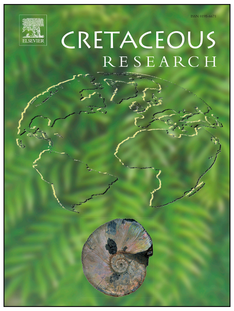

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Lepidorbitoides (Foraminifera) from the lower Maastrichtian Kallankuruchchi Formation, Cauvery Basin, India: morphometry and paleobiogeography

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Abstract

The southernmost occurrence of the early Maastrichtian larger benthic foraminifera (LBF) in Tethys is known from the Kallankuruchchi Formation in the Cauvery Basin, SE India, represented by *Lepidorbitoides-Siderolites* assemblages. The systematics, age and paleobiogeography of *Lepidorbitoides* here have as yet remained unresolved due to lack of information particularly on the nepionic arrangement, whereas their links with the Western Tethyan and Caribbean biogeographic domains were speculated. *Lepidorbitoides,* studied from the same level in seven samples in two separate areas, invariably possess quadriserial nepionts and adauxiliary chamberlets, whose mean number ranges from 3.79 to 4.67. The ratio between the sample means of the internal diameter of deuteroconch and protoconch varies between 1.72 and 1.86. The equatorial layer in the early stage consists of arcuate chambers with basal stolons, and ogival-to spatulate chamberlets with annular and oblique stolons in the later stages. These features are consistent with the phylogenetically advanced members of the Western Tethyan *Lepidorbitoides* lineage, such as *L. minor* (Schlumberger) and *L. socialis* (Leymerie), and all samples were assigned to the transitional development stages of these species based on the morphometry. The taxonomic status of some *Lepidorbitoides* species, originally described from the Kallankuruchchi Formation and widely adopted in previous works, such as *L. blanfordi* (Rao) and *L. inornata* (Rao), are not justified. We extend the geographic range of Western Tethyan *Lepidorbitoide*s to southern India.

Keywords: *Lepidorbitoides*; Morphometry; Maastrichtian; Cauvery Basin; India

1. Introduction

The larger benthic foraminiferal (LBF) genus *Lepidorbitoides* Silvestri, 1907, along with closely allied *Orbitoides* d'Orbigny, 1848 and *Omphalocyclus* Bronn, 1853, occurs commonly in circum-tropical Campanian- Maastrichtian shallow-marine deposits (Fig. 1) (Fleury et al., 1985; van Gorsel, 1978; Goldbeck and Langer, 2009 and references therein; Robles-Salcedo et al., 2013). Morphological change in time, as recorded in the embryon and the equatorial layer of the test, and wide geographic distribution make *Lepidorbitoides* a valuable stratigraphic marker (Papp, 1954, 1955; Mac Gillavry 1955; van Gorsel, 1975, 1978; Caus et al., 1988; Drooger, 1993; Özcan and Özkan-Altıner, 1999a, b). This facilitates the global correlation in shallow-marine realm (Aguilar et al., 2002; Goldbeck and Langer, 2009). Cauvery Basin, interpreted to be a part of the tropical-subtropical climatic zone in Maastrichtian times (Zakharov et al., 2011), marks the southernmost occurrence of *Lepidorbitoides* in the southern hemisphere. Here, *Lepidorbitoides* occurs abundantly in the Dherani limestone member of the shallow marine Kallankuruchchi Formation, which is widely exposed in the Ariyalur region. The Kallankuruchchi Formation, historically known as the Gryphaea-beds, is characterized by the common occurrence of gryphaeid oysters, inoceramids, echinoids, terebratulid brachiopods, rare ammonoids and abundant LBF (Stoliczka, 1873; Rao, 1941). The LBF are represented by abundant orbitoidiform taxa, variously assigned to *Orbitoides*, *Lepidorbitoides*, and *Orbitocyclina* in the previous works, and other less diagnostic genera such as *Siderolites* Lamarck, 1801 and *Goupillaudina* Marie, 1958. Despite its biostratigraphic and paleobiogeographic significance, a detailed study of *Lepidorbitoides* from the Kallankuruchchi Formation is lacking, a fact evidenced by previous works that resulted in conflicting taxonomical and paleobiogeographic conclusions (Rao, 1941; van Gorsel, 1978; Hart et al., 2000; Goldbeck and Langer, 2009).

Since the previous studies are based mostly on the vertical and oblique sections of the *Lepidorbitoides* from the thin sections and the nepionic development of the genus is not known, a study of embryon and equatorial chambers in oriented sections is necessary. We have carried out a morphometric study of *Lepidorbitoides* specimens from the Dherani limestone member in two localities to the north and northeast of Ariyalur area in the Cauvery Basin for a more robust description of the nepionic features of the genus. The data are also used to assess phylogenetic stage of the genus by comparing them with the evolutionary model of *Lepidorbitoides* from the Western Tethys and to evaluate the Maastrichtian palaeobiogeography of the genus.

