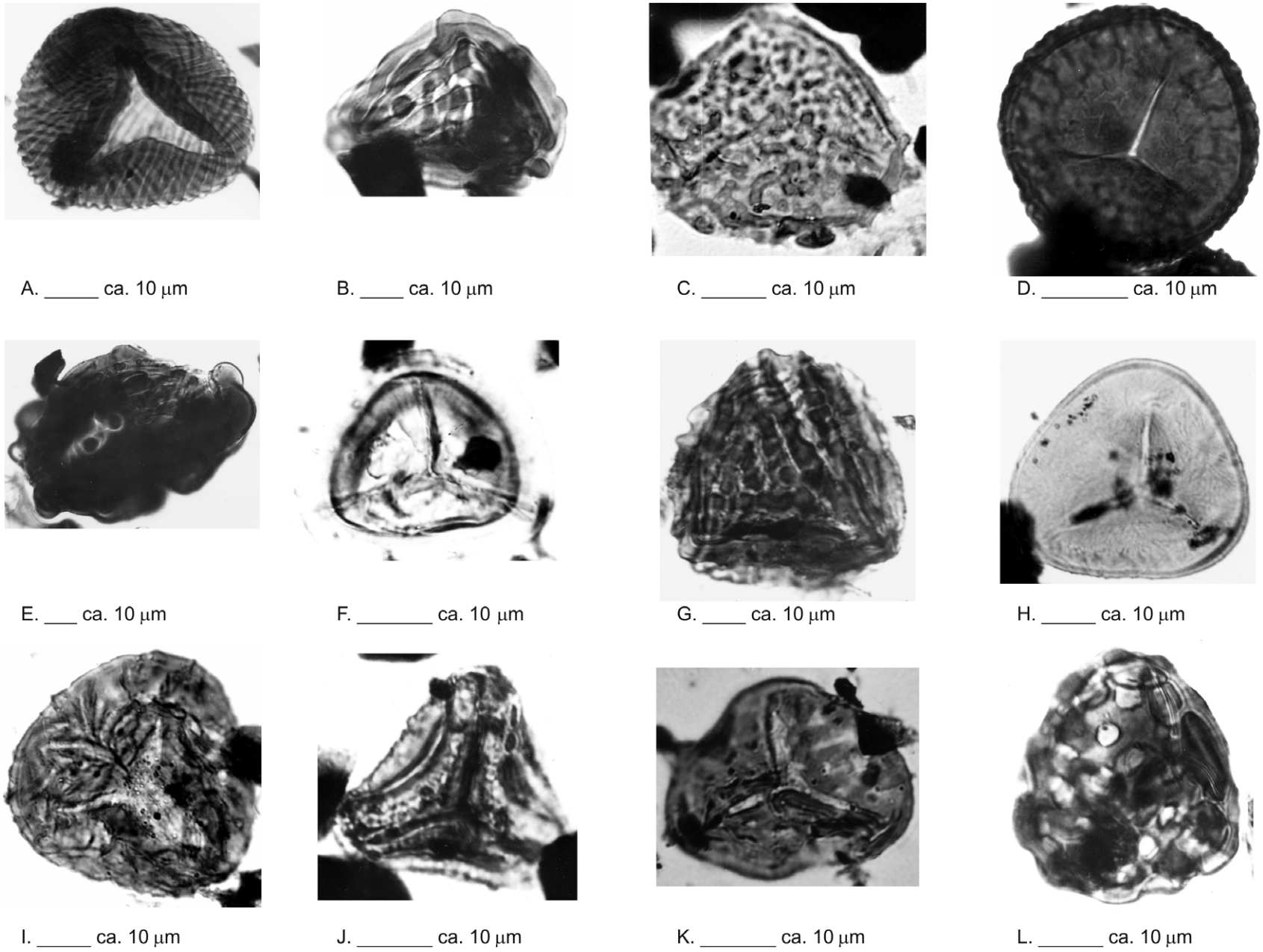


Figure 10. **A**, *Cicatricosisporites venustus* Deâk, 1963. **B**, *Contignisporites* sp. **C**, *Ghoshiatriletes gondwanensis* D'rozario & Banerjee, 1989. **D**, *Hamulatisporites hamulatus* Krutzsch, 1959. **E**, *Nodosisporites costatus* Deâk, 1964. **F**, *Staplinisporites caminus* (Balme), Pocock, 1962. **G**, *Striatella seebergensis* Mädler, 1964. **H**, *Tigrisporites halleinis* Klaus, 1960. **I**, *Triplexisporites playfordii* (de Jersey & Hamilton) Foster, 1979. **J**, *Foveogleicheniidites confossus* (Hedlund) Burger, 1976. **K**, *Foveosporites canalis* Balme, 1957. **L**, *Ischyosporites crateris* Balme, 1957.

