

Development of radiolarians and planktonic foraminifera across some Cretaceous stage boundaries

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Abstract

Changes in both taxonomic composition and morphological diversity of Cretaceous radiolarian and foraminiferal assemblages are considered. Within the Boreal Realm, at the Jurassic-Cretaceous boundary, Late Jurassic *Parvicingula*-rich radiolarian assemblages changed into associations dominated by *Stichocapsa* and *Spinicingula*. The radiolarian family Parvicingulidae went extinct in the late Barremian-early Aptian, in correspondence with OAE 1. A marked speciation of the radiolarian genus *Crolanium*, which first appeared in the late Barremian, and the last occurrence of most of its species, including the index species *C. cuneatum*, characterises the latest Albian. Spheroid and discoid radiolarians predominated during the Cenomanian, while the Turonian saw a notable development of all radiolarian morphotypes; this event matches OAE 2 well. A marked change in radiolarian assemblages occurred across the Santonian-Campanian boundary: the late Santonian warmer-water assemblage of *Pseudoaulophacus floresensis* changed into early Campanian cold-water associations with *Prunobrachium crassum*; this event appears to be linked to OAE 3. Several phases are defined in the evolution of planktonic foraminifera. The first major adaptive radiation occurred during the Aptian; during this interval a great variety of trochoid forms appeared, as well as planispiral morphotypes and taxa with radially elongate chambers. The Albian-Cenomanian interval was a time of polytaxic development, following OAE 1. The Cenomanian-Turonian boundary was an obvious oligotaxic stage in the evolution of planktonic foraminifera (OAE 2 event). The next polytaxic stage commenced in the early Turonian and lasted until the Maastrichtian. However, in the early to late Santonian interval, the genus *Marginotruncana* died out. This faunal turnover can be ascribed to a cooling event and to OAE 3. The latest Santonian-early Campanian is characterised mainly by the genus *Globotruncana*, which increased again in diversity and abundance. The Cretaceous/Paleogene (K/Pg) boundary constitutes the most sudden extinction event in the history of planktonic foraminifera.

Keywords: Radiolaria, planktonic Foraminifera, species diversity,

anoxic event, Cretaceous stage boundaries.

Résumé

Les changements dans la composition taxonomique et la diversité morphologique des assemblages de radiolaires et de foraminifères du Crétacé sont considérés. Dans la région boréale, à la limite Jurassique-Crétacé les assemblages de radiolaires riches en *Parvicingula* du Jurassique supérieur sont remplacés par des associations où dominent *Stichocapsa* et *Spinicingula*. La famille de radiolaires Parvicingulidae disparaît durant le Barrémien supérieur-Aptien inférieur, en conformité avec OAE 1. Une spéciation marquée des radiolaires du genre *Crolanium*, apparaissant pour la première fois au Barrémien supérieur, et la dernière présence enregistrée de la plupart de ses espèces, l'espèce guide *C. cuneatum* y compris, caractérisent l'Albien terminal. Les radiolaires sphéroïdes et discoïdes prédominent au cours du Cénomanién, alors qu'on assiste pendant le Turonien à un développement notable de tous les morphotypes de radiolaires; cet événement s'accorde bien avec OAE 2. Un changement marqué des assemblages de radiolaires se produit à la transition Santonien-Campanien: l'assemblage d'eau plus chaude à *Pseudoaulophacus floresensis* (Santonien supérieur) est remplacé au Campanien inférieur par des associations d'eau froide à *Prunobrachium crassum*; cet événement peut être corrélé à OAE 3. Plusieurs phases sont également définies dans l'évolution des foraminifères planctoniques. La première grande radiation adaptative se produit au cours de l'Aptien; durant cet intervalle, une grande variété de formes trochoïdes apparaissent, ainsi que des morphotypes planispiraux et des taxons munis de chambres allongées radialement. L'intervalle Albien-Cénomanién est caractérisé par un développement polytaxique, conformément à OAE 1. La limite Cénomanién-Turonien correspond de toute évidence à un stade oligotaxique dans l'évolution des foraminifères planctoniques (événement OAE 2). Le stade polytaxique suivant débute au Turonien supérieur et se poursuit jusqu'au Maastrichtien. Cependant, le genre *Marginotruncana* disparaît dans l'intervalle Santonien inférieur-Santonien supérieur. Cette transformation faunique peut être imputée à un épisode de refroidissement et à OAE 3. Le Santonien supérieur-Campanien inférieur est caractérisé essentiellement par le genre *Globotruncana*, dont la diversité et l'abondance augmentent encore. La limite Crétacé/Paléogène (K/Pg) constitue l'épisode d'extinction le plus abrupt de l'histoire des foraminifères planctoniques.

Mots-clefs: Radiolaria, foraminifères planctoniques, diversité des espèces, événement anoxique, limites des étages du Crétacé.

Introduction

Biodiversity assessments of radiolarian assemblages in the geological past have allowed to trace different evolutionary rates of siliceous micro-organisms (VISHNEVSKAYA, 1997) and to define intervals of minimum biodiversity. A low diversity of Cretaceous radiolarians and their relatively small numbers have commonly been recorded both from intervals associated with oxygen-depleted (anoxic) events; in the boreal province, these are characterised by the presence of endemic taxa.

The most significant Early Cretaceous biodiversity minimum has been documented from the Aptian, while similar minima occurred at the Albian-Cenomanian and Cenomanian-Turonian boundaries. The total number of Cenomanian species is 75, which is twice less than the species count in the middle Albian. Near the end of the Cenomanian, the species number increased to 140-150, but at the Cenomanian-Turonian boundary half of these went extinct, including the family Rotaformidae and the intricately ornamented genus *Godia*. A marked change in radiolarian assemblages occurred across the Santonian-Campanian boundary (Fig. 1).

How can these phenomena be explained? A specific palaeogeographic event which lasted between the Barremian until the latest Albian is referred to as OAE 1. In many places in Europe, the Albian-Cenomanian boundary marks a sharp change in sedimentation: a transition from clayey-sandy sediments to a purely carbonate facies. Remarkable events in the evolution of ammonites, inoceramid bivalves, planktonic foraminifera, radiolarians and other fossil groups are linked to this Albian-Cenomanian boundary interval. The latest Albian and Cenomanian-Turonian transitional periods corresponded to OAE 1 and 2, respectively (JENKYNS, 1980; JARVIS *et al.*, 1988; KUHNT *et al.*, 1992). Both periods were characterised by changes in the aeration regime of ocean waters. The weaker OAE 3 event is situated near the Santonian-Campanian boundary. All these important abiotic events exerted influence upon evolutionary trends of biota, foraminifera and radiolarians included. Radiolarians, better represented than foraminifera in sediments which accumulated during anoxic events, are of a particular biostratigraphic significance.

The Jurassic-Cretaceous boundary

Comparison of data on diversity dynamics of radiolarians and benthic foraminifera as well as ammonites in the Upper Jurassic of the Boreal Realm shows that intervals with a significant decrease in taxonomic diversity in both groups (the late Volgian crisis) were synchronous (MITTA & VISHNEVSKAYA, 2006). This crisis coincided with marked changes in ammonite morphotypes and radiolarian skeletons. Specimens of upper Volgian (= Berriasian) *Parvicingula* are small sized, have small pores, weak distinct ridges or almost no external circumferential ridges (Pl. 1). In the Boreal and north Tethyan realms (PESSAGNO, 1977; HULL, 1997), there is a high degree of endemism on account of the great abundance of *Parvicingula*-like morphotypes with external cephalic spines and apophyses (KOZLOVA, 1994; VISHNEVSKAYA, 1998, 2001). Also noted was a decrease of number of chambers in late Volgian representatives of the genera *Parvicingula*, *Spinicingula* and *Stichocapsa*. The marked extinction of radiolarians at the end of the Jurassic began during the Volgian Stage, and most likely was the result of marine regression and climatic cooling. This is confirmed by the predominance of cold-water representatives of the genus *Parvicingula* in radiolarian associations, and by the boreal ammonite family Craspeditidae in the seas of central Russia, Timan-Petchora and west Siberia

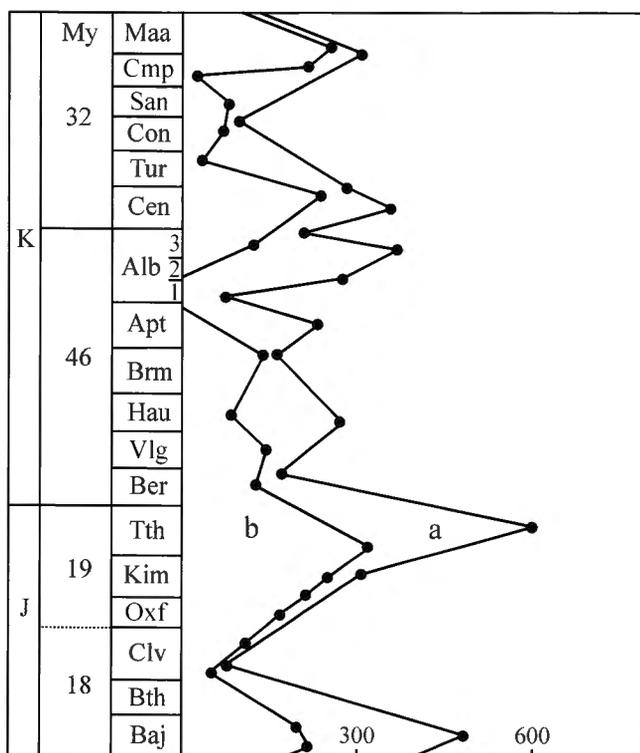


Fig. 1 — Biodiversity of radiolarian species across the various boundaries in the Jurassic-Cretaceous; a = number of species in Tethyan Realm, b = in Boreal Realm.

(MITTA & VISHNEVSKAYA, 2006).

The rapid radiolarian evolution and an increase in morphological diversity of *Parvicingula* with the development of numerous abnormal skeletons may have been caused by stressful conditions. Probably, only the more widely adapted, often primitive, forms of *Parvicingula* and *Stichocapsa* survived and gave rise to new evolutionary forms.

A change of Jurassic *Parvicingula*-rich assemblage into associations in which *Stichocapsa* and *Spinicingula* are abundant is noted at the Jurassic-Cretaceous boundary. *Parvicingula* predominates early-middle Volgian (Kimmeridgian-Tithonian) faunas, whereas among late Volgian (Berriasian) assemblages, *Stichocapsa* and *Spinicingula* are commonest. Just at the Jurassic-Cretaceous boundary (in the earliest Berriasian), the *Thanarla* group originated.

Thus, a rise of armed skeletons, as well as a decrease of volume size and number of chambers, occurred in the late Volgian genera *Parvicingula* and *Stichocapsa*. Probably, this was caused by hydrological changing and cooling. This level is known to be period of significant rearrangement of the oceanic plane; it is associated with tectonic and other abiotic events.

Based on correlation with the first appearance of nannoconids, the Jurassic-Cretaceous boundary in the Tethyan Realm (Turkey) corresponds to the first occurrence of the radiolarians *Becus nodulosus* (DUMITRICA), *Diceratosaturnalis dicranacanthos* (SQUINABOL), *Deviatus diamphidius* (FOREMAN), *Pyramispongia bormsteinensis* (STEIGER), *Acaeniotype diaphorogona* FOREMAN, *Emiluvia pessagno* FOREMAN, *Archaeodictyomitra apiarium* (RÜST) [*sensu* KOCHER] (see MEKIK *et al.*, 1999), as well as of the genera *Pseudodictyomitra* and *Thanarla* *sensu lato*.

Due to radiolarian provincialism, correlation of radiolarian biozones between the Boreal (north Eurasia and America) and Tethyan realms (southern Europe) is hampered during the Late Jurassic-Early Cretaceous interval.

Planktonic foraminifera of the Jurassic and lowermost Cretaceous (Berriasian-Barremian) comprised very small trochospiral forms with simple 'globigerine' morphology (globular chambers, simple apertures and absence of ornament and keels). These primitive taxa were very rare in oceanic settings and lived in shallow marginal seas (LECKIE, 1987). The adaptation of foraminifera to a planktonic mode of life was provided by gradual changes in test structure and cytoplasm. Planktonic foraminifera of different test morphotypes occupied oceanic zones of different bathymetry and distance from the shoreline (HART &

BAILEY, 1979; HART, 1980; CARON & HOMEWOOD, 1983; GORBACHIK, 1986, 1997; GORBACHIK & KOPAEVICH, 1992).

Morphological changes in radiolarian and foraminiferal skeletons during the Aptian

The radiolarian family Hsuidae was well represented during the Jurassic (VISHNEVSKAYA, 2001), and died out in the early Aptian. Only very few species of the genus *Hsuum*, which was widely distributed during the Jurassic, are found in the Lower Cretaceous, where they differ very much from typical representatives by having a lower number of chambers and a subspherical form. The genus *Hsuum* did not leave any genus-level descendants during the Late Jurassic and Early Cretaceous and rapidly disappeared in the early Aptian. The extinction of the family Parvicingulidae occurred during the early Aptian too, and corresponds to OAE 1. Within the *Thanarla* group, the species *T. conica*, *T. gutta* and *T. pacifica* died out in the middle-late Aptian (Pl. 2). The radiolarian genus *Crolanium* first appeared during the late Barremian-early Aptian (Fig. 2). O'DOHERTY (1994) noted that morphological changes in the *Parvicingula* group led from the conical shape of *Crolanium puga* (SCHAAF) (only the earliest specimens) to a test with a more triangular transverse section and finally to a tetrahedral-shaped test at its most typical configuration, a modification which took place in the adult ontogenetic stages. Following data published by PESSAGNO (1977), the genus *Crolanium* compares to the genus *Xitus* and belongs to the family Xitidae. Numerous abnormal forms in *Crolanium* with massive apophyses, often armed with strong spines, occurred during the latest Barremian-early Aptian (VISHNEVSKAYA, 2001, pls 28, 29). During the Aptian, the genus *Godia* flourished (Pl. 3). Amongst dictyomitrids, *Pseudodictyomitra lodogaensis* PESSAGNO and *Dictyomitra montisserei* (SQUINABOL) first appeared just above the Aptian-Albian boundary.