2. Geological setting and Stratigraphy

The Cauvery Basin fringing the southeastern coastal area of India preserves an almost complete Upper Cretaceous-Paleocene sequence in the Ariyalur-Pondicherry depression, formed by the Late Jurassic-Early Cretaceous rifting (Sastri et al., 1981). The deposits of the Campanian-Maastrichtian Ariyalur Group, widely exposed along a belt trending roughly NE-SW in the Ariyalur area, are subdivided into three formations: Sillakudi, Kallankuruchchi and Kallamedu (Fig. 2A-C). The Kallankuruchchi Formation, ca. 40 m thick, is a prominent shallow marine carbonate unit characterized by the occurrence of large shells of various invertebrate groups, as well as LBF. The unit has been subdivided into several members (Tewari et al., 1996; Ramkumar, 1999). Tewari et al. (1996) recognized the Tancem Limestone, Dalmia biostromal limestone and Dherani sandstone members, roughly equivalent to the lower arenaceous and

Inoceramus limestone and upper fragmented shell limestone and Gryphean limestone members of Ramkumar (1999). The Tancem Limestone member is a thick-bedded to massive bioclastic limestone, composed of mainly rudist fragments. The Dalmia biostromal member is a highly fossiliferous limestone, predominantly made up of the shells of oysters (e. g. *Pycnodonte*), inoceramids, terebratulid brachiopods, echinoids (e. g. *Gongrochanus*), bryozoans, sponges and rare ammonites, and is recognized in the field by the occurrence of *Pycnodonte* colonies (Stoliczka, 1873; Ayyasami, 1990; Radulovic and Ramamoorthy, 1992; Srivastava, 2012) (Fig. 3). We could not find any LBF in this unit, while Tewari et al. (1996) noted the occurrence of *Orbitoides* sp., *Lepidorbitoides* sp. and *Siderolites* sp. The Dherani limestone member is a thick-bedded, friable grainstone with abundant LBF, bryozoans, sponges and rare large invertebrates.

The *Lepidorbitoides* studied here comes from a ca. 1.5-2 m-thick friable, fragmental limestone bed just above the Gryphaea beds of the Dalmia biostromal member, corresponding to the Dherani Limestone member of Tewari et al. (1996). This bed contains abundant *Lepidorbitoides* accompanied by *Siderolites calcitrapoides* and *Goupillaudina daguini* and lacks *Orbitoides* and *Omphalocyclus*, as noticed in some of the previous works (Rama Rao, 1957; Fleury et al., 1985; Tewari et al., 1996; Hart et al., 2000). The Kallankuruchchi Formation is unconformably overlain either by the shallow marine siliciclastics of the Ottakoil member of the Maastrichtian Kallemedu Formation or the fluvial and coastal marine sandstones of the same unit containing dinosaur remains.

The age of the Kallankuruchchi Formation is not firmly constrained, while it was mostly dated either as Maastrichtian (early Maastrichtian) or late Campanian-early Maastrichtian based on

LBF, rare planktonic foraminifera, ammonites, and other stratigraphically less significant fossil groups (Figure 4). The unit was constrained by Rai et al (2013) as early Maastrichtian in age based on presence of late Maastrichtian nannofossils CC25 *Arkhangelskiella cymbiformis* Zone in the overlying Ottakoil sandstone. Nevertheless, a more precise direct dating of this unit is not yet available partly because of the absence high-resolution fossil taxa and facies limitations. The Kallankuruchchi Formation was interpreted to represent a transgressive carbonate ramp setting with occasional hardgrounds, shoals, tidal channels and storm beds (Tewari et al., 1996; Ramkumar, 1999; Watkinson et al., 2007).

3. Historical background

The occurrence of LBF in Cauvery Basin has been known since Stoliczka (1873) assigned the orbitoidiform specimens from the Kallankuruchchi Formation in Chakkanathapuram to *Orbitoides faujasi* (Defrance) (Fig. 4). The only figure (Pl. 12, fig. 5) illustrating the outer chambers of the equatorial layer undoubtedly shows the pointed arcuate chamberlets in the equatorial section. Vredenburg (1908) assigned the specimens figured by Stoliczka to *Orbitoides minor* by referring the rhombic character of the equatorial chambers, a characteristic feature observed in the outer parts of the equatorial layer of this species, introduced by Schlumberger (1901) from the Maastrichtian type-section. Rao (1941) erected two new species from the same area, *L. inornata* for the specimens supposedly lacking the external piles (granules) and *L. blanfordi* for the specimens with well-developed pillars and arcuate to rhomboidal equatorial chamberlets, previously assigned to *O. minor* by Vredenburg (1908). Rao argued that *L. blanfordi* differs from *O. minor* (*O. faujasi* of Stoliczka) in the shape of the equatorial chamberlets, which are spatulate to ogival in shape in the latter species. It is worth to note that this author did not illustrate any equatorial section of *L. blanfordi*, which according to him differs from Western Tethyan *L. minor*. Rao further proposed a Caribbean affinity for *L. inornata* because of the lack of piles, a feature attributed to some Caribbean *Lepidorbitoides* (Thiadens, 1937). This species concept of Rao (1941) was used invariably in following works (Rama Rao, 1957; Gowda, 1964; Srivastava and Tewari, 1967), while Nagappa (1959) and Ravindran (1980) recorded *Lepidorbitoides* sp. from the Ariyalur group without specific identification. Van Gorsel (1975, 1978) noted that, in the lack of any information about the nepionic stage, the relationship of these Asian forms to European *Lepidorbitoides* would be uncertain. Lastly, Hart et al. (2000) assigned the Ariyalur specimens to *Lepidorbitoides* cf. *socialis* (Leymerie, 1851), representing the final evolutionary stage of the genus in the late Maastrichtian in Western Tethys (peri-Mediterranean/Europe), without any illustration or description of the nepionic stage. The latter authors, however, noted the contradiction on the occurrence of ‘most advanced’ developmental stage of the genus in upper Campanian-lower Maastrichtian deposits and concluded that further taxonomic work should be carried out for a more robust species identification.