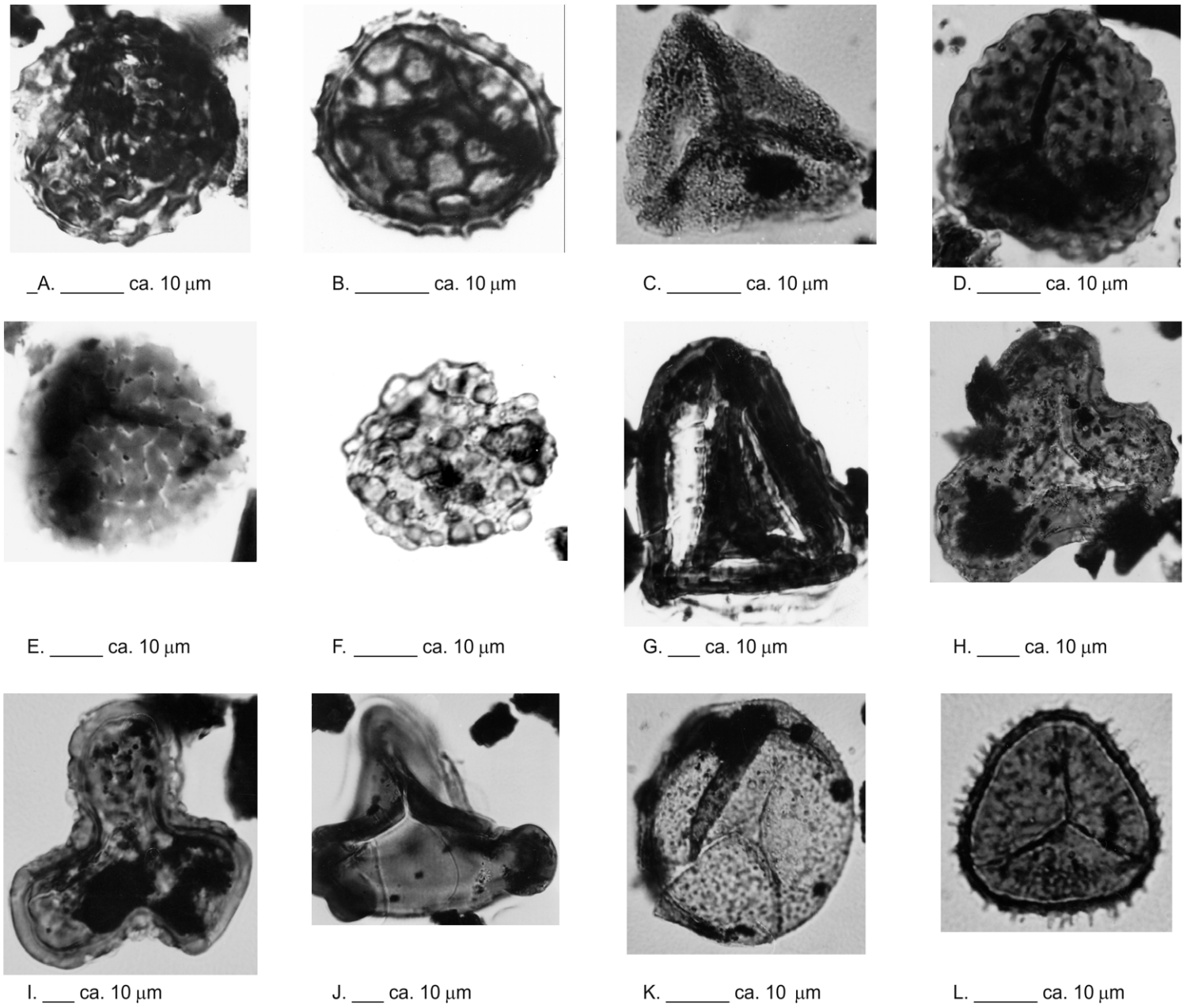


Figure 11. **A**, *Klukisporites variegatus* Couper, 1958. **B**, *Lycopodiumsporites reticulum* (Rouse) Dettman, 1963. **C**, *Microreticulatisporites parviretis* Balme, 1957. **D**, *Scrobiculifoveotriletes* sp. **E**, *Corrugatisporites* sp. **F**, *Gemmatriletes morulus* Pierce, 1961. **G**, *Trilobosporites* sp. 1, **H**, *Trilobosporites* sp. 2. **I**, *Trilobosporites* sp. 3. **J**, *Trilobosporites* sp. 4. **K**, *Osmundacidites wellmanii* Couper, 1953. **L**, *Ceratosporites equalis* Cookson & Dettmann, 1958.