The first major adaptive radiation of planktonic foraminifera occurred in the Aptian (LECKIE, 1987). During this interval, a great variety of trochoid forms appeared (especially species of *Hedbergella*), as well as planispiral morphotypes (*Globigerinelloides*) and taxa with radially elongate chambers (*Leopoldina*) (Fig. 3). By the late Aptian, morphological features such as primitive apertural plates and accessory apertures (*Ticinella*, *Globigerinelloides*) had appeared. The diversity of planktonic foraminifera reached a maximum in the mid- to late Aptian and subsequently declined

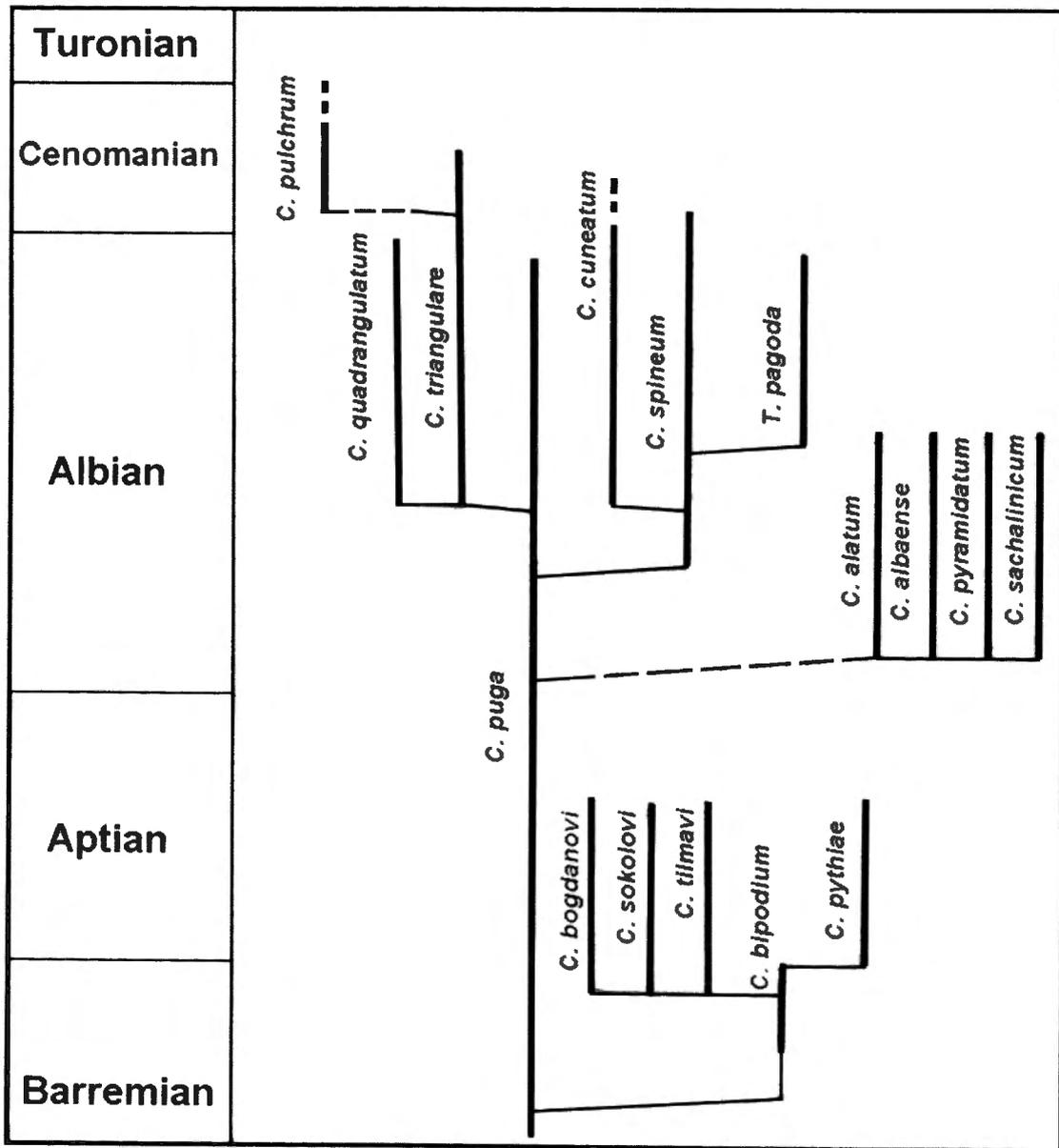


Fig. 2 — Time of occurrence of species of the genus *Crolanium* (modified after O'DOGHERTY, 1994).

markedly during the latest Aptian-early Albian (LECKIE, 1987; COCCIONI & LUCIANI, 2002). Twin-chambered and bilobated abnormal planktonic foraminifera have also been described from the Aptian (VENTURATI, 2006) as potential proxies of palaeoenvironmental response to OAE 1.

Assemblages and morphological transformations of radiolarian and foraminiferal skeletons during the late Albian-early Turonian

Albian-Turonian radiolarians have been well studied

from western European sections (BAK, 2006), in the western (O'DOGHERTY, 1994; ERBACHER & THUROW, 1997) and eastern Mediterranean (YURTSEVER *et al.*, 2003; BRAGINA, 2004; BABAZADEN & DE WEVER, 2004; VISHNEVSKAYA *et al.*, 2006), as well as in North America (PESSAGNO, 1977), while data for the Pacific region are scanty (BASOV & VISHNEVSKAYA, 1991; VISHNEVSKAYA, 2001).

Phylogenetic and morphological features which developed in Albian-Turonian radiolarian skeletons are useful for biostratigraphic and palaeoenvironmental interpretations. The evolution of radiolarians during the late Albian was marked by the development and

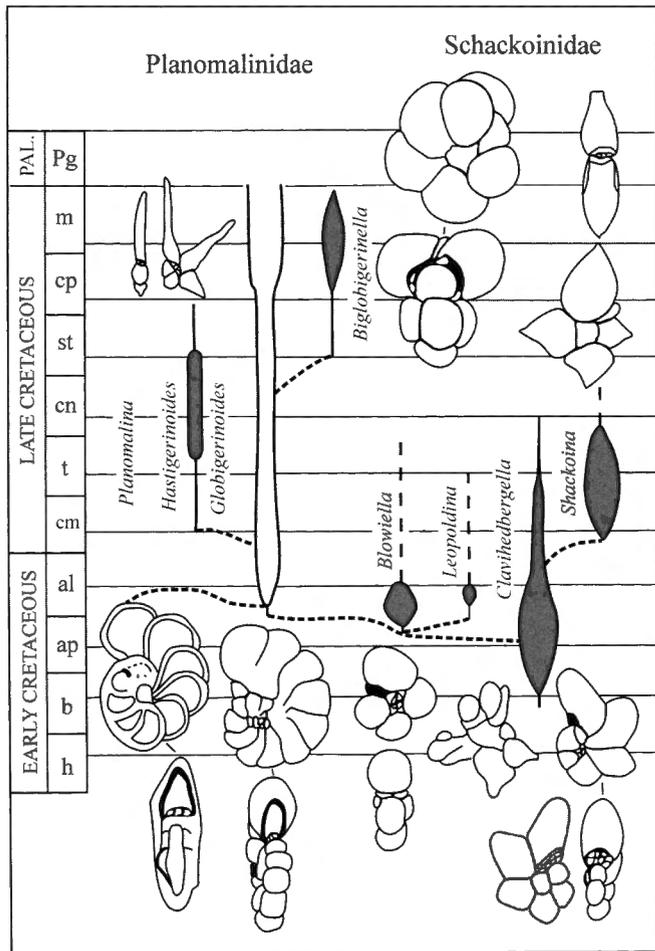


Fig. 3 — Phylogenetic development of planomalinids and schackoinids at the generic level (after GORBACHIK, 1986; VISHNEVSKAYA *et al.*, 2006).

perfection of skeletal features necessary for floating in the pelagic zone, changeable environments which yield evidence of tectonic movements (*e.g.*, the appearance of tuffs and phosphoritic nodules in black clays of the uppermost Albian) and pertinent morphological innovations of radiolarian skeletons. The diversity and distinctive features of late Albian assemblages consist of an abundance of high-conical tests with triangular and quadrangular distal sections and with lateral costae in the corners grading into terminal legs (Pl. 4). Tests of this kind belong to the genus *Crolanium*, which is represented by numerous latest Albian forms such as *C. cuneatum* (SMIRNOV & ALIEV), *C. puga* (SCHAAF), *C. spineum* PESSAGNO, *C. triangulare* (ALIEV), *C. triquetrum* (PESSAGNO) and others (Fig. 2). Also the last dictyomitrid, cyrtocapsid and stichocapsid representatives with sagittate initial chamber and distinct longitudinal rows of pores, were abundant, such as *Dictyomitra tekschaensis* ALIEV,

Cyrtocapsa perspicua SQUINABOL and *Stichocapsa euganea* SQUINABOL. In the Albian, species of the genera *Pantanellium*, *Podobursa* and *Tethysetta* went extinct. In addition to changes in generic composition, there were remarkable innovations amongst species; for instance, some spumellarians (discoid *Orbiculiforma multangula* PESSAGNO and *Porodiscus kavilkinensis* ALIEV), nassellarians (*Theocampe cylindrica* SMIRNOVA & ALIEV, *Thanarla conica* ALIEV) and nearly all species of the genus *Crolanium* disappeared during the terminal Albian (Fig. 2). Within the *Thanarla* group, *T. pulchra* appears to be restricted to the middle Albian-latest Cenomanian, whereas *T. brouweri* and *T. conica* died out at the end of the Albian. The proportion between spumellarians and nassellarians was approximately 1:1 to 1:2. The same ratio characterised late Albian assemblages from the Crimean-Caucasus region and the southern Russian Platform (VISHNEVSKAYA *et al.*, 2005, 2006).

Based on the abundance and diversity of *Theocampe* in the upper Albian-upper Cenomanian of the equatorial Atlantic (Ivorian Basin) and tropical Atlantic (sites 1258, 1261, off Surinam), it was assumed that this genus originated and diversified in the then opening equatorial Atlantic gateway (MUSAVU-MOUSSAVOU & DANELIAN, 2006). Within the Tethyan Realm, the base of the Cenomanian is established on account of a substantial renewal in composition of radiolarian genera: *Guttacapsa* and *Lipmanium* represent new types of nassellarians to appear at this boundary, and biconvex, spongy pseudoaulophacoid discs with triangular sections become numerous amongst spumellarians (genera *Alievium* and *Pseudoaulophacus*). Nevertheless, the Cenomanian radiolarian assemblages were predominated by spherical and discoid forms, and spherical ones represented half of all nassellarians, which were not numerous. The cryptothoracic Nassellaria correspond to the genera *Holocryptocanium* DUMITRICA and *Dorypyle* SQUINABOL, which cryptocephalic Nassellaria comprise only *Diacanthocapsa* SQUINABOL. Typical species are the cryptocephalic and cryptocephalothoracic *Holocryptocanium astiensis* PESSAGNO, *H. barbui* DUMITRICA, *H. geysersensis* PESSAGNO, *H. tuberculatum* DUMITRICA and *Excentropyllomma cenomana* DUMITRICA. The Cenomanian was marked by the mass appearance of subspherical-ellipsoid three-chambered cryptocephalic species of *Diacanthocapsa* such as *D. antiqua*, *D. brevithorax*, *D. euganea*, *D. matsumotoi* and *D. ovoidea*, and of pseudocephalic *Dictyomitra maleolla* ALIEV, *D. disparlita* ALIEV, *Pseudodictyomitra pseudomacrocephala* (SQUINABOL) and *P. sagitafera* (ALIEV).

Analyses of morphological features of radiolarian skeletons from across the Albian-Cenomanian boundary (a marked predominance of discoid and spheroid groups over cyrtoid morphotypes) suggest certain ecological changes, i.e., a relative shoaling of the basin at the time. This is also evident from deposition of carbonate sediments with rich assemblages of planktonic foraminifera. Thus, variations in the proportion of different morphological radiolarian and foraminiferal groups could be the result of bathymetric, rather than climatic, changes. From the viewpoint of morphological-functional adaptation, the disappearance of multichambered skeletons and an abundance of new cryptocephalic forms implies that Cenomanian radiolarians actively colonised pelagic settings at that time.

The less abundant calcareous planktonic microfossils and radiolarians from the bituminous member, an anoxic event marker, are represented mainly by dwarfish specimens in the upper Cenomanian. Remarkable are abundant small planktonic foraminifera of the genus *Hedbergella* which are comparable in size to radiolarians and monstrous specimens. Radiolarians are accompanied by abundant siliceous sponge spicules often of irregular shapes which probably is indicative of abnormal salinity in the sedimentary basin. Radiolarians are represented mostly by simple discoid forms and primitive species of *Dictyomitra*. Thus, radiolarians from the uppermost Cenomanian (anoxic facies) are characterised in general by dwarfed skeletons, an increased abundance of spongy spumellarian and nassellarian forms against the background of reduced morphological diversity, smooth external sculpture and by a distorted porosity system (frequently with irregular transition between spongy and pseudoaulophacoid structures). Monstrous (irregular discs with protuberances of unequal length and width) and abundant cryptocephalic forms appeared amongst them. At the same time, conserving properties of sediments enriched in organic matter, P, Ag, and other elements were favourable for retention of *Diacanthocapsa euganea* (SQUINABOL) and *Pseudodictyomitra pseudomacrocephala* (SQUINABOL) with intact apertural tubes (VISHNEVSKAYA, 2001, pl. 129), which provide evidence for the presence of organic matter in large quantities and anoxic environments. The early Turonian radiolarian assemblage of the *Alievium superbum* Zone includes numerous taxa that do not occur in underlying strata.