4. Materials and Methods

Seven samples were collected from two localities, Chokkanathapuram (11^{o}15’99” N; 79^{o}07”68’E) and Kallankuruchchi (11^{o}09’52” N; 79^{o}06”78’E) from the Dherani limestone member of the Kallankuruchchi Formation (Figs. 2B, 3A, E). This work is based on the loose specimens extracted from the friable limestone and the investigation of the oriented sections prepared through equatorial and axial planes of the test. The equatorial sections of megalospheric generation (A-forms), essential for taxonomy, require the grinding of the lateral parts of the free test on both sides of the equatorial layer by a fine grinding paper to a certain level in the equatorial layer to obtain a section exposing the embryon and equatorial chambers. The measurements and counts used in the morphometry include number of the adauxiliary chamberlets (adc: these are the chamberlets directly arising from the deuteroconch), inner diameters of the protoconch and deuteroconch (P and D) perpendicular to their common axis and their ratios (D/P), executed in the equatorial sections of the megalospheric specimens (Fig. 5). The microspheric specimens (B-forms) are rare and only one specimen was sectioned. Because of poor quality of this section, microspheric generation was excluded from the description.

5. Result

5.1 Description of the *Lepidorbitoides*

5.1.1 General test features (Fig. 6):

Only megalospheric (A-forms) specimens have been studied. The microspheric generation is very rare and only one was found among 154 sectioned specimens. The test is of medium size, circular, mostly symmetrical with regard to the equatorial layer, and lenticular-discoidal. The test diameter and thickness range between 1200-4700 µm and 600-1450 µm respectively. The surface is smooth with uniformly distributed piles, coarser the central part of the test about (110-160 µm in diameter) and finer towards the periphery (30-65 µm in diameter). The equatorial layer is about 30-50 µm high near the embryon, and it reaches up to 80-90 µm along its periphery. The lateral chamberlets are open, in vertical rows, 60-110 µm in diameter in the central part of the test.

5.1.2 Embryon and nepionic stage:

The embryon consists of a (sub)-circular protoconch (P) and a kidney-shaped, larger deuteroconch (D) with thick hyaline wall (Fig. 7.1-3). The protoconch shows a single stolon, ca. 10 microns in diameter, located in a marginal position with respect to the P-D axis in the equatorial layer (Fig. 7.2). The deuteroconch possesses invariably two stolons at the junction with the protoconch on either side of the P-D axis, leading to the formation of auxiliary chambers, almost same size as the other chambers around the embryon. The average diameters of protoconch and deuteroconch range between 99.21-113.75 µm and 171.75-195.83 µm respectively (Table 1). The ratio of deuteroconch to protoconch (parameter D/P) varies from 1.72 to 1.86. The radial stolons, easily detected because of the iron-infilling on the deuteroconch wall, lead to the formation of adauxiliary chamberlets. The number of adauxiliary chamberlets counted in 139 specimens varies between 1 and 7, with sample averages between 3.79-4.67. The equatorial chambers arising from the auxiliary chamberlets exhibit short spiral development on the protoconchal side (Figs. 7C, 8-10).

5.1.3 Equatorial chamberlets and stolons:

The equatorial chamberlets notably vary in shape through ontogeny. The early chambers are commonly open arcuate in shape and the bases of the chambers do not touch to each other (Fig. 5B). These chambers have only basal stolons, and occasionally may exhibit oblique stolons (Fig. 7.1). The following chambers are ogival in shape and the walls of the adjacent chambers may have a common wall consisting of annular stolons. The oblique stolons are formed on the lateral sides of these chamberlets (Fig. 7.4-5), and occasionally more than one of them are observed next to each other in the same chamberlet wall (Fig. 7.5). These chamberlets are usually either ogival or spatulate in shape at the peripheral parts of the equatorial layer. Typical hexagonal chamberlets may appear occasionally at the periphery of the equatorial layer.