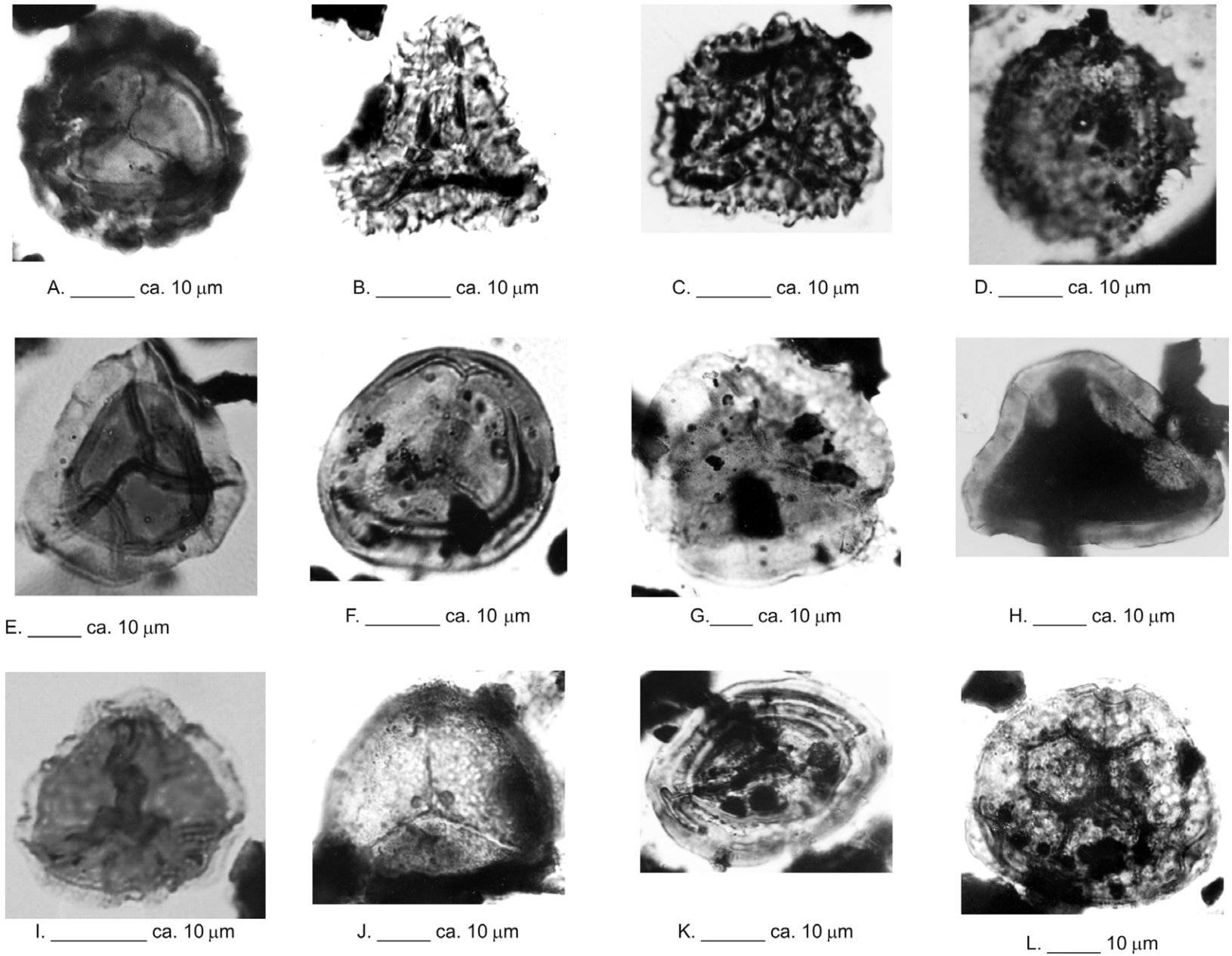


Figure 12. **A**, *Luberisporites luberi* Nakoman, 1976. **B**, *Ornamentifera echinata* (Bolkhovitina, 1953) Bolkovitina, 1966. **C**, *Ornamentifera tuberculatus* (Grigorjeva) Bolkovitina, 1966. **D**, *Raistrickia grovensis* Schopf, Wilson & Bentall, 1944. **E**, *Perotriletes granulatus* Couper, 1953. **F**, *Cingulatisporites levispeciosus* Pflug, 1953. **G**, *Murospora florida* (Balme) Pocock, 1961. **H**, *Murospora florida* (Balme) Pocock, 1961. **I**, *Undulatitriletes hertensis* Klein, 1959. **J**, *Densoisporites microrugulatus,* Brenner, 1963. **K**, *Taurocusporites reduncus* (Bolkhovitina) Stover 1962. **L**, *Rouseisporites reticulatus* Pocock, 1962.