The Cenomanian-Turonian transition was a period of compositional changes amongst species and higher-rank taxa. The terminal Cenomanian is marked by the extinction of the family Rotaformidae (which appeared

in the Albian) and of the genera *Obeliscoites* and *Godia* amongst nassellarians and spumellarians, respectively. Early representatives of the genus *Alievium* (*A. antiquum* PESSAGNO) gradually died out as well (Fig. 4). The radiolarian assemblage from bituminous marls and clays of the uppermost Cenomanian is characterised by a smaller size of skeletons, an increased proportion of spongy forms amongst spumellarians and nassellarians, which are of reduced morphological diversity and have smooth external sculpture and a distorted pore arrangement. Only matrix which was enriched in organic matter was conducive to the retention of specimens with well-preserved apertural tubes. The end of the Cenomanian was marked by the appearance of the index species *Crucella cachensis* PESSAGNO. In the basal Turonian, the main changes occurred at the species level. New species, which appeared at that time, are *Alievium superbum* (SQUINABOL), *Archaeospongoprimum triplum* PESSAGNO, *Paronaella pseudoaulophacoides* O'DOHERTY, *Patella heroica* O'DOHERTY, *Vitorfus morini* EMPSON-MORIN, *Dictyomitra densicostata* PESSAGNO, *D. striata* LIPMAN, *Ultranapora cretacea* (SQUINABOL), *U. dendrocanthos* (SQUINABOL) and others, as based on material from the eastern Mediterranean (BRAGINA, 2004; VISHNEVSKAYA *et al.*, 2006; VISHNEVSKAYA & KOPAEVICH, 2007). The only higher-rank taxon of that time was the genus *Afens*.

Based on material from the Carpathians, it has been shown that radiolarian assemblages in the earliest Turonian consisted mainly of small (< 50 µm) opportunistic forms of the genus *Holocryptocanium* (BAK, 2006), similar to the latest Cenomanian. The small size and predominance of smooth-walled taxa amongst benthic foraminifera (*Ammodiscus*) also documents stressful conditions on the sea floor, probably related to oxygen deficiency, according to BAK (2006). The foraminiferal species *Thalmanammia meandertornata* NEAGU & TOCORJESCU, *Ammodiscus cretaceus* (REUSS) and *Rotalipora silesica* (HANZLÍKOVÁ) are half the size of those from normal assemblages in oxic sediments (BAK, 2006).

Based on Crimean sequences, the positive $\delta^{13}\text{C}$ excursion from +2,7‰ up to a peak of +4,3‰ at the Cenomanian-Turonian boundary coincides with a shift to more negative $\delta^{18}\text{O}$ values may be interpreted as a result of warming (FISHER *et al.*, 2005). Anoxic events were determined even in the northern sequences of the Peri-Tethyan Realm and in the Pacific Province (sites 171, 585 with content of organic matter rising to 9,9 %). It has been recorded that all microfossils showed a trend to decrease in number and diversity in the organic

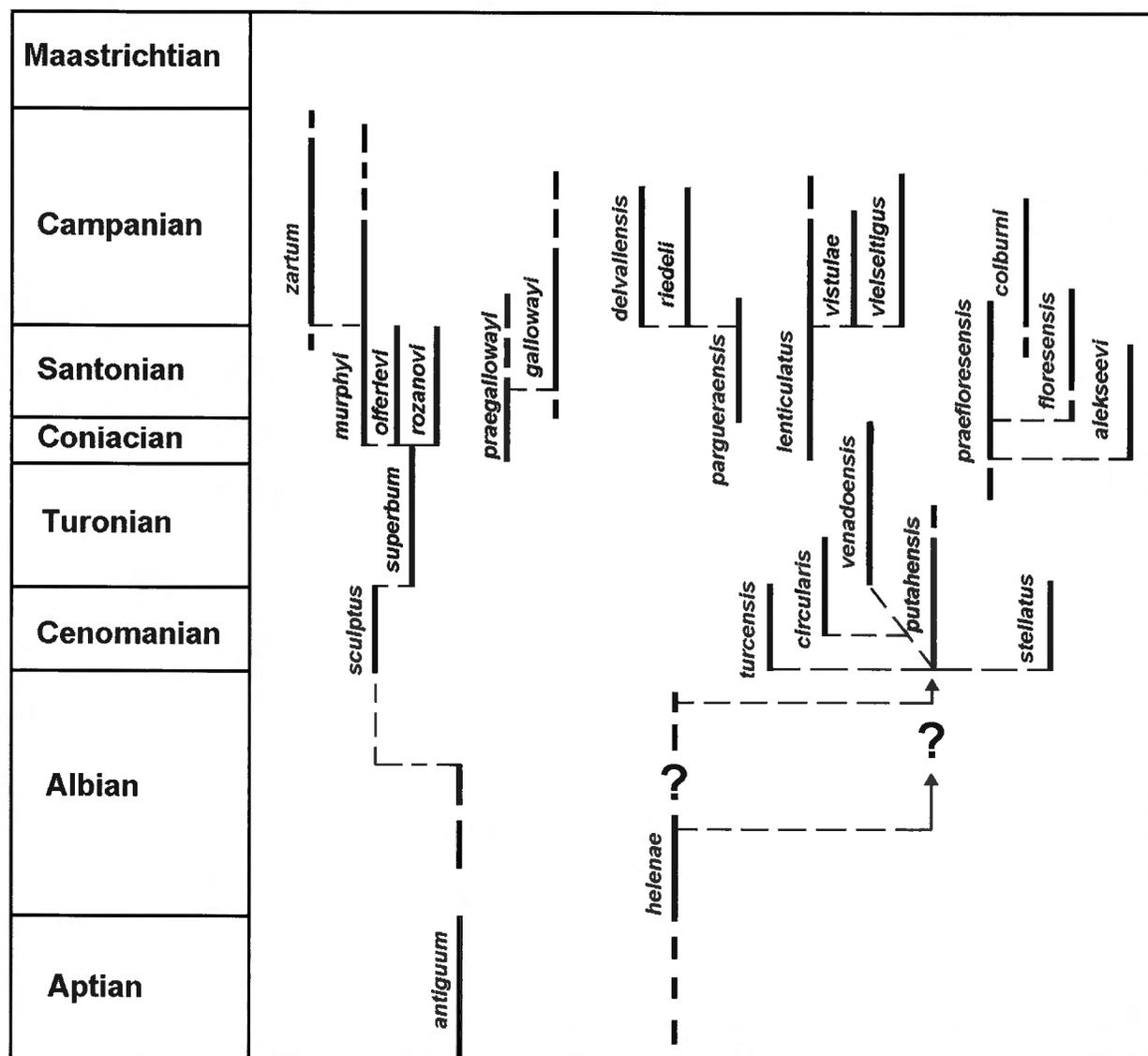


Fig. 4 — Phylogenetic lineages of some representatives of the genera *Alievium*, *Becus* and *Pseudoaulophacus* (modified after O'DOHERTY, 1994).

rich marls of the uppermost Cenomanian in northern England. The increase in content of $\delta^{13}\text{C}$ +4‰ - +5‰ within an anoxic level, in contrast to values +2‰ - +3‰ in the underlying and overlying strata, is interpreted as an indication of rapid burial of tremendous volumes of organic matter in sediments and a high bioproductivity in the world's oceans (JENKINS, 1980; SCHLANGER *et al.*, 1987).

Similar observations were made across the Cenomanian-Turonian boundary of northeast England, where the $\delta^{13}\text{C}$ content rises to +3,5‰ - +4,3‰ in the bituminous clay, while underlying and overlying limestones reveal +2,7‰ - +2,9‰. Towards the Tethys, this $\delta^{13}\text{C}$ value changes from +3‰ - +4,8‰ in sections in northern Germany, up to +4,47‰ - +3,72‰ at sites

549 and 551 in the Atlantic and to +3‰ - +3,2‰ in the coeval interval in Switzerland and Italy (SCHLANGER & JENKINS, 1976). Moreover, a positive peak was recorded from the base of the Turonian in the Pacific.

An explosion of planktonic foraminiferal diversity occurred during the late Albian-Cenomanian, showing a rapid evolution of the family Rotaliporidae with diverse morphological features (LECKIE, 1987; GORBACHIK & KOPAEVICH, 1992, 2002; KUZNETZOVA & KORCHAGIN, 2004; VISHNEVSKAYA *et al.*, 2006). When analysing morphological peculiarities of globigerinid species, which successively appeared during the Albian-Cenomanian, new features or new combinations of features can be observed which characterise an evolutionary trend terminated in the Cenomanian

(evolutionary lineage *Hedbergella trocoidea*-*Ticinella roberti*-*Ticinella praeticinensis*-*Rotalipora* spp.):

1. the transformation of subspherical chambers into flattened ones commenced in the late Aptian and late Albian and in early *Rotalipora subticinensis* and *R. ticinensis* during the late Albian;
2. an extension of the umbilical area and formation of relevant plates with additional apertures (evolutionary lineage *Ticinella roberti*-*Ticinella praeticinensis*-*Rotalipora subticinensis*);
3. the transformation of additional umbilical apertures into umbilical-sutural apertures typical of some species of *Ticinella*, e.g., *T. praeticinensis*-*T. primula*, *T. raynaudi* during the middle and late Albian, and of early *Rotalipora subticinensis* and *R. ticinensis* during the late Albian;
4. the formation of additional sutural apertures beyond the umbilicus in Cenomanian species such as *Rotalipora gandolfi* and others;
5. the transformation of a rounded, wide peripheral

edge into a sharply keeled one in the late Albian (*R. subticinensis*-*R. ticinensis*) and in Cenomanian forms of *Rotalipora* (Fig. 5). The keel of *Ticinella*-*Rotalipora* transitional species developed first due to the formation of spinose sculpture along the peripheral edge and then due to flattening of chambers on the umbilical and spiral side into sharply keeled forms in the late Albian (*R. subticinensis*-*R. ticinensis*) and in Cenomanian forms of *Rotalipora*. The keel of *Ticinella*-*Rotalipora* transitional species developed first due to the formation of spinose sculpture along the peripheral edge and then due to flattening of chambers on the umbilical and spiral sides also along the peripheral edge. As a result, biconvex tests characteristic of forms of *Rotalipora* in the terminal Albian gave way to variable spiral-convex species in the Cenomanian. The Cenomanian species of *Rotalipora* had a combination of the following features: relatively wide umbilicus, sutural

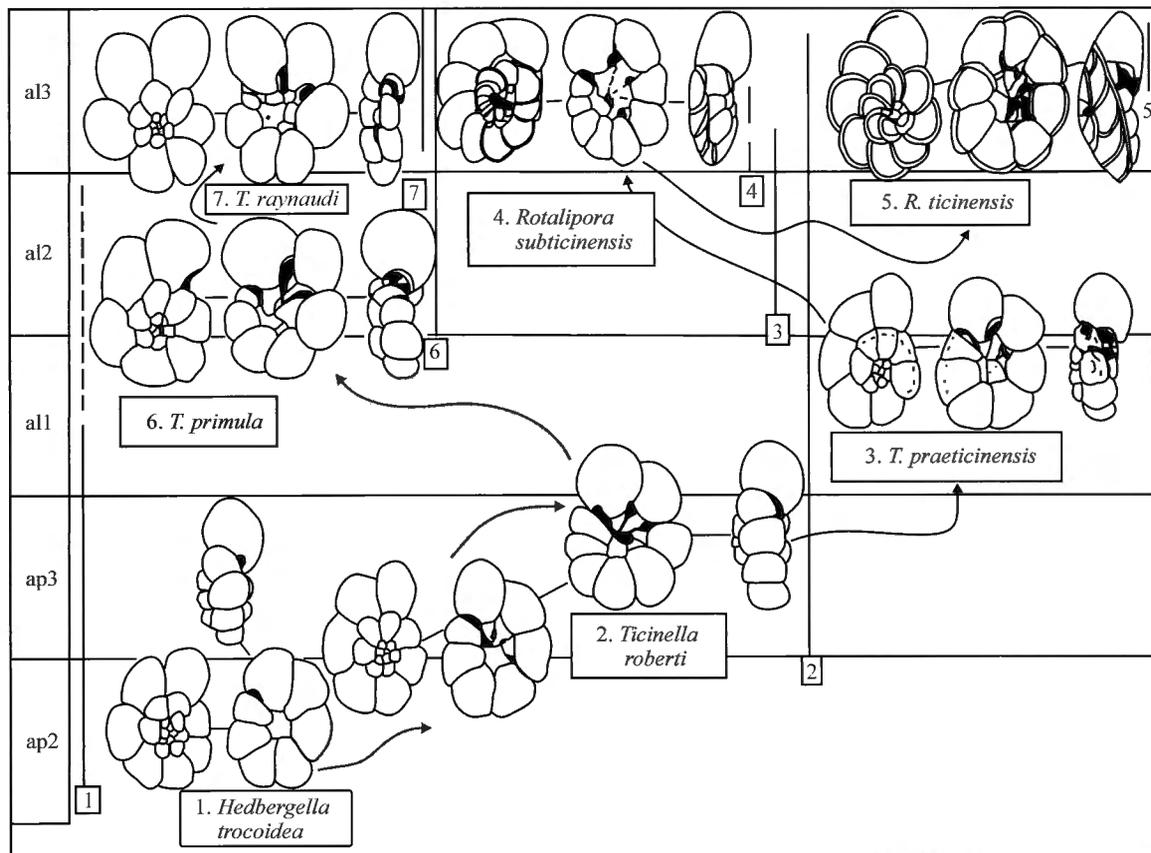


Fig. 5 — Phylogenetic lineages of some representatives of the genera *Hedbergella*, *Ticinella* and *Rotalipora* (after GORBACHIK, 1986; VISHNEVSKAYA *et al.*, 2006).

additional apertures, keel, flattened chambers and spiral-convex shape (GORBACHIK, 1986; GORBACHIK & KOPAEVICH, 1992; KOPAEVICH & KUZMICHEVA, 2002). Keeled taxa also appeared in the late Albian in a group of planispiral planktonic foraminifera (*Planomalina praebuxtorfi-buxtorfi*) (VISHNEVSKAYA *et al.*, 2006, figs 5, 6). Total diversity remained high into the Cenomanian and these assemblages are characterised by a great variety of morphologies (Pls 5, 6): keeled taxa (*Rotalipora*, *Praeglobotruncana*), various taxa with radially elongate chambers (*Schackoina*) and a biserial morphotype (*Heterohelix*). Double-keeled taxa of the genus *Dicarinella* with umbilical-extraumbilical primary aperture and supplementary apertures with portici first appeared in the late Cenomanian (CARON, 1985).