5.2 Morphometry and species designation

Lepidorbitoides, along with its ancestor *Helicorbitoide*s, forms a single evolutionary lineage ranging from the (late) Campanian to Maastrichtian in Tethys, subdivided into seven successive species based on the morphometric criteria and some qualitative features such as the arrangement of spiral chambers, shape of the equatorial chambers and type of stolons (Papp, 1954, 1955; van Gorsel, 1975; Drooger, 1993; Özcan & Özkan Altıner, 1999a, b). Mac Gillavry (1955), on the other hand, argued that two species, *L. minor* from Netherlands and *L. socialis* from France have had independent origins based on his preliminary work. Caus et al. (1988) also concluded that *L. minor* and *L. socialis* are time-equivalent after studying the same localities. We think that the insufficient planktonic foraminiferal and calcareous nannofossil data presented by these authors do not fully justify the age-relationship of the localities, and planktonic foraminiferal and calcareous nannofossil zones adopted for the comparison of the aforementioned species should be considered by caution. The evolutionary scheme of Tethyan *Lepidorbitoides* is shown in Figure (Fig. 11). The most significant changes after the formation of quadriserial nepionts include the increase in the number of adauxiliary chamberlets and a notable increase in the deuteroconch diameter with respect to the protoconch. The shape of the equatorial chamberlets and type of the stolons are considered significant at species level. The arcuate chambers are replaced with pointed arcuate, ogival and spatulate ones through the time as equatorial chambers become more densely spaced in the equatorial layer. This trend can also be observed in the successive stages of a single specimen of a species representing an advanced developmental stage in *Lepidorbitoides* lineage, such as *L. minor* and *L. socialis*. The simple arcuate chamberlets possess only basal stolons, while the ogival and spatulate chamberlets have annular and oblique stolons.

The relation of nepionic arrangement, expressed by the sample means of number of adauxiliary chamberlets (adc) and the sample means of protoconch (P) and deutroconch (D) and their ratios (D/P) in seven samples from the Kallankuruchchi Formation are shown in Figures 12-14 (also see Table 1). The parameter adc in all samples fall very close to the morphometric limit of *L. minor* and *L. socialis,* within the species limit of *L. minor*, except for the only sample KAL5A, which falls to the *L. socialis* field. The sample means of protoconch and deuteroconch in Tethys have proven to show a wide distribution and are not used in the species discrimination (Figs. 12, 13). According to the D/P parameter, samples fall very close to *L. minor-L. socialis* boundary, either within the former or latter species (Fig. 14). Considering above parameter, specifically the adc and D/P, we assign our samples to a transitional developmental stage of *L. minor* and *L. socialis* based on the morphometric species definition proposed by van Gorsel (1978). Since adc is a more significant parameter than D/P, we conclude that all samples, except for KAL5A, are within the species limits of *L. minor* and assign our specimens to *L.* ex. interc. *minor-socialis* following Drooger (1993) for the species designation for the intermediate forms of two successive species of an evolutionary lineage.

5.3 Age of the studied samples

A general contradiction on the age assignment of Upper Cretaceous LBF in the literature stems from the modifications in the global correlation of planktonic foraminifera with respect to the Campanian-Maastrichtian boundary in the last decades. A correlation of the evolutionary stages of *Lepidorbitoides* with planktonic foraminifera and other fossil groups has been loosely established in the boreal and sub-tropical regions of Tethys in Europe (van Gorsel, 1975, 1978; Caus et al., 1988). The tentative correlation chart with planktonic foraminifera proposed by van Gorsel (1975, 1978) is based on the scanty data from the Maastricht tuff chalk in the Netherlands, the Campanian type-section in Aubeterre (France), and additional data from the Vienna Basin, Sweden and the Pyreneans in Spain (Fig. 11B). This author also used LBF, such as *Orbitoides*, *Siderolites*, *Pseudosiderolites*, *Praesiderolites*, *Omphalocyclus*, *Hellenocyclina*, *Clypeorbis*, to characterize the accompanying fauna and biostratigraphic zones spanning the late Campanian-Maastrichtian time interval (Figure 11B). In this zonation, the *R. calcarata* zone, the upper boundary of which was regarded to coincide with Campanian-Maastrichtian boundary (sensu Bolli, 1966), was crucial to fix the stratigraphic position of *L. campaniensis* as a marker species in the upper Campanian and lowermost Maastrichtian, following the developmental stages of *Lepidorbitoides*. The base of the *Lepidorbitoides minor* Zone was recognized here above the *G. gansseri* Zone, the first appearance (FA) datum of which was placed in a significantly younger level in the Maastrichtian. The most advanced species of the lineage, *L. socialis*, was correlated with *A. mayaroensis* Zone.

A revised concept for the correlation of the planktonic foraminiferal zones to belemnite and ammonite zones and magnetostratigraphy lowers the *R. calcarata* and *G. gansseri* zones significantly with respect to the Campanian-Maastrichtian boundary (sensu Robaszynski and