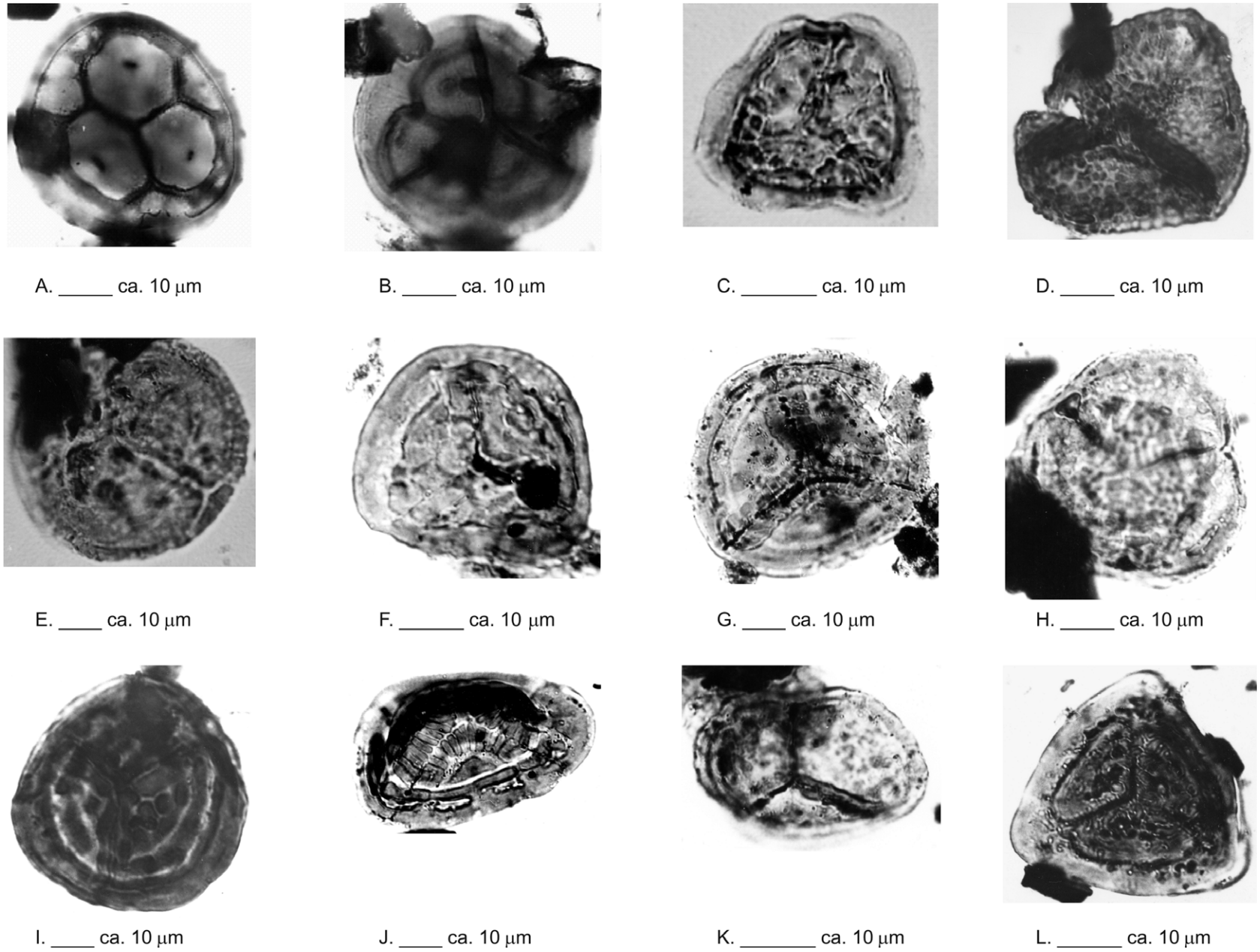


Figure 13. **A**, *Zlivisporis blanensis* Pacltová, 1961. **B**, *Zlivisporis* sp. **C**, *Asbeckiasporites wirthii* von der Brelie, 1964. **D**, *Foraminisporis asymetricus* (Cookson & Dettmann) Dettmann, 1963. **E**, *Foraminisporis foraminis* Krutzsch, 1959. **F**, *Interulobites algoensis* Scott, 1976. **G**, *Nevesisporites tribullatus* Nakoman, 1976. **H**, *Nevesisporites vallatus* De Jersey & Paten, 1964. **I**, *Taurocusporites segmentatus* Stover, 1962. **J**, *Taurocusporites* sp. **K**, *Antulsporites baculatus* (Archangelsky & Gamerro) Archangelsky & Gamerro, 1966b. **L**, *Cyatheacidites annulatus* (Cookson) Potonié, 1956.