A short-term decline in planktonic foraminiferal diversity occurred during the latest Cenomanian-earliest Turonian, an interval characterised by the extinction of the genus *Rotalipora*, a marked absence of other keeled morphotypes at many localities and an abundance of large, relatively simple taxa of the genus *Whiteinella* (Pl. 7). The other feature of this interval is the clear prevalence of non-keeled, small forms belonging to the genera *Hedbergella*, *Schackoina* and *Heterohelix*. The perforate, elongated chambers and tubulospine schackoinids may represent the best tool for survival by achieving a better oxygen and nutrient uptake (COCCIONI & LUCIANI, 2004). The mid-Turonian coincides with a rapid recovery and diversification of keeled taxa of the genera *Marginotruncana* and *Dicarinella* (Fig. 6). Representatives of this group have a double-keeled test with a multiple aperture (CARON, 1985). The primary aperture usually is covered by portici, and also infralaminar supplementary apertures existed. *Marginotruncana* differs from *Dicarinella* in its umbilical, sigmoidal and raised sutures. These forms represent a new evolutionary lineage, which originated from the genus *Praeglobotruncana* and reached maximum diversity during the Coniacian-Santonian. At the same time, *Praeglobotruncana* declined rapidly. The early to mid-Turonian is slightly different, with a planktonic percentage up to 60-70% and a predominance of keeled, Tethyan forms such as *Helvetoglobotruncana*, *Dicarinella* spp. and *Marginotruncana* spp. (HART, 2007).

Morphological changes of radiolarian skeletons across the late Santonian-early Campanian

Maximum erosion in the Pacific Ocean was recorded in the Late Cretaceous, with peaks at the Cenomanian-Turonian and Santonian-Campanian boundaries, linked to tectonic activity, rearrangement of lithospheric plates, locally accompanied by a new volcanism phase (BASOV & VISHNEVSKAYA, 1991). Radiolarian species of the latter interval which record such a type of events are illustrated in Pl. 8.

Turonian-Santonian strata along the western Pacific margin (Okhotsk and Japan seas) are rarely represented by pelagic facies. The presence of Coniacian, Santonian and lowermost Campanian tuff gravelites and agglomerates with fragments of siliceous rocks, broken shells of *Inoceramus* and volcanogenic impurities within sedimentary strata (western Kamchatka) suggest increased tectonic activity in the northwesterly zone of the Pacific region. The presence of stratigraphic intervals with facies of dissolved or redeposited sediments at the Cenomanian-Turonian and Santonian-Campanian boundaries has been recorded from sections penetrated by numerous wells in the Pacific Ocean. Probably, this is linked to the global regression at the Santonian-Campanian boundary (BARNSE *et al.*, 1995). The Santonian-Campanian boundary interval is characterised everywhere in the amphiboreal province (in the English Chalk) by a positive $\delta^{13}\text{C}$ excursion of around +0,3‰ with maximum values up to +2,9‰ (JARVIS *et al.*, 2006). Within the English Chalk, seven sections with the Santonian-Campanian boundary display considerable differences, but in all cases the basal Campanian consists of flints. Inoceramid and oyster shell debris is also abundant throughout the uppermost Santonian-lowermost Campanian (JARVIS *et al.*, 2006).

Based on data from the North Pacific, a warm-water late Santonian *Pseudoaulophacus floresensis* assemblage was associated with the planktonic foraminifera *Archaeoglobigerina bosquensis* PESSAGNO, *Hedbergella delrioensis* (CARSEY), *H. holmdelensis* OLSSON, *Heterohelix globulosa* (EHRENBERG), *H. reussi* (CUSHMAN) and *Globigerinelloides ultramicra* (SUBBOTINA) (Pl. 9). The planktonic foraminiferal assemblage consists of small (< 200 μm), opportunistic forms of these four genera (Pl. 9). The late Santonian radiolarian assemblage of *Pseudoaulophacus floresensis* in western Kamchatka includes *Archaeospongoprunum*

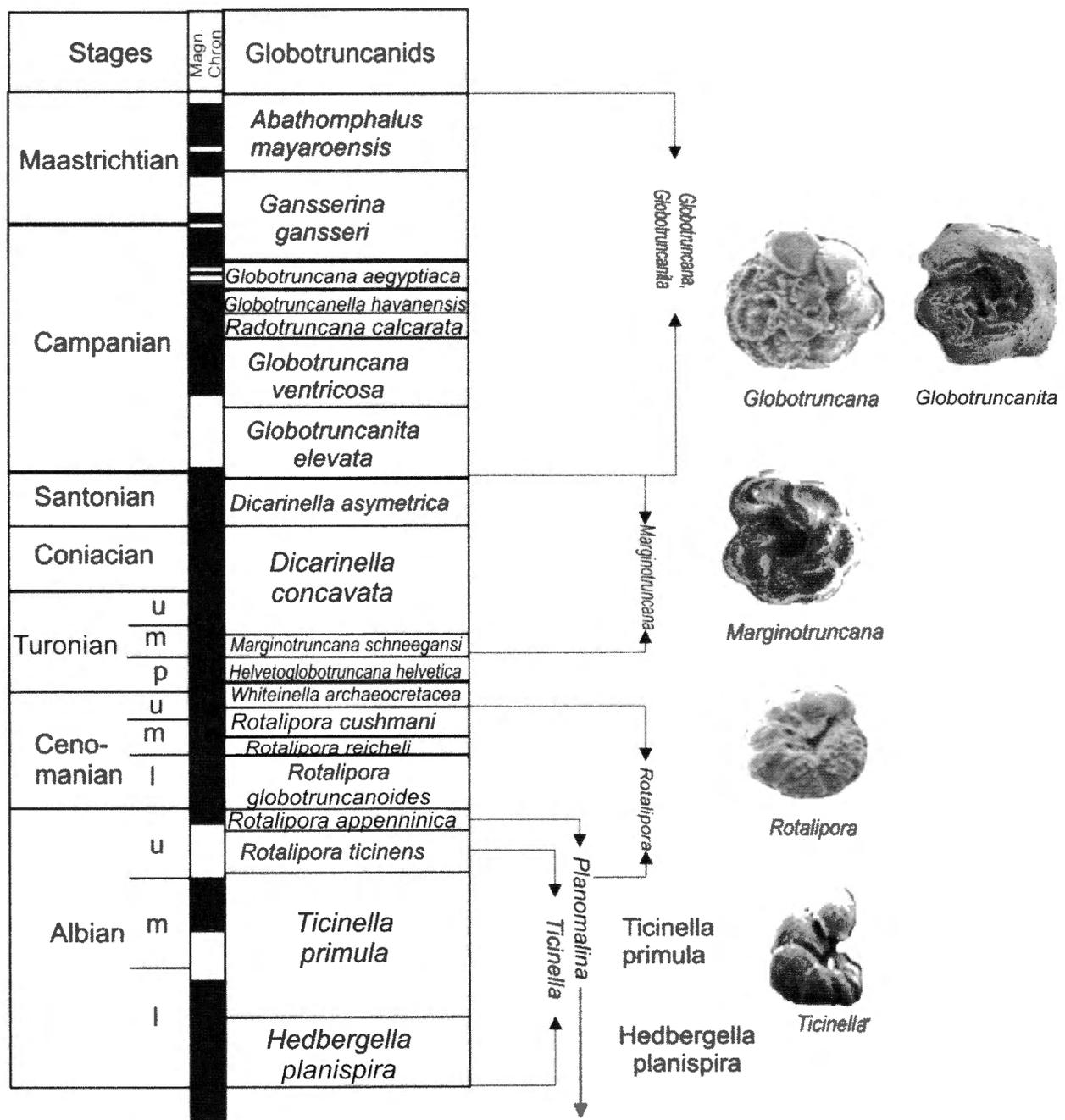


Fig. 6 — Planktonic foraminiferal zonal scheme (globotruncanids) with the main bioevents for the Albian-Maastrichtian (modified after ROBASZYNSKI & CARON, 1995).

bipartitum PESSAGNO, *Orbiculiforma quadrata* PESSAGNO, *Pseudoaulophacus floresensis* PESSAGNO, *P. ex gr. praefloresensis* PESSAGNO, *Lipmanium sacramentoensis* PESSAGNO, *Dictyomitra urakawaensis* TAKETANI, *D. densicostata* PESSAGNO, *Amphipyndax ellipticus* NAKASEKO & NISHIMURA, *A. stocki* (CAMPBELL & CLARK) and others (VISHNEVSKAYA *et al.*, 2005). The assemblage consists of numerous

representatives of the family Pseudoaulophacidae (Fig. 4), which are assumed to have been widely distributed in relatively low palaeolatitudes, where they reached an acme (URQUHART, 1995) near the end of the Santonian and the start of the Campanian.

The Santonian radiolarian assemblage of western Siberia is very poor; there is a predominance of discoidal spongy spumellarians: an association with single

Prunoidea and Discoidea (KOZLOVA & GORBARETZ, 1966). Just above the Santonian-Campanian boundary, siliceous sedimentation started with a relative abundance of taxa. The lower Campanian radiolarian assemblages of the Siberian Arctic are dominated by several genera, namely *Orbiculiforma* (four species), *Prunobrachium* (five), *Dictyomitra* (two), *Lithostrobos* (two) and *Amphipyndax* (three). Total diversity is low, but there is a strong predominance of *Prunobrachium* and *Lithostrobos* in the majority of samples (VSV, pers. obs.). This radiolarian association was proposed as the lower Campanian *Prunobrachium crassum* assemblage (KOZLOVA & GORBARETZ, 1966).

In contrast to the Siberian *Prunobrachium crassum* assemblage (KOZLOVA & GORBOVETZ, 1966; AMON, 2000), the *Prunobrachium crassum* assemblage from Kamchatka is diverse and includes *Protoxiphotractus perplexus* PESSAGNO, *Protoxiphotractus kirbui* PESSAGNO, *Stylosphaera hastata* CAMPBELL & CLARK, *Heliodiscus borealis* VISHNEVSKAYA, *Spongasteriscus rozanovi* VISHNEVSKAYA, *Prunopyle stansilavi* VISHNEVSKAYA (Pl. 10), *Cornutella californica* CAMPBELL & CLARK, *Coniforma antiochensis* PESSAGNO, *Stichomitra livermorensis* (CAMPBELL & CLARK), as well as numerous representatives of *Amphipyndax stocki* (CAMPBELL & CLARK), *A. conicus* NAKASEKO & NISHIMURA, *A. ellipticus* NAKASEKO & NISHIMURA, *A. strecta* EMPSON-MORIN and other species (VISHNEVSKAYA *et al.*, 2005). The Campanian radiolarian assemblage comprises a lot of species with a wide distribution in coeval associations of the southern Hemisphere (HOLLIS, 1997). In some samples, these radiolarians were found together with numerous cold-water benthic foraminifera, such as *Stensioeina* cf. *exsculpta* (REUSS), *Osangularia* aff. *florealis* (WHITE) and *Hyperammina* cf. *nodosariaformis* (SUBBOTINA). Single planktonic foraminifera are associated with these early Campanian radiolarians in western Kamchatka. Representatives of pseudoaulophacids form a minor constituent of radiolarian assemblages; they are only commoner in more southerly sections in Sakhalin sections.

Oxygen-isotope analysis of Santonian-Campanian macrofossils from Antarctica (PIRRIE & MARSHALL, 1990) indicates low high-palaeolatitude (approximately 60 °S; compare LAWVER *et al.*, 1985) temperatures and suggests that cooling occurred between the Santonian-Campanian and Maastrichtian. Moreover, these events coincide with $\delta^{13}\text{C}$ excursion fluctuations from +5,13‰ up to -7,24‰. The changing of $\delta^{13}\text{C}$ excursion from +2,5 up to +0,7 has been recorded in the Peri-Caspian region of the Tethys, while a negative $\delta^{13}\text{C}$ excursion

around 0 - -7 is characteristic of sequences in the Atlantic (sites 384 and 524) and in Spain and Tunisia at the Cretaceous-Paleocene boundary (NAIDIN & ALEKSEEV, 1981) and interpreted as an indication of mass extinctions.

The late Santonian-earliest Campanian is distinguished by the presence of many heliodiscides; spherical skeletons with eccentric microsphere, as well as primitive spherical skeletons with centric inner sphere in the Pacific Region, which easily survived crises (Pl. 10).