Caron, 1995). The correlation of *G. gansseri* Zone with the upper Campanian and lower Maastrichtian has significant consequences for the stratigraphic ranges of late Cretaceous LBF, which require a thorough revision, although the first occurrence of *G. gansseri* appears to be not isochronous. The first appearance datum of this species is interpreted either as corresponding to the base of the Maastrichtian stage in high latitudes (Li and Keller, 1998) or below the Campanian-Maastrichtian boundary in a low latitude setting (Voigt et al., 2012). We here adapt the stratigraphic scheme of Gradstein et al. (2012) for the correlation of the *G. gansseri* Zone with GTS2012, and for the correlation of the evolutionary stages of *Lepidorbitoides*. The correlation of *Lepidorbitoides* with planktonic foraminifera in Turkey (Özcan and Özkan-Altıner, 1999b; Özcan, 2007) reveals that the primitive forms of *L. minor* and also *L. socialis* first appear in the *G. gansseri* Zone in late Campanian- early Maastrichtian times (Fig. 15). The advanced stages of *L. socialis* with numerous adauxiliary chamberlets are characteristic for the *A. mayaroensis* Zone. The previous poor records of *G. gansseri*, established without zonal precision, from the Kallankuruchchi Formation were used to interpret the age of the unit as late Campanian-early Maastrichtian (sensu Hart et al., 2000). Our data from Turkey suggest that transitional forms of *L. minor* and *L. socialis* appear in the *G. gansseri* Zone crossing the Campanian-Maastrichtian boundary (sensu Gradstein et al., 2012), suggesting a similar stratigraphic position for the studied material. We favor an early Maastrichtian age for the Dherani Limestone member based on a) the developmental stage of *Lepidorbitoides*; b) the occurrence of *Siderolites calcitrapoides*, a common Maastrichtian species in Tethys; and c) the absence of any typical Tethyan Campanian LBF, such as *Praesiderolites, Pseudosiderolites,* and *Arnaudiella*.

6. Discussion

The *Lepidorbitoides* species widely used in the Upper Cretaceous stratigraphy of the Cauvery Basin, i.e., *L. blanfordi* Rao, 1941 and *L. inornata* Rao, 1941, are not justified in this study. The description of these taxa is based on incomplete test features or test characters never illustrated (Rao, 1941). Later studies on the Cauvery Basin *Lepidorbitoides* also failed to provide a detailed description of the nepionic stage and other test features. In addition, we were unable to identify any form corresponding to *Orbitocyclina ariyalurensis* Rao, 1941. The equatorial section of this species illustrated by Rao (1941) shows that the embryon, with two auxiliary chambers, is followed by a long primary spire. It is interesting to note that Rao did not illustrate any equatorial section of *L. minor-socialis* (his *L. blanfordi*), the most common and possibly only *Lepidorbitoides* in the Ariyalur region, but instead illustrated a perfect equatorial section of *O. ariyaluensis*. Based on the nepionic acceleration, this form is either a primitive *Lepidorbitoides* from an older level in the Upper Cretaceous sequence, and thus has been mistakenly incorporated to the Ariyalur collection of the author, or a very rare Maastrichtian form of unknown affinity. The fact that most of the Ariyalur specimens are iron-stained such that the chamberlets are occupied by ferruginous material, and a perfect contrast is formed between the chamberlet walls and cavities may suggest that Rao's *O. ariyaluensis* is possibly from a different locality. We could not observe any specimen without pillars (piles) in the studied material. The absence of pillars in some specimens, supposedly a characteristics feature of *L. inornata*, is not confirmed here. The section illustrated by Rao does not clearly show the peri-embryonic part of the nepiont of this species. We think that *L. inornata* corresponds to *L.* ex. interc. *minor-socialis.* We show that the *Lepidorbitoides* in Cauvery basin have similar morphologic features, such as development of similar stolon system in the equatorial chamberlets and morphometric features as of Western Tethyan *Lepidorbitoides*. A Caribbean affinity for the Cauvery Basin *Lepidorbitoides*, as proposed by Rao (1941) is not supported. Our study supports the paleobiogeographic interpretation of van Gorsel (1978), who extended the boundaries of his ‘Eurasian assemblage’ to southern India and Madagascar and considered the Late Cretaceous LBF from the Indo-Malayan region to be of ‘unknown affinity’. According to Goldbeck and Langer (2009), India is a part of Asian faunal province, which includes *Lepidorbitoides*, *Orbitoide*s, *Omphalocyclus* and *Siderolites* in its western part (Indian subcontinent), whereas these genera are little known at species level. Our data indicate that at least the western part of this province is characterized by *Lepidorbitoides* of Western Tethyan affinity.

6. Concluding Remarks

The orbitoidal foraminifera in the Kallankuruchchi Formation in the Cauvery Basin are characterized by *Lepidorbitoides* Silvestri, occurring abundantly in the Dherani limestone member. The seven samples studied from this unit in Chokkanathapuram and Kallankuruchchi revealed that the *Lepidorbitoides* is characterized by the transitional development stages of *L. minor* and *L. socialis* relying on the evolutionary scheme of the genus, morphometry and species limits proposed by van Gorsel (1978) and Özcan and Özkan-Altıner (1999b). We propose that the age of the Dherani limestone member is early Maastrichtian based on the developmental state of *Lepidorbitoides*, occurrence of *Siderolites* and absence of typical Campanian LBF. The specimens without piles (*L. inornata*), never described in equatorial sections in the previous studies, have not been found in the Kallankuruchchi Formation. This species was used to demonstrate the Caribbean origin of some Cretaceous orbitoidal taxa in India. *Orbitocyclina ariyalurensis* Rao is a problematic species and previous records for its occurrence in

Kallankuruchchi Formation is challenged here. We failed to find this species in the studied material. *Orbitocyclina ariyalurensis* is either from an older stratigraphic unit and, thus, has been mistakenly interpreted to occur in the Maastrichtian deposits of the Cauvery Basin by Rao (1941) or it represents a separate rare lineage of unknown affinity.