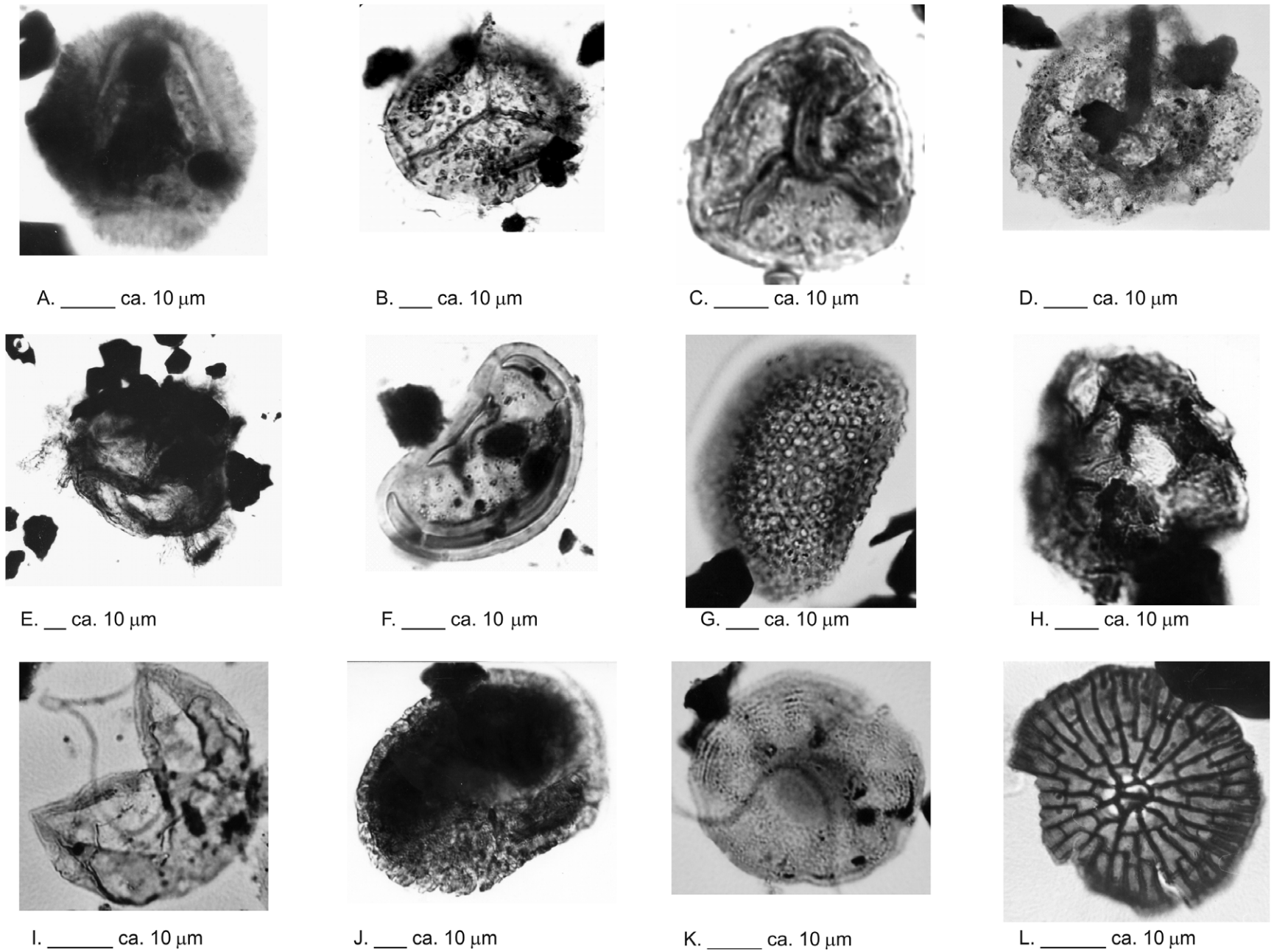


Figure 14. **A**, *Diatomozonotriletes* sp. **B**, *Indotriletes explanatus* (Luber) Playford, 1991. **C**, *Undulatitriletes* sp. **D**, *Zonalasporites arcusus* Balme 1957. **E**, *Balmeisporites* sp. **F**, *Laevigatosporites* sp. **G**, *Ischyomonoletes* sp. **H**, *Sphaeroplea* sp. **I**, *Ovoidites* sp. **J**, *Schizosporis reticulatus* Cookson & Dettmann, 1959 emend. Pierce, 1976. **K**, *Chomotriletes* sp. **L**, *Microthyriacites* sp.