An explosion of planktonic foraminiferal diversity occurred during the entire Campanian-Maastrichtian interval and especially marked the uppermost Maastrichtian. The genus *Globotruncana* was derived from the *Marginotruncana* group by migration of the extra-umbilical-umbilical primary aperture towards an umbilical position and by replacement of the portici by tegilla (MASLAKOVA, 1978, 1995; CARON, 1985). The disappearance of the marginotruncanids near the Santonian-Campanian boundary reflects a brief episode of climatic cooling in the terminal Santonian-early Campanian (PETRIZZO, 2000, 2002). HUBER *et al.* (2002) recorded that the early Campanian marked the boundary between 'hot greenhouse' and 'cool greenhouse' regimes. Isotope data presented by JENKYN *et al.* (1994) suggested that, in the chalk seas of northwest Europe, the temperature fell below 20°C. The Campanian-Maastrichtian was a time of maximum diversification of planktonic foraminifera; numerous forms with complex morphologies, lower reproduction potential and preferred deep-water habitats existed during this interval (Fig. 6). Abnormal planktonic foraminifera with twinned last chambers were described from the uppermost Santonian to Maastrichtian (VENTURATI, 2006). All these taxa were unable to adapt to changing environmental conditions (*Globotruncana*, *Globotruncanita*, *Contusotruncana*, *Gansserina*, *Rugoglobigerina*, *Rugotruncana* and *Abathomphalus*) and did not survive the end of the Cretaceous. The planktonic foraminiferal assemblages are very scanty at the interval just below K/Pg boundary and at the base of the Danian. The planktonic foraminiferal extinction occurred over a short period, with 5% of the species disappearing in the terminal Maastrichtian, 70% of the species becoming extinct at the K/Pg boundary and about 25% of species ranging into the early Danian. The species that died out at the K/Pg boundary were large, complex tropical and subtropical forms that inhabited great and intermediate water depths (MOLINA *et al.*, 1998; KOPAEVICH & BENIAMOVSKII, 1999; KOPAEVICH, 2008). As a typical crisis level, the K/Pg

boundary is also characterised by a predominance of only primitive spherical tests of radiolarian species (HOLLIS, 1997; VISHNEVSKAYA, 1997; VISHNEVSKAYA *et al.*, 2005).

Conclusions

A rise of armed skeletons, as well as a decrease in size and number of chambers, occurred in the genera *Parvicingula* and *Stichocapsa* near the Jurassic-Cretaceous boundary (i.e., the late Volgian). This was probably triggered by hydrological changes and cooling; this level is known as a period of significant rearrangement of oceanic plates and is associated with tectonic and other abiotic events.

Multicyrtoid Nassellaria were important elements in the Aptian-Albian and in the uppermost Albian. Amongst radiolarians, most species of *Crolanium* and diverse last representatives of dictyomitrids, cyrtocapsids, and stichocapsids with sagittate initial chamber and distinct longitudinal rows of pores became extinct at the Albian-Cenomanian boundary. Concomitantly, the new genera *Guttacapsa* and *Lipmanium* appeared, accompanied by a mass development of biconvex, spongy pseudoaulopacoid discoid forms (*Alievium*, *Pseudoaulophacus*) and three-chambered cryptocephalic cyrtids and pseudaulophacoid dictyomitrids. The terminal Cenomanian was marked by the extinction of the family Rotaformidae and of the genera *Obeliscoites* and *Godia* amongst nassellarians and spumellarians, respectively. The earliest representatives of the genus *Alievium* (*A. antiquum*) also died out at that time. Across the Cenomanian-Turonian boundary, radiolarian assemblages experienced compositional changes at the species and higher-rank levels. Many new species, the index taxon *Alievium superbum* included, and the new genus *Afens* appeared at the beginning of the Turonian. The next phase of transgression commenced in the middle or second half of the Cenomanian, when all morphological groups of radiolarians and planktonic foraminifera appeared.

The Albian-Cenomanian transition was a time of rapid development of rotaliporids, a highly specialised group of planktonic foraminifera, which became extinct in the terminal Cenomanian. Rotaliporids coexisted with other groups of planktonic foraminifera, and this was the polytaxic stage in the evolution of foraminifera. From the viewpoint of morphological-functional analysis, it can be concluded that morphological features newly formed or transformed during the late Albian-early Cenomanian facilitated adaptation

of globigerinids to pelagic environments. Owing to supplementary apertures and large pores, their tests were lighter, more buoyant and enhanced exchange of cytoplasm with an external medium. The sculpture elements such as keels, tubercles, spines and ridges, typical of *e.g.*, *Costellagerina lybica* (BARR) increased test surface, improved the contact with the surrounding seawater and enhanced floating ability.

The Cenomanian-Turonian boundary period was associated with the development of anoxic environments, which spread almost throughout the Peri-Tethys and determined the 'bloom' of primitive cosmopolitan taxa. This was a well-marked oligotaxic stage in the evolution of planktonic foraminifera. The next polytaxic stage commenced in the early Turonian and lasted until the Maastrichtian.

The presence of numerous representatives of the radiolarian genera *Theocapsomma* and *Cryptamphorella* with submerged cephalothorax and *Excentrosphaerella* with eccentric inner microsphere at the Albian-Cenomanian, Cenomanian-Turonian and Santonian-Campanian boundaries probably indicate good adaptation of these skeletal types to a marked change in water depth, climate or possible oxygen content. All these events are in good correlation with OAE 1, OAE 2 and possibly OAE 3.

The K/Pg extinction constitutes the most sudden extinction event in the history of planktonic foraminifera. However, it cannot be ruled completely that the earliest Danian forms may have their ancestors amongst certain primitive and more resistant terminal Maastrichtian forms. The K/Pg boundary, as typical crisis level, also is characterised by only primitive spherical tests amongst radiolarians.

Ongoing and future studies of planktonic foraminiferal and radiolarian evolution across crisis intervals will undoubtedly enhance correlation with other biotic and abiotic events and allow these events to be specified in even more detail.

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Explanations of the plates

PLATE 1

Late Jurassic (late Volgian) radiolarians from siliceous clays in northern Russia (Volga region); sample G, upper Volgian Stage (*subditus* Zone) of the Uljanovsk Volga Basin.

- Fig. 1 — *Stichocapsa devorata* (RÜST), x 300.
 Fig. 2 — *Phormocampe favosa* KHUDYAEV, x 300.
 Fig. 3 — *Parvicingula?* *cristata* KOZLOVA, x 300.
 Fig. 4 — *Parvicingula* aff. *spinosa* (GRILL & KOZUR), x 200.
 Fig. 5 — *Parvicingula* aff. *alata* KOZLOVA, x 300.
 Fig. 6 — *Parvicingula* cf. *multipora* (KHUDYAEV), x 250.
 Fig. 7 — *Parvicingula* aff. *thomesensis* PESSAGNO, x 300.
 Fig. 8 — *Platycryphalus?* *pumilus* RÜST, x 300.
 Fig. 9 — *Orbiculiforma* ex gr. *mclaughlini* PESSAGNO, x 300.

PLATE 2

Aptian-early Albian radiolarians of eastern Sakhalin (Nabil River Basin, S1/11), all x 150.

- Fig. 1 — *Cenodiscaella nummulitica* var. *cenomanica* ALIEV.
 Figs 2-3 — *Hsuum raricostatum* JUD.
 Fig. 4 — *Pseudodictyomitra carpatica* LOZYNIAK.
 Fig. 5 — *Thanarla* aff. *veneta* (SQUINABOL).
 Fig. 6 — *Thanarla conica* (SQUINABOL).
 Fig. 7 — *Thanarla brouveri* (TAN).
 Fig. 8 — *Thanarla* aff. *gutta* JUD.
 Fig. 9 — *Dictyomitra* cf. *montisserei* (SQUINABOL).
 Fig. 10 — *Pseudodictyomitra* cf. *lodogaensis* PESSAGNO.
 Fig. 11 — *Pseudodictyomitra paronai* (ALIEV).

PLATE 3

Aptian-early Albian radiolarians of Eastern Sakhalin (Nabil River Basin, S1/12), all x 150.

- Fig. 1 — *Godia pelta* O'DOHERTY.
 Fig. 2 — *Godia decora* (LI & WU).
 Fig. 6 — *Godia tecta* (TUMANDA).
 Fig. 4 — *Alievium* cf. *sculptus* (SQUINABOL).
 Fig. 5 — *Archaeospongoprimum patricki* JUD.
 Fig. 6 — *Dictyomitra* cf. *montisserei* (SQUINABOL).
 Fig. 7 — *Xitus* aff. *clava* (PARONA).
 Fig. 8 — *Hiscocapsa grutterinki* (TAN).
 Fig. 9 — *Hiscocapsa asseni* (TAN).
 Fig. 10 — *Turbocapsula* aff. *costata* (WU).
 Fig. 11 — *Thanarla* sp.
 Figs 12-13 — *Amphipyndax mediocris* (TAN).
 Fig. 14 — *Pseudodictyomitra paronai* SCHAAF.

PLATE 4

Late Albian radiolarian assemblage with *Crolanium cuneatum* from the Russian Platform (Penza area, borehole 10).

- Figs 1-2 — *Orbiculiforma nevadaensis* PESSAGNO, x 100.
 Fig. 3 — *Porodiscus kavilkinensis* ALIEV, x 90.
 Fig. 4 — *Cavaspongia euganea* (SQUINABOL), x 100.
 Fig. 5, 7 — *Spongocyclia trachodes* RENZ, x 100.
 Fig. 6 — *Spongopyle insolita* KOZLOVA, x 120
 Figs 8, 10, 12-14 — *Crolanium cuneatum* (SMIRNOVA & ALIEV), x 100.
 Fig. 9 — *Dictyomitra montisserei* (SQUINABOL), x 100.
 Figs 11, 15-16 — *Crolanium triangulare* (ALIEV), x 100.

PLATE 5

Foraminifera from upper Albian strata (*Stolizkaia dispar* Zone) in northern Caucasus.

- Figs 1-2, 4-5 — *Blefusciuana globigerinellinoides* (SUBBOTINA); 1. specimen 285-5, spiral side, Podkumok River, x 170; 2. specimen 285-6, umbilical side, Baksan River, x 250; 4. specimen 285-11, spiral side, Baksan River, x 130; 5. specimen 285-10, umbilical side, Baksan River, x 220.
 Fig. 3 — *Globigerinelloides ultramicrus* (SUBBOTINA), specimen 285-2, lateral side, Podkumok River, x 170.
 Figs 6-9 — *Hedbergella accurata* GORBATCHIK & ALEXANDROVA; 6. holotype 287-1, spiral side, x 140; 7. specimen 287-4, umbilical side, x 150; 8. specimen 287-2, peripheral edge, Baksan River, x 150; 9. specimen 285-14, spiral side, Kheu River, x 170.
 Figs 10-12, 14 — *Hedbergella simplicissima* (MAGNE & SIGAL), 10a, b. specimen 285-15, spiral and umbilical side, respectively, x 115 and x 113, respectively; 11. specimen 285-1, umbilical side, Kheu River, x 130; 12. specimen 285-16, peripheral edge, Kheu River, x 150; 14. specimen 287-12, Baksan River, x 150.
 Figs 13, 16 — *Hedbergella delrioensis* (CARSEY); 13. specimen 287-13, spiral side, x 190; 16. specimen 287-11, peripheral edge, Baksan River, x 150.
 Fig. 15 — *Costellagerina libyca* (BARR), specimen 287-14, umbilical side, Kheu River, x 185.
 Figs 17-18 — *Hedbergella planispira* (TAPPAN); 17. specimen 285-6, spiral side, Podkumok River, x 190; 18. specimen 285-7, umbilical side, Baksan River, x 200.
 Fig. 19 — *Blefusciuana albiana* BOUDAGHER-FADEL *et al.*, specimen 285-12, umbilical side, Kheu River, x 185.

PLATE 6

Foraminifera from the upper Albian (*Stolizkaia dispar* Zone; Figs 1-13, 17-19) and lower Cenomanian (*Mantelliceras mantelli*; Figs. 14-16, 20) in the northern Caucasus.

- Figs 1-4 — *Blefusciuana aptiana orientalis* BOUDAGHER-FADEL *et al.*; 1. specimen 285-6, umbilical side, Kheu River, x 140; 2. specimen 285-7, peripheral edge, Podkumok River, x 140; 3. specimen 285-11, spiral side, Baksan River, x 130; 4. specimen 285-10, umbilical side, Baksan River, x 200.
 Figs 5-7 — *Planomalina buxtorfi* (GANDOLFI); 5. specimen 285-1, lateral side, x 85; 6. specimen 285-9, peripheral edge, x 135; 7a, b. specimen 285-6, lateral side and peripheral edge, respectively, x 90 and x 120, respectively, Kheu River.
 Figs 8-9 — *Rotalipora appenninica* (RENZ); 8. specimen 285-7, spiral side, Kheu River, x 110; 9. specimen 285-8, umbilical side, Kheu River, x 115.
 Figs 10-13 — *Rotalipora ticinensis* (GANDOLFI); 10. specimen 285-10, spiral side, Baksan River, x 115; 11. specimen 287-15, spiral side, Baksan River, x 115; 12. specimen 287-16, umbilical side, Baksan River, x 115; 13. specimen 287-17, umbilical side, Baksan River, x 115.
 Figs 14-15 — *Rotalipora globotruncanoides* SIGAL; 14. specimen 287-18, spiral side, Baksan River, x 115; 15. specimen 287-19, umbilical side, Baksan River, x 115.
 Figs 16, 20 — *Rotalipora gandolfi* LUTERBACHER & PREMOLI SILVA; 16. specimen 287-20, spiral side, Baksan River, x 115; 20. specimen 287-21, umbilical side, Kheu River, x 115.
 Figs 17-19 — *Gavelinella baltica* (BROTZEN); 17. specimen 285-12, spiral side, x 200; 18. specimen 285-13, umbilical side, x 150; 19. specimen 285-14, peripheral edge, Baksan River, x 160.

PLATE 7

Foraminifera from the Cenomanian-Turonian boundary interval in Crimea (Selbukhra Mountain), all illustrated in spiral, umbilical and marginal aspect (a, b and c, respectively).

- Figs 1a-c, 2a-c — *Whiteinella archaeocretacea* PESSAGNO, *Whiteinella archaeocretacea* Zone (1) and *Helvetoglobotruncana helvetica* Zone (2), both x 130.
 Fig. 3 a-c — *Whiteinella brittonensis* (LOEBLICH & TAPPAN), *Whiteinella archaeocretacea* Zone, x 130.
 Fig. 4a-c — *Hedbergella delrioensis* (CARSEY), *Whiteinella archaeocretacea* Zone, x 130.
 Fig. 5a-c — *Whiteinella baltica* DOUGLAS & RANKIN, *Whiteinella archaeocretacea* Zone, x 120.
 Fig. 6a-c — *Whiteinella aprica* (LOEBLICH & TAPPAN), *Helvetoglobotruncana helvetica* Zone, x 120.
 Figs 7a-c, 8a-c — *Dicarinella imbricata* (MORNOD), *Helvetoglobotruncana helvetica* Zone, x 120.