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Figure Captions

Figure 1. Global distribution of *Lepidorbitoides* (synthesized from van Gorsel, 1978; Fleury et al., 1985; Goldbeck and Langer, 2009). Letters F, N, S and T (F: France, N: Netherlands, the Maastrichtian stratotype, S: Spain, and T: Turkey) refer to localities from Western Tethys for which the morphometric data are available, that were used for the morphometric comparison of the Indian specimens. The paleogeographic map is from Scotese (2014).

Figure 2. A- Location of the study area in SE India. B- Geological map of Ariyalur area and location of the studied outcrops (sample abbreviations: CHO and KAL). C- Lithostratigraphy of the Campanian-Maastrichtian deposits in the Cauvery Basin. Map and lithostratigraphy are simplified after Tewari et al. (1996). The ‘Dherani sandstone’ in Tewari et al. (1996) is here replaced by the ‘Dherani Limestone’ after Hart et al. (2000). The stratigraphic level with *Lepidorbitoides* probably corresponds to the ‘Gryphean fragmental shell limestone’ unit of Ramkumar (1999).

Figure 3. Field aspects of the Kallankuruchchi Formation and common fossils in Chokkanathapuram (A-D, K-L) and Kallankuruchchi localities (E-J). Sample localities are shown in A and E. Close-up view of Dalmia biostrome (B-C, F-I) and bed with *Lepidorbitoides* in the Dherani Limestone member (G-H) and their fossil associations (D, J-L). py: *Pycnodonte*, ino: inoceramids, amm: ammonoids, te: *Teichichnus* isp. (identified by Dr. Huriye Demircan, MTA, Ankara), go: *Gongrochanus herschelianus* (identified by Dr. Nils Schlüter, Berlin), br: bryozoans, le: *Lepidorbitoides*.

Figure 4. Stratigraphically significant fossils recorded in previous woks from the Kallankuruchchi Formation and assigned biostratigraphic zones and ages. White lines refer to the works on the planktonic foraminifera and bold lines either to studies on LBF, other fossil groups or the stratigraphy of the unit.

Figure 5. Axial (A) and equatorial sections of *Lepidorbitoides* test (B-C) from Chokkanathapuram and Kallankuruchchi localities showing the equatorial and lateral layers, piles, disposition of the equatorial chamberlets and terminology. A: KAL.5D-18, B: CHO.2-1, C: CHO.5-19. P: protoconch, D: deuteroconch, pr: protoconchal stolon, ds: deuteroconchal stolon, rs: radial stolon, bs: basal stolon, as: annular stolon, os: oblique stolon, ac: auxiliary chamberlets, adc: adauxiliary chamberlets, ech: equatorial chambers and chamberlets.

Figure 6. External views (1-2) and axial sections (3-5) of *Lepidorbitoides* ex. interc. *minor-socialis* from the Kallankuruchchi Formation. 1: KAL.5A-16, 2: KAL.5B-6, 3: KAL.5A-28, 4:

CHO.2-3, 5: KAL.5C-27. e: embryon, el: equatorial layer, lc: lateral chamberlets, pi: piles (granules).

Figure 7. The embryon, shape of equatorial chambers/chamberlets and stolons in *Lepidorbitoides* ex. interc. *minor-socialis* in samples CHO.2 and CHO.5. 1: CHO.5-19, 2: CHO.2-1, 3: CHO.2-5, 4: CHO.5-17, 5: CHO.5-12, 6: CHO.5-6, 7-9: CHO.5-1. Note early arcuate chamberlets followed by pointed arcuate to ogival chamberlets of the same specimen in 7-9 and spatulate chamberlets in 6. See Figure 7 for the abbreviations. Thick arrow shows the position of embryon.

Figure 8. Equatorial sections of *Lepidorbitoides* ex. interc. *minor-socialis* from the Kallankuruchchi Formation in Chokkanathapuram locality. 1: CHO.2-1 (see Fig. 5A for the same specimen), 2: CHO.2-4, 3: CHO.2-5, 4: CHO.2-13, 5: CHO.4-12, 6: CHO.5-22, 7: CHO.4-20, 8: CHO.4-7, 9: CHO.5-19 (see Fig. 5B for the same specimen), 10: CHO.5-15, 11: CHO.5-12.

Figure 9. The embryon and adauxiliary chamberlets in *Lepidorbitoides* ex. interc. *minor-socialis* in Chokkanathapuram and Kallankuruchchi localities.

Figure 10. Equatorial sections of *Lepidorbitoides* ex. interc. *minor-socialis* in Kallankuruchchi locality. 1: KAL.5A-11, 2: KAL.5A-3, 3: KAL.5A-25, 4: KAL.5A-15, 5: KAL.5B-3, 6: KAL.5D-17, 7: KAL.5D-10, 8: KAL.5D-15.