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Appendix 1. Species list of palynomorphs from offshore wells C-B1 and O-A1 (Figs 4–14).

Gymnosperm pollen
Balmeiopsis limbatus (Balme) Archangelsky, 1977 emend. Norvick & Burger, 1976
Cedripites sp.
Classopollis cf. *C. echinatus* Burger, 1965
Classopollis torosus (Reissinger, 1950; Balme, 1957) Couper, 1958 emend. Burger, 1965
Diporites aspis Pocknall & Mildenhall, 1984
Ephedripites sp. 1
Ephedripites sp. 2
Ephedripites sp. 3
Ephedripites sp. 4
Ephedripites sp. 5
Ephedripites sp. 6
Exesipollenites tumulus Balme, 1957
Ginkocycadophytus nitidus (Balme) De Jersey, 1962
Lactoripollenites cf. *L. africanus* Zavada & Benson, 1987
Microcachryidites antarcticus (Cookson) Couper, 1953
Podocarpidites ellipticus Cookson, 1947
Podocarpidities sp.
Steevipollenites sp.
Zonalapollenites dampieri Balme, 1957
Zonalapollenites segmentatus Balme, 1957
Zonalapollenites trilobatus Balme, 1957
Zonalapollenites turbatus Balme, 1957

Angiosperm pollen
Acaciapollenites myriosporites (Cookson) Mildenhall, 1972 ex Jansonius & Hills, 1976
Andreisporis mariae Belsky, Boltenhagen & Potonié, 1965
Buttinia andreevii Boltenhagen, 1967
Buxaceaepollenites cainozoicus Sah, 1967
Bytneripollis coronarius Konzalová, 1976
Constantinisporis jacquei Belsky, Boltenhagen & Potonié, 1965
Crototricolpites sp.
Dorreenipites sp.
Harrisipollenites sp.
Liliacidites trichotomosulcatus Singh, 1971
Margocolporites sp.
Orbiculapollis globosus Chlonová, 1961
Quadraplanus brossus Stover, 1973
Tetracolporites ixerboides Pocknall & Mildenhall, 1984
Tetracolporites spectabilis Pocknall & Mildenhall, 1984
Tetracolporites sphericus Couper, 1960 emend. Pocknall & Mildenhall, 1984
Triangulorites pachyexinus Kar & Kumar, 1986
Victorisporis robertii Belsky, Boltenhagen & Potonié, 1965

Pteridophyte and Bryophyte spores
Antulsporites baculatus (Archangelsky & Gamerro) Archangelsky & Gamerro, 1966b
Appendicisporites dentimarginatus Brenner, 1963
Appendicisporites matesovae (Bolkhovitina) Norris, 1967
Appendicisporites tricorinatatus Weyland & Greifeld, 1953
Appendicisporites tricuspidatus Weyland & Greifeld, 1953
Asbeckiasporites wirthii von der Brelie, 1964
Balmeisporites sp.
Biretisporites potoniaei Delcourt & Sprumont, 1955
Camarozonosporites cretaceus (Weyland & Krieger) Potonié, 1956
Ceratosporites equalis Cookson & Dettmann, 1958
Cicatricosisporites australiensis (Cookson) Potonié, 1956
Cicatricosisporites hughesii Dettmann, 1963
Cicatricosisporites venustus Deâk, 1963
Cingulatisporites levispeciosus Pflug, 1953
Concavisporites obtusangulus (Potonié) Krutzsch, 1959
Contignisporites sp.
Corrugatisporites sp.
Cyatheacidities annulatus (Cookson) Potonié, 1956
Cyathidites australis Couper, 1953
Cyathidites rimulis Balme, 1957
Cyathidites kerguelensis Cookson, 1947
Cyathidites splendens Harris, 1965
Cyathidites minor Couper, 1953
Cyathidites punctatus (Delcourt & Sprumont) Delcourt, Dettmann & Hughes, 1963
Densoisporites microrugulatus, Brenner, 1963
Diatomozonotriletes sp.
Divisisporites divisus Pflug, 1953