PLATE 8

Santonian radiolarians from Kamchatka (Figs 1-10: Ust-Palana; Figs 11-13: Kinkil Isthmus).

- Fig. 1 — *Pseudoaulophacus venadoensis* PESSAGNO, sample 202/01, x 180.
 Figs 2-3 — *Pseudoaulophacus floresensis* PESSAGNO, sample 202/01, x 190.
 Fig. 4 — *Orbiculiforma monticelloensis* PESSAGNO, sample 202/01, x 160.
 Fig. 5 — *Orbiculiforma quadrata* PESSAGNO, sample 234/01, x 125.
 Fig. 6 — *Pseudoaulophacus* cf. *lenticulatus* (WHITE), sample 234/01, x 155.
 Fig. 7 — *Dictyomitra densicostata* PESSAGNO, sample 202/01, x 190.
 Fig. 8 — *Dictyomitra urakawaensis* TAKETANI, sample 202/01, x 275.
 Fig. 9 — *Amphipyndax stocki* (CAMPBELL & CLARK), sample 202/01, x 260.
 Fig. 10 — *Diacanthocapsa* aff. *euganea* SQUINABOL, sample 234/01, x 110.
 Fig. 11 — *Stichomitra foraminosa* TAKETANI, sample 171/01, x 325.
 Fig. 12 — *Dictyomitra* ex gr. *formosa* SQUINABOL, sample 171/01, x 330.
 Fig. 13 — *Stichomitra* aff. *manifesta* FOREMAN, sample 171/01, x 240.

PLATE 9

Santonian planktonic foraminifera from Kamchatka (Ust-Palana).

- Fig. 1 — *Heterohelix reussi* (CUSHMAN), sample 173/99, x 210.
 Figs 2-3 — *Heterohelix globulosa* (EHRENBERG), sample 173/99, x 160 and x 150, respectively.
 Figs 4, 11 — *Archaeoglobigerina bosquensis* PESSAGNO, sample 173/99, x 130.
 Fig. 5 — *Hedbergella holmdelensis* OLSSON, sample 173/99, x 200.
 Fig. 6 — *Hedbergella delrioensis* (CARSEY), sample 159/99, x 220.
 Figs 7-8 — *Hedbergella* aff. *holmdelensis* OLSSON, sample 159/99, x 200 and x 210, respectively.
 Figs 9-10 — *Globigerinelloides ultramicra* (SUBBOTINA), sample 159/99, x 200 and x 190, respectively.
 Fig. 12 — *Archaeoglobigerina* aff. *bosquensis* PESSAGNO, sample 159/99, x 210.

PLATE 10

Boreal species of Coniacian-early Campanian radiolarians from northern Russia, all x 200. Provenance is as follows: lower Campanian, Vatyra River Basin, Koryak Mountains (Figs 1-4; sample 64/S1998); lower Campanian, Tykhaya River Basin, western Kamchatka (Figs 5-7; sample 64/00); lower Campanian, Ust-Palana River Basin (Fig. 8; sample 134/01); upper Santonian, Volga River Basin (Fig. 9; sample O-2003-1-68) and Coniacian, Don River Basin (Fig. 10; sample 541).

- Fig. 1 — *Spongasteriscus rozanovi* VISHNEVSKAYA.
Figs 2-3 — *Heliodiscus borealis* VISHNEVSKAYA.
Fig. 4 — *Prunopyle stanislavi* VISHNEVSKAYA.
Figs 5-7 — *Excentrosphaerella kamchatica* VISHNEVSKAYA & DUMITRICA.
Fig. 8 — *Clathrocyclas* sp.
Fig. 9 — *Alievium olferievi* VISHNEVSKAYA.
Fig. 10 — *Cyrtocapsa* sp.

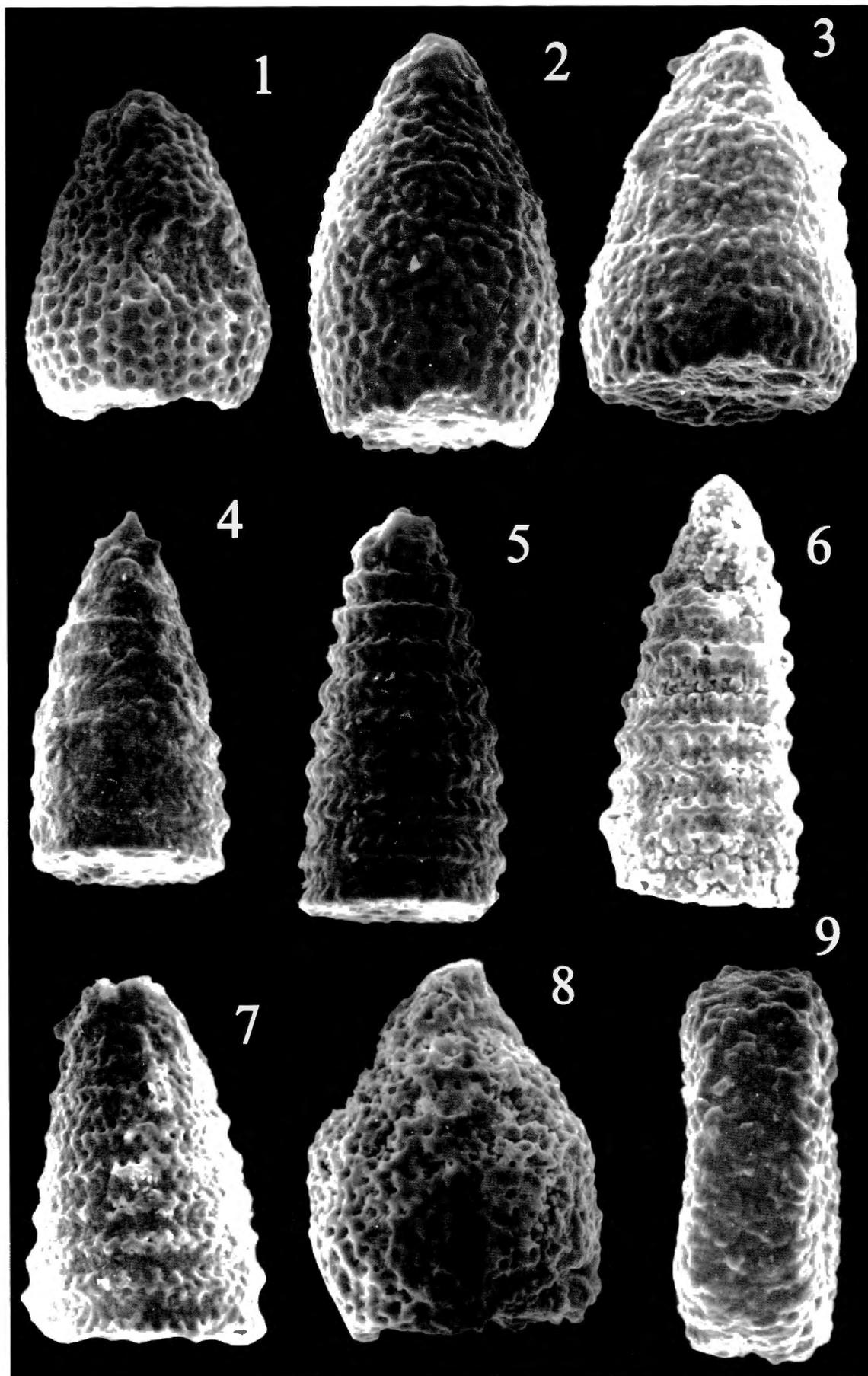


PLATE 1

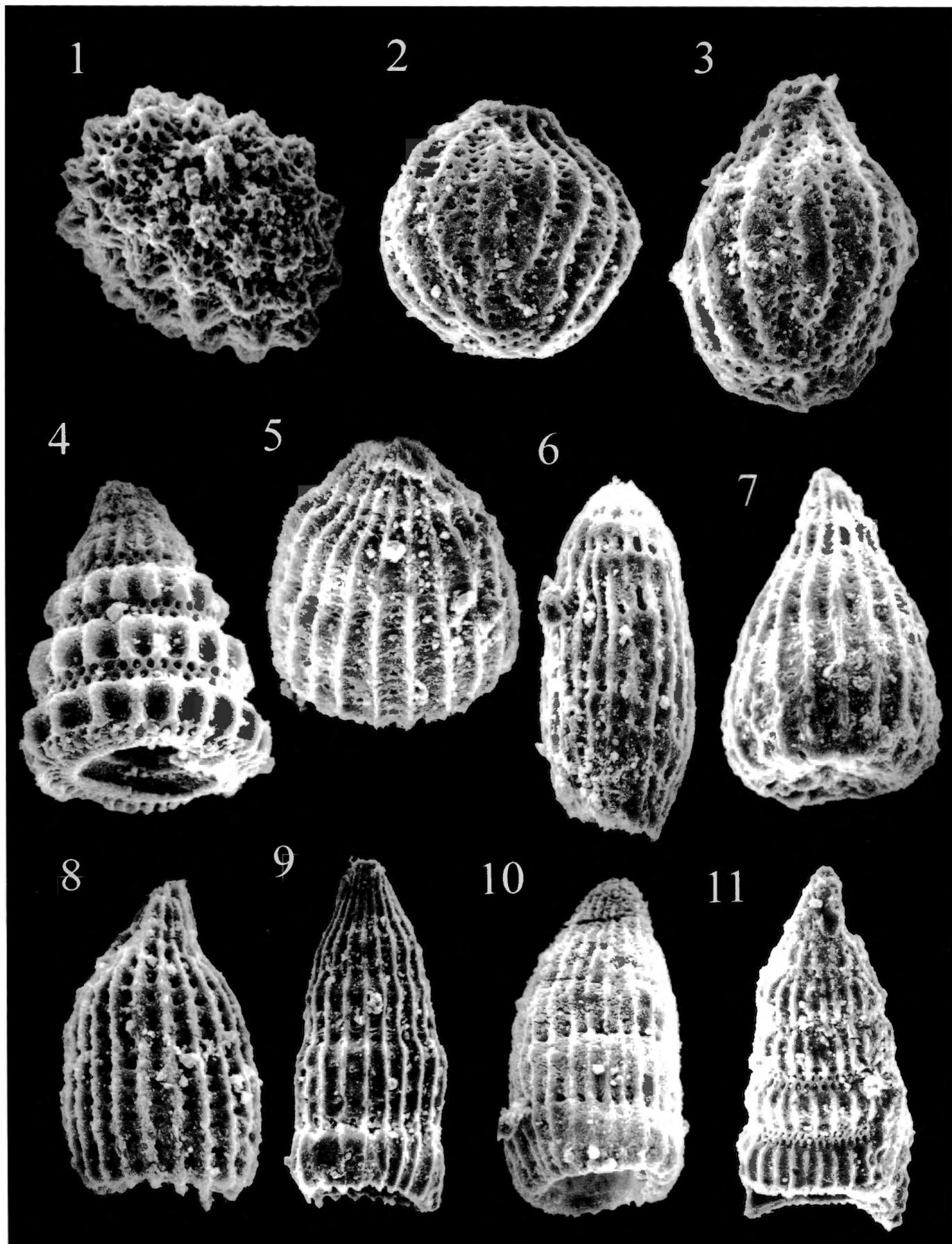


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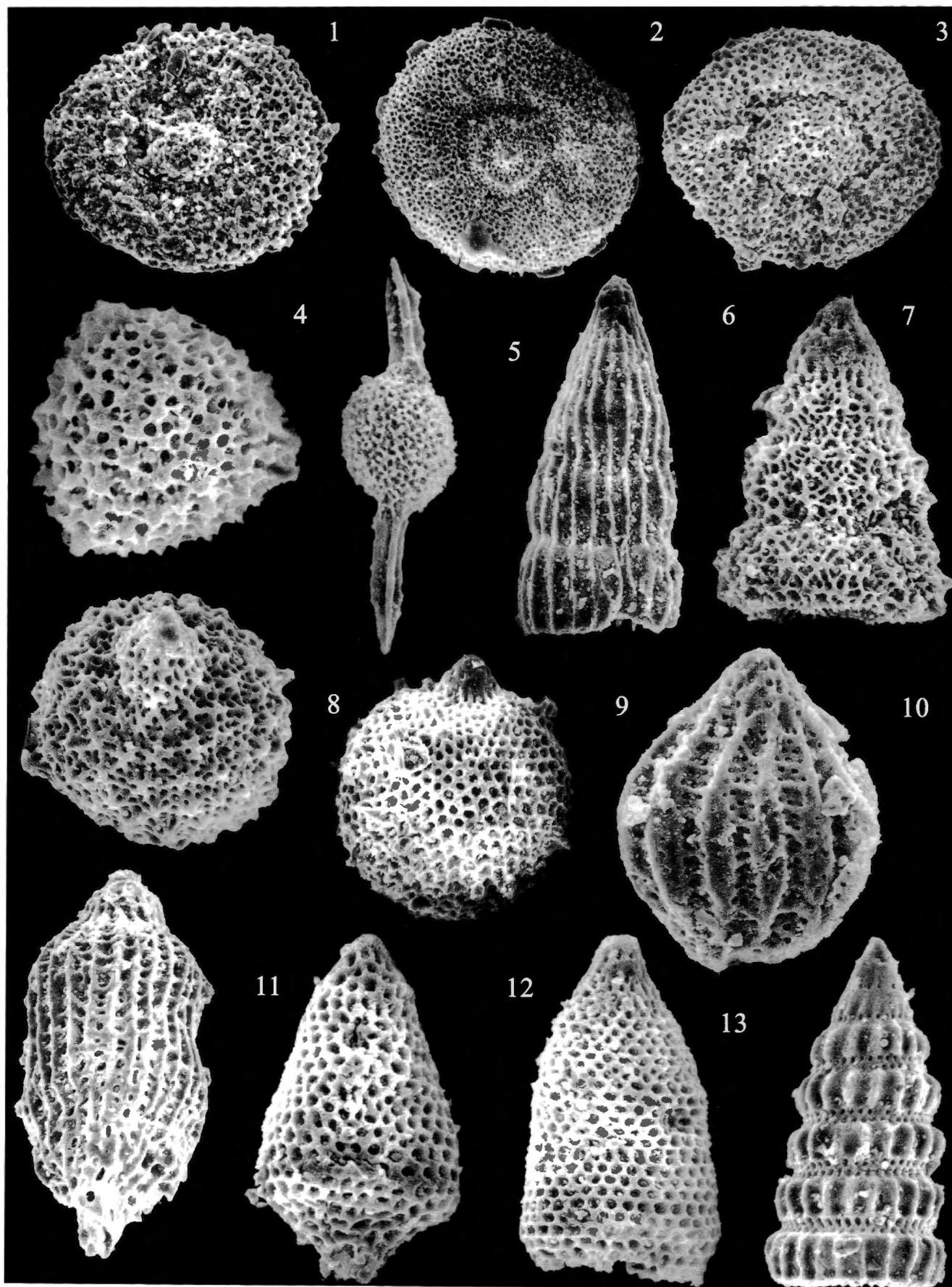