Figure 11. A- Nepionic arrangement and nepionic acceleration recorded in the *Helicorbitoides-Lepidorbitoides* lineage, and morphometric species concept in Western Tethys (modified after van Gorsel, 1975, 1978). The chambers with single stolon (Y) after the formation of embryon (protoconch and deuteroconch) are shown by green color. Arrows denote the spirals. The nepionic arrangement after the introduction of second auxiliary chamberlet (ac) in *L. bisambergensis* and onwards is called 'quadriserial'. The subspecies *L. bisambergensis asymmetrica* has conspicuously asymmetrical auxiliary chamberlets (Özcan and Özkan-Altıner, 2001). B- Relationship of *Lepidorbitoides* species (zones) to the planktonic foraminiferal zones according to van Gorsel (1978). C-Shape of the equatorial chamberlets and stolons as observed in equatorial sections: a and b- arcuate, c-pointed arcuate, d-ogival, e-spatulate chamberlets (from van Gorsel, 1975).

Figure 12. Relation between the number of adauxiliary chamberlets (adc) and protoconch diameter (P) in the studied samples and their comparison with *Lepidorbitoides* populations from Europe and Turkey. The numbers along the empty circles refer to the code numbers of the samples from Europe (Netherlands, France, and Spain) studied by van Gorsel (1975). The black circles refer to samples from Turkey (Özcan and Özkan-Altıner, 1999a, b): Samples in *L. bisambergensis* field; 19: sample CIDE.K-84, in *L. socialis* field: 24: CIDE.G-56, 25: CIDE.G-38, 26: CIDE.G-26, 27: CIDE.G-5, 28: CIDE.K-88. Locations of the samples from Europe are tabulated in van Gorsel (1975).

Figure 13. Relation between the number of adauxiliary chamberlets (adc) and deuteroconch diameter (D) in the studied samples and their comparison with *Lepidorbitoides* populations from

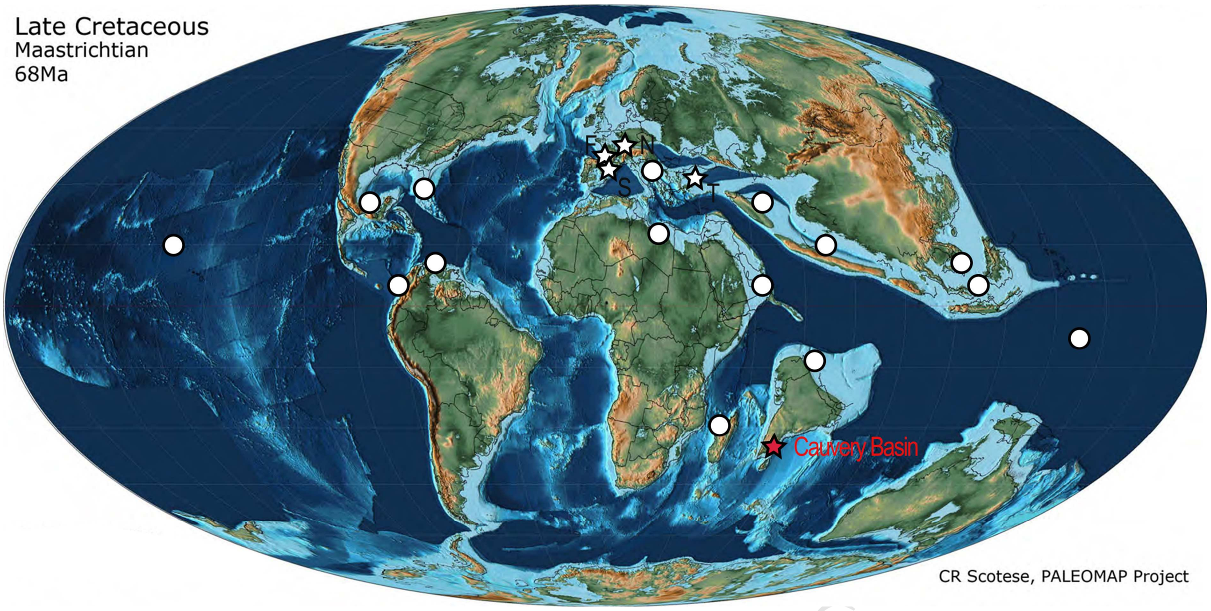
Europe and Turkey. The numbers along the empty circles refer to the code numbers of the samples from Europe (Netherlands, France, and Spain) studied by van Gorsel (1975). See Figure 12 for explanation.

Figure 14. Relation between the number of adauxiliary chamberlets (adc) and ratio of deuteroconch-protoconch (D/P) in the studied samples and their comparison with *Lepidorbitoides* populations from Europe. The numbers along the empty circles refer to the code numbers of the samples from Europe (Netherlands, France, and Spain) studied by van Gorsel (1975). See Figure 12 for explanation.

Figure 15. Stratigraphic relationships between the *Lepidorbitoides* species in Turkey, their correlation to planktonic foraminiferal zones and tentative position of Cauvery Basin *Lepidorbitoides*. Arrows indicate the continuation of species (in typological sense; e.g., specimens having *L. campaniensis*-type nepiont may co-occur with specimens having *L. bisambergensis*- type nepionts). Question marks show either the stratigraphic intervals without data or uncertainties in the delineation of the species boundaries (slightly modified from Özcan and Özkan-Altıner (1999b).