Divisisporites euskirchenensis non Thompson; Cookson & Dettmann, 1958
Foraminisporis asymetricus Krutzsch, 1959
Foraminisporis foraminis Krutzsch, 1959
Foveogleicheniidites confossus (Hedlund) Burger, 1976
Foveosporites canalis Balme, 1957
Gemmatriletes morulus Pierce, 1961
Ghoshiatriletes gondwanensis D'rozario & Banerjee, 1989
Gleicheniidites apilobatus Brenner, 1963
Gleicheniidites circindites (Cookson) Dettmann, 1963
Gleicheniidites feronensis (Delcourt & Sprumont) Delcourt & Sprumont, 1959
Gleicheniidites radiatus (Bolkhovitina) Krutzsch, 1959
Gleicheniidites rasilis (Bolkhovitina) Krutzsch, 1959
Gleicheniidites senonicus Ross, 1949
Gleicheniidites sp.
Gleicheniidites toriconcavus Krutzsch, 1959
Gleichenites limbatus Agranovskaja, 1960
Hamulatisporites hamulatus Krutzsch, 1959
Indotriletes explanatus (Luber) Playford, 1991
Interulobites algoensis Scott, 1976
Ischyomonoletes sp.
Ischyosporites crateris Balme, 1957
Klukisporites varigatus Couper, 1958
Laevigatosporites sp.
Luberisporites luberi Nakoman, 1976
Lycopodiumsporites sp.
Lycopodiumsporites reticulumsporites (Rouse) Dettmann, 1963
Mediobaculisporis mediobaculus Krutzsch, 1959
Microreticulatisporites parviretis Balme, 1957
Murospora florida (Balme) Pocock, 1961
Murospora truncata Singh, 1971
Nevesisporites tribullatus Nakoman, 1976
Nevesisporites vallatus De Jersey & Paten, 1964
Nodosisporites costatus Deâk, 1964
Ornamentifera echinata (Bolkhovitina) Bolkhovitina, 1966
Ornamentifera tuberculatus Bolkovitina, 1966
Osmundacidites wellmanii Couper, 1953
Perotriletes granulatus Couper, 1953
Psilatriletes radiatus Brenner, 1963
Raistrickia grovensis Schopf, Wilson & Bentall, 1944
Rouseisporites reticulatus Pocock, 1962
Scrobiculifoveotriletes sp.
Staplinisporites caminus (Balme) Pocock, 1962
Stereisporites electoides Krutzsch, 1963
Stereisporites stereoides (Potonié & Venitz, 1934) Pflug, 1953
Striatella seebergensis Mädler, 1964
Taurocusporites reduncus Bolkhovitina, 1962
Taurocusporites segmentatus Stover, 1962
Taurocusporites sp.
Tigrisporites halleinis Klaus, 1960
Trilobosporites sp. 1
Trilobosporites sp. 2
Trilobosporites sp. 3
Trilobosporites sp. 4
Triplexisporites playfordii (de Jersey & Hamilton) Foster, 1979
Undulatisporites microcutis Pflug, 1953
Undulatitriletes hertensis Klein, 1959
Undulatitriletes sp.
Zlivisporis blanensis Pacltová, 1961
Zlivisporis sp.
Zonalasporites arcusus Balme, 1957

Algae
Ovoidites sp.
Schizosporis reticulatus Cookson & Dettmann, 1959
Sphaeroplea sp.

Incertae sedis
Chomotriletes sp.

Fungi
Microthyriacites sp.