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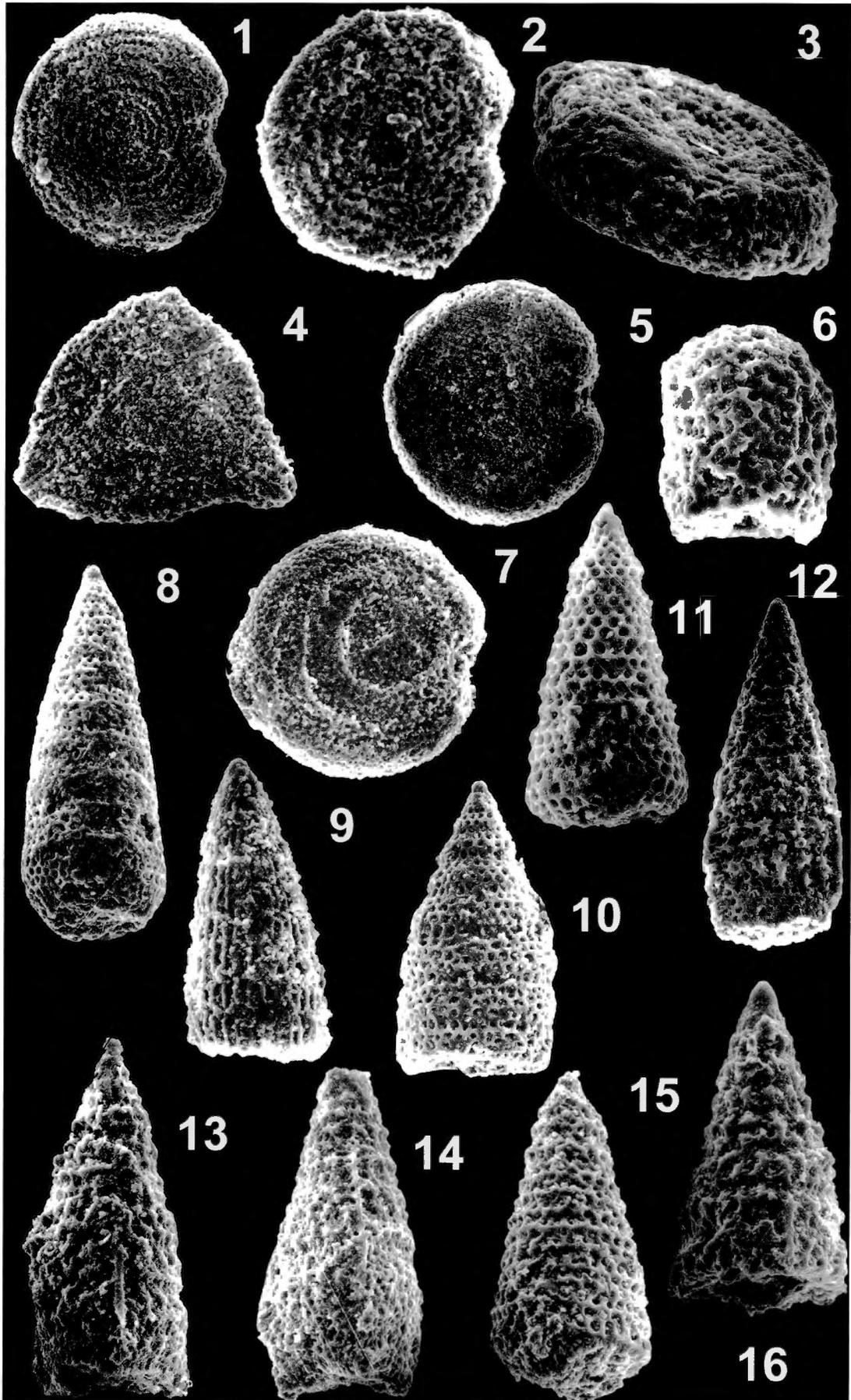


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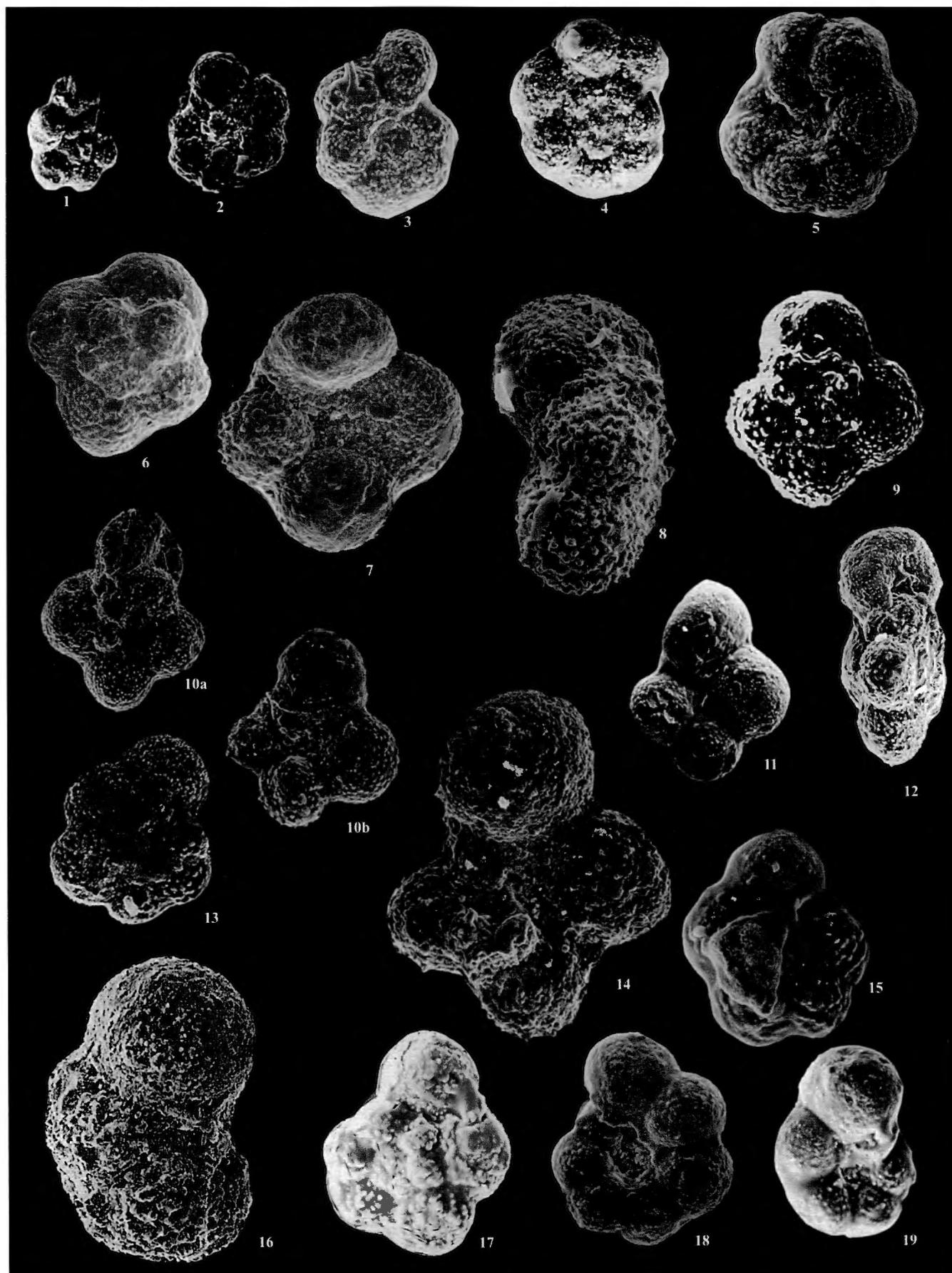


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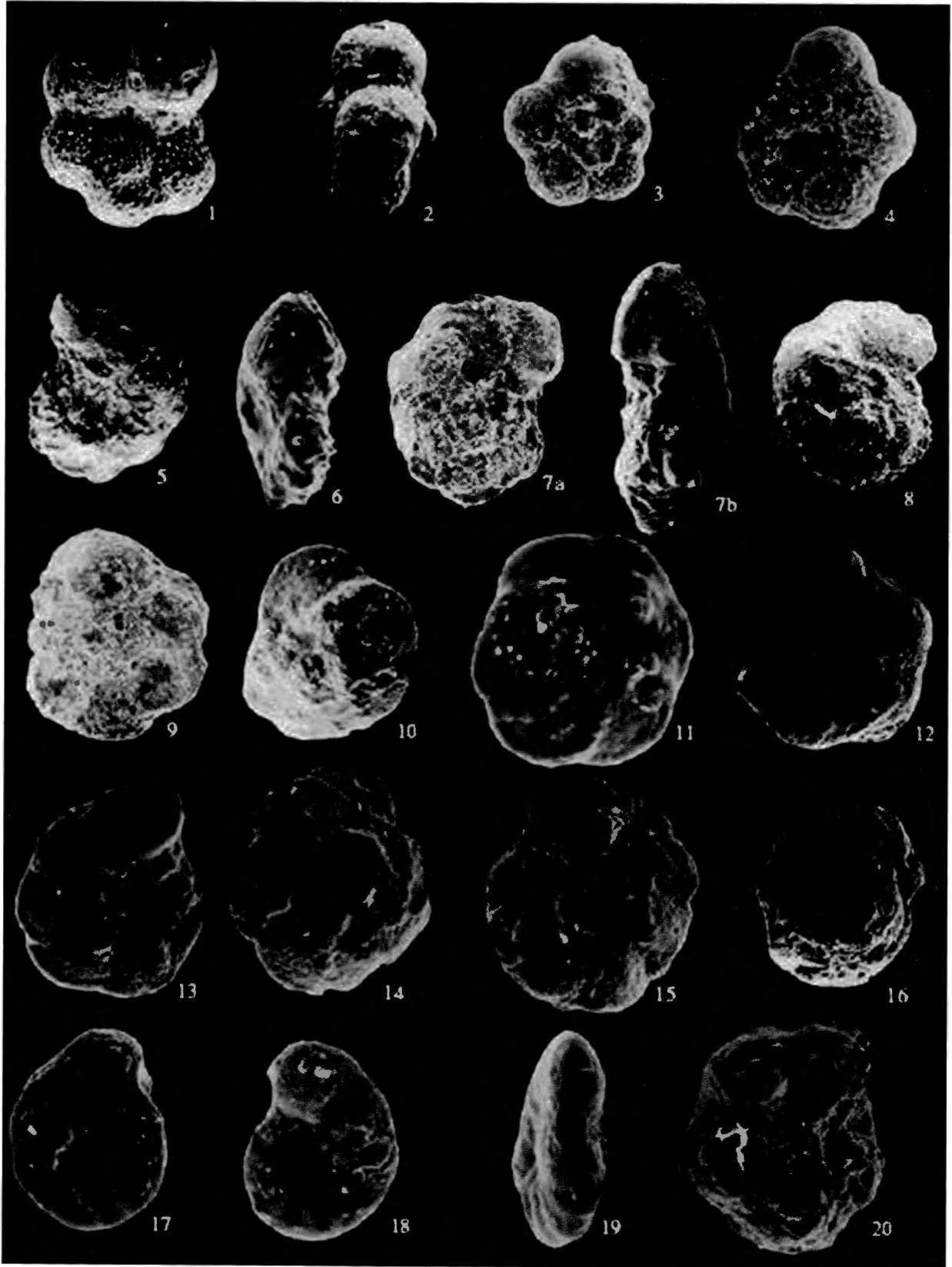


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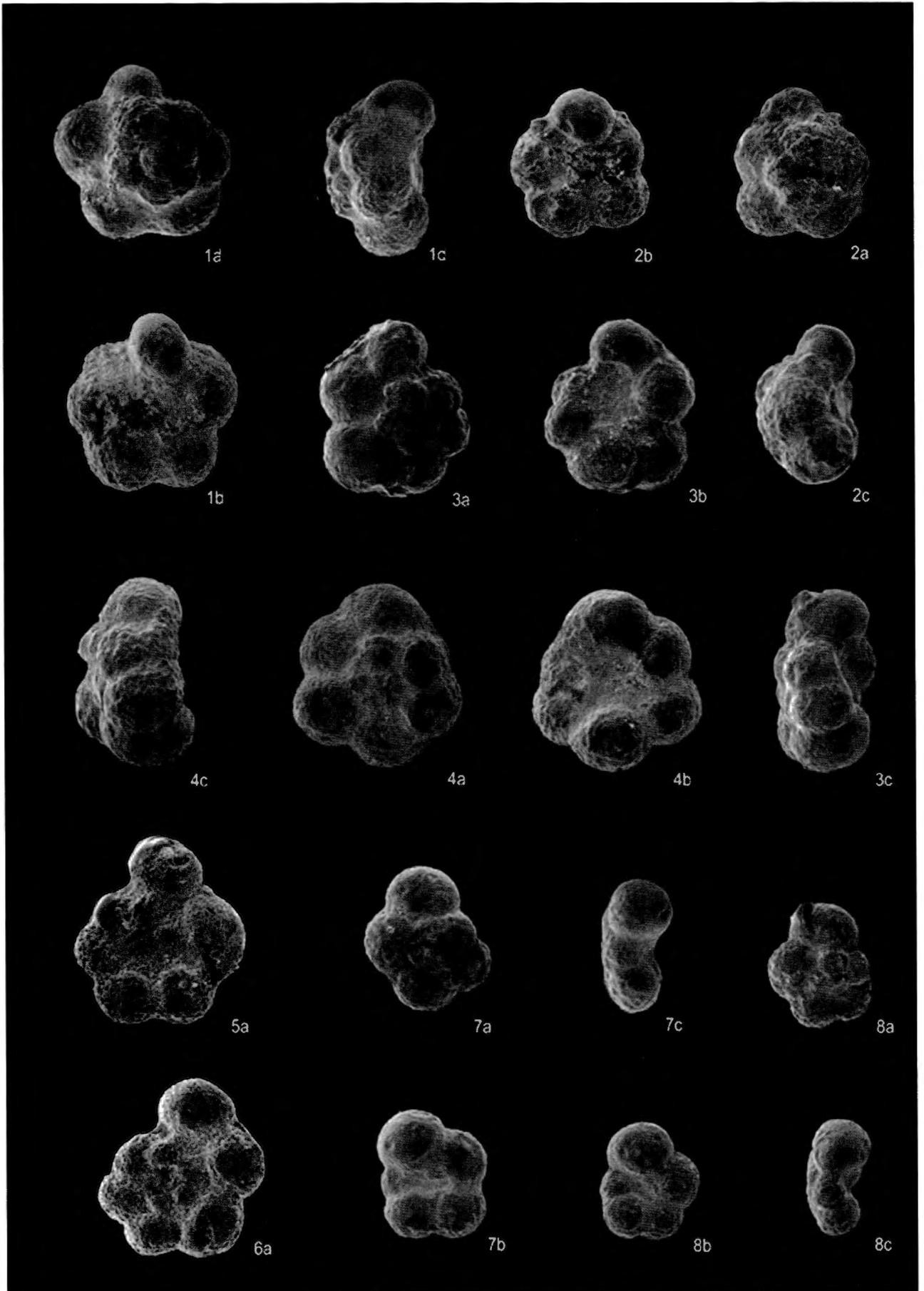


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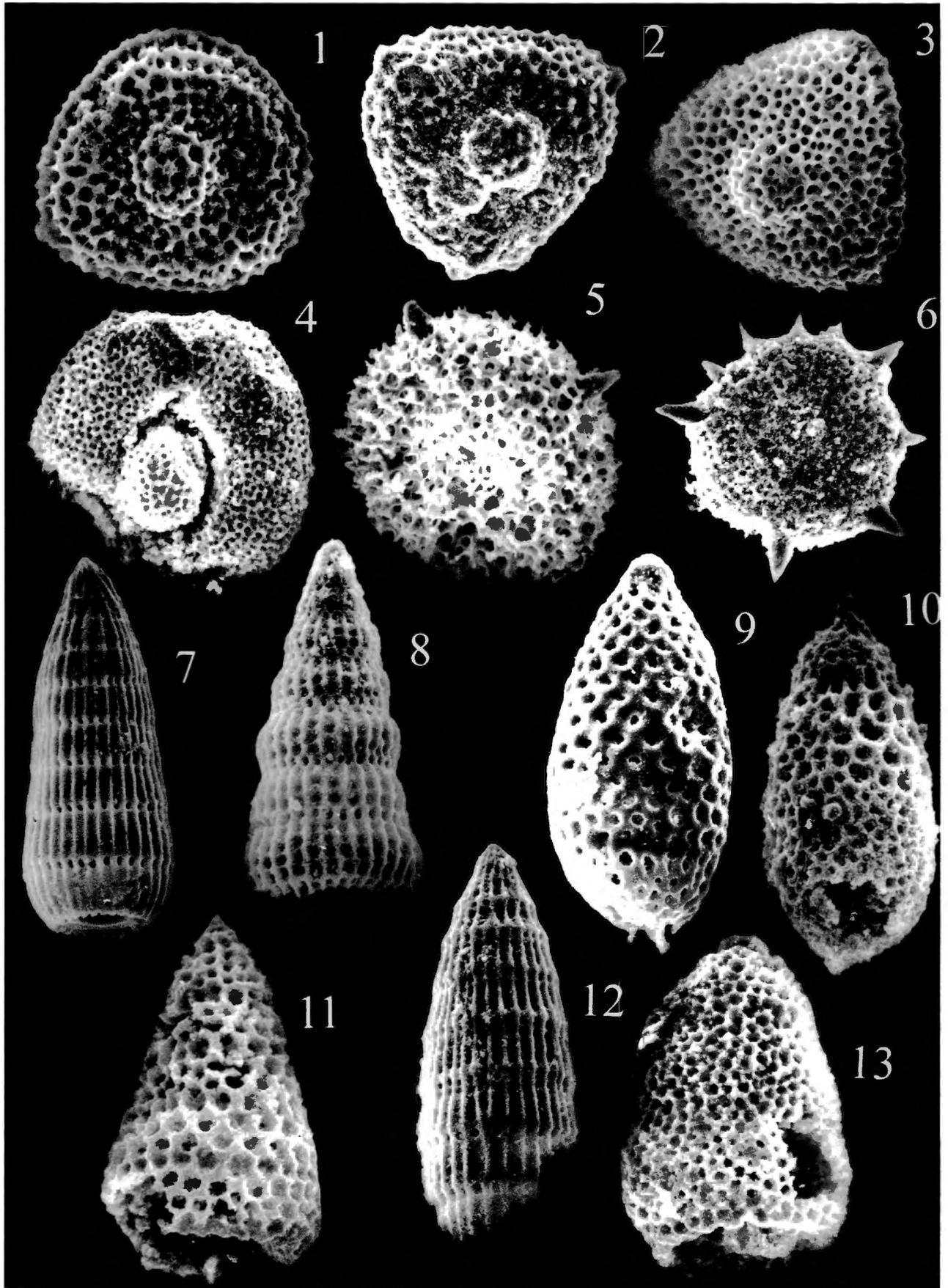


PLATE 8

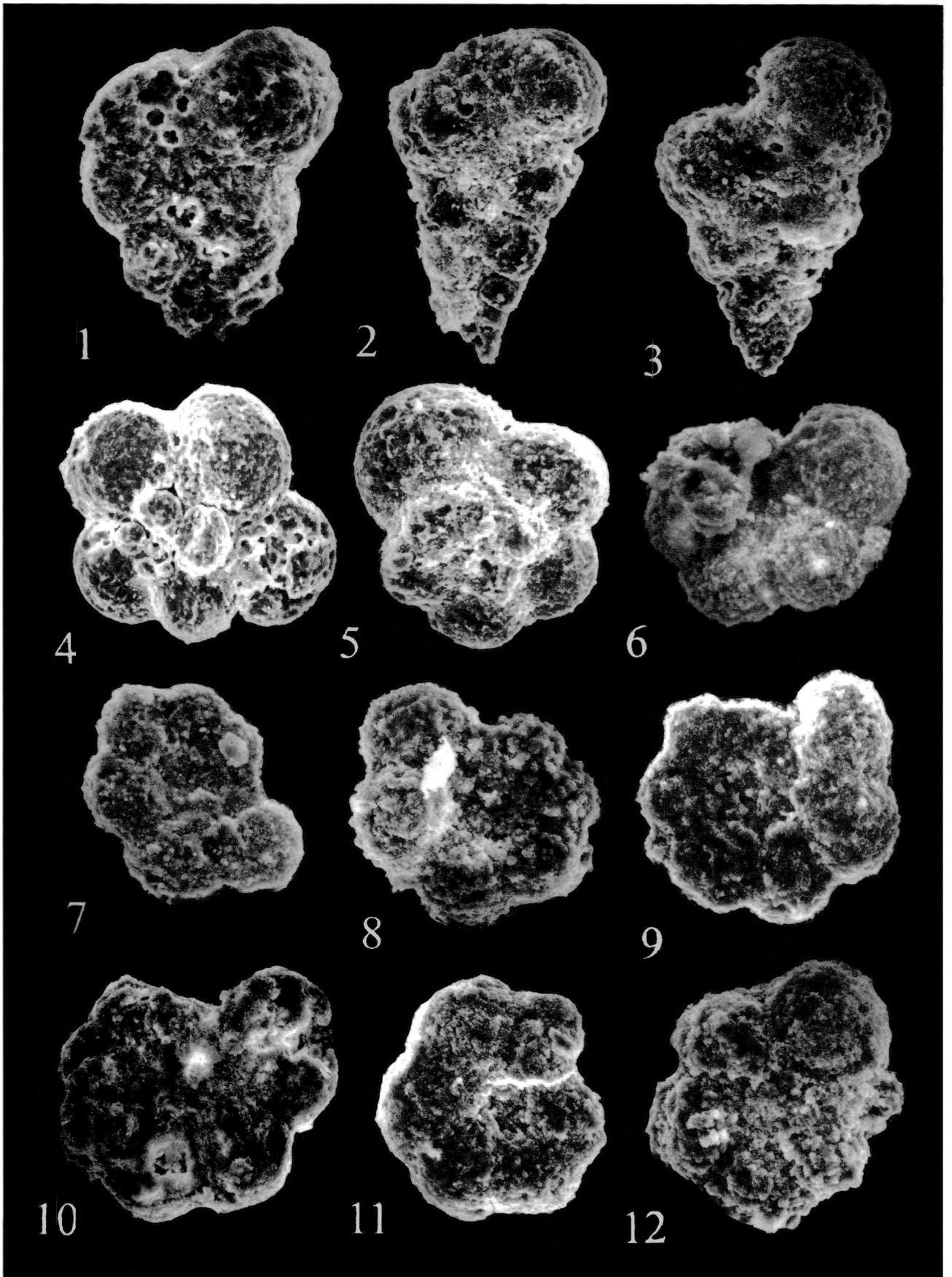


PLATE 9

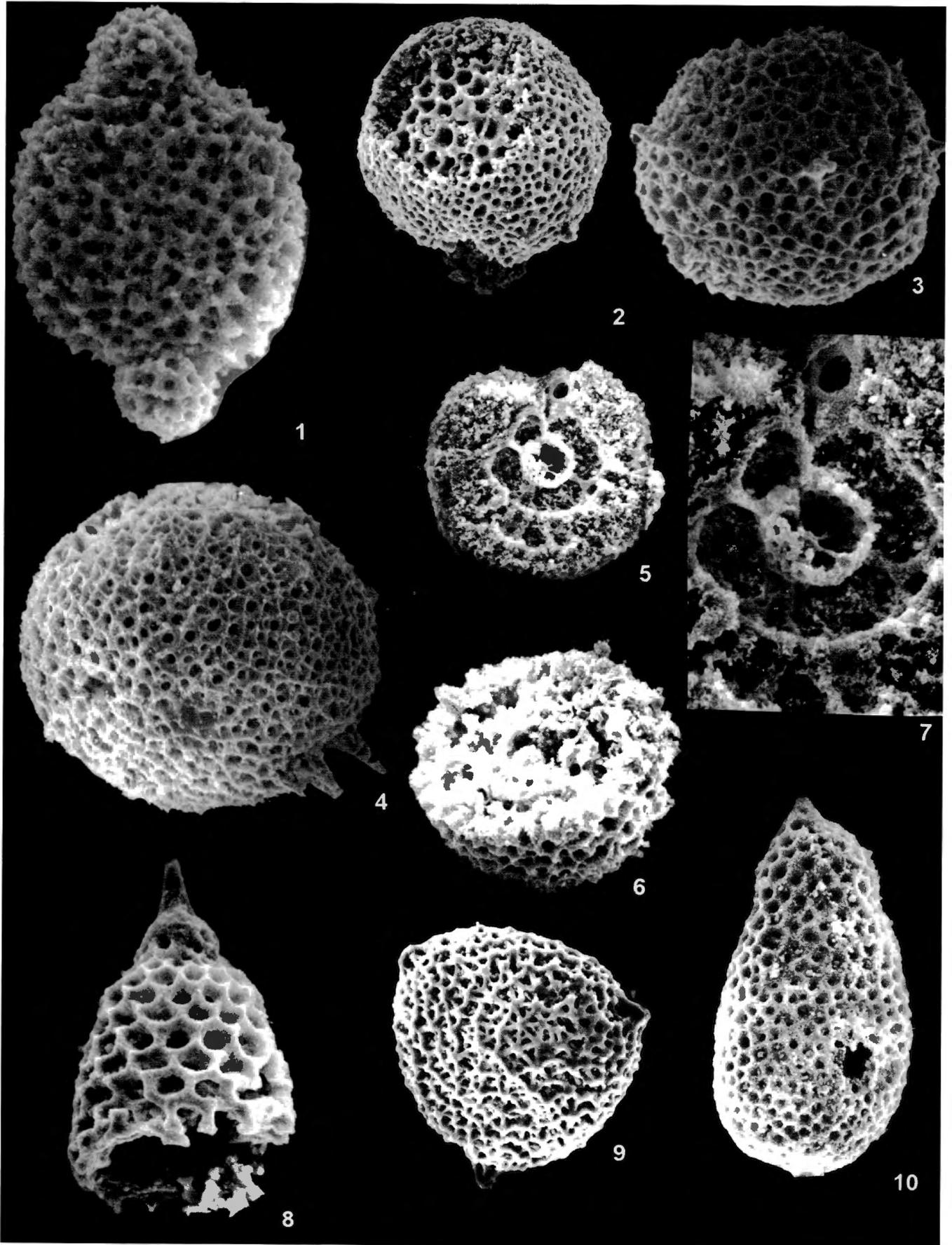


PLATE 10