Table 1. Morphometric data of *Lepidorbitoides* from Kallankuruchchi Formation (see text for the nomenclature). N denotes the number of measured specimens in each sample.

SAMPLE	N	P		D		D/P	adc	
		range	mean±s.e	range	mean±s.e		range	mean
CHO.2	19	70-120	99.21±2.96	130-275	181.58±7.53	1.83	3-5	3.80
CHO.4	25	80-125	105.63±2.62	125-250	189.20±5.07	1.79	1-6	3.79
CHO.5	13	75-125	103.75±4.61	145-255	193.46±10.01	1.86	3-6	4.27
KAL.5A	20	80-140	107.50±3.61	140-250	188.50±6.19	1.75	3-7	4.67
KAL.5B	18	90-140	113.89±3.41	160-245	195.83±5.27	1.72	3-6	4.45
KAL.5C	20	80-130	100.00±2.37	125-210	171.75±5.51	1.72	3-4	4.21
KAL.5D	24	85-140	107.92±2.78	160-250	191.46±4.37	1.77	3-7	4.40


Late Cretaceous
Maastrichtian
68Ma
F
N
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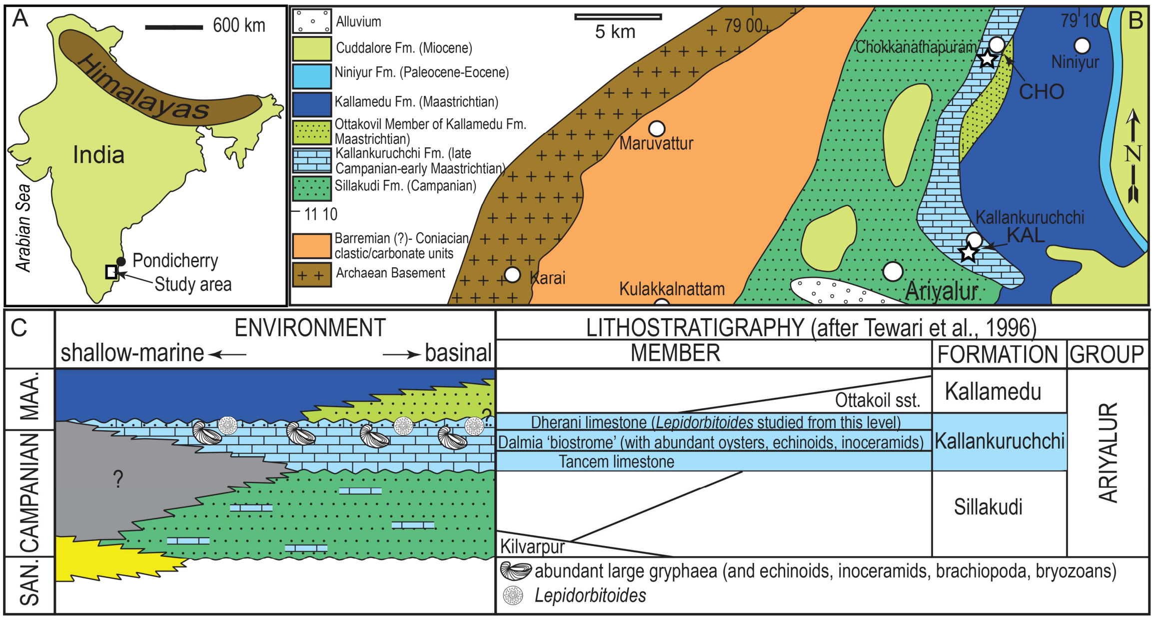
T
Cauvery Basin
CR Scotese, PALEOMAP Project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Himalayas
India
Arabian Sea
Pondicherry
Study area
Alluvium
Cuddalore Fm. (Miocene)
Niniyur Fm. (Paleocene-Eocene)
Kallamedu Fm. (Maastrichtian)
Ottakovil Member of Kallamedu Fm. Maastrichtian)
Kallankuruchchi Fm. (late Campanian-early Maastrichtian)
Sillakudi Fm. (Campanian)
11 10
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Archaean Basement
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B
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ENVIRONMENT
shallow-marine
basinal
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CAMPANIAN
SAN.
?
LITHOSTRATIGRAPHY (after Tewari et al., 1996)
MEMBER
FORMATION
GROUP
Ottakoil sst.
Kallamedu
Dherani limestone (*Lepidorbitoides* studied from this level)
Dalmia 'biostrome' (with abundant oysters, echinoids, inoceramids)
Kallankuruchchi
Tancem limestone
Sillakudi
ARIYALUR
Kilvarpur
abundant large gryphaea (and echinoids, inoceramids, brachiopoda, bryozoans)
Lepidorbitoides


CHO.5
CHO.4
CHO.2
Kallankuruchchi Fm.
A
Dalmia 'biostrome'
py
B
5 cm
C
py
7.5 cm
D
bed with *Lepidorbitoides*
KAL.5A-5D
Dherani sandstone
Dalmia 'biostrome'
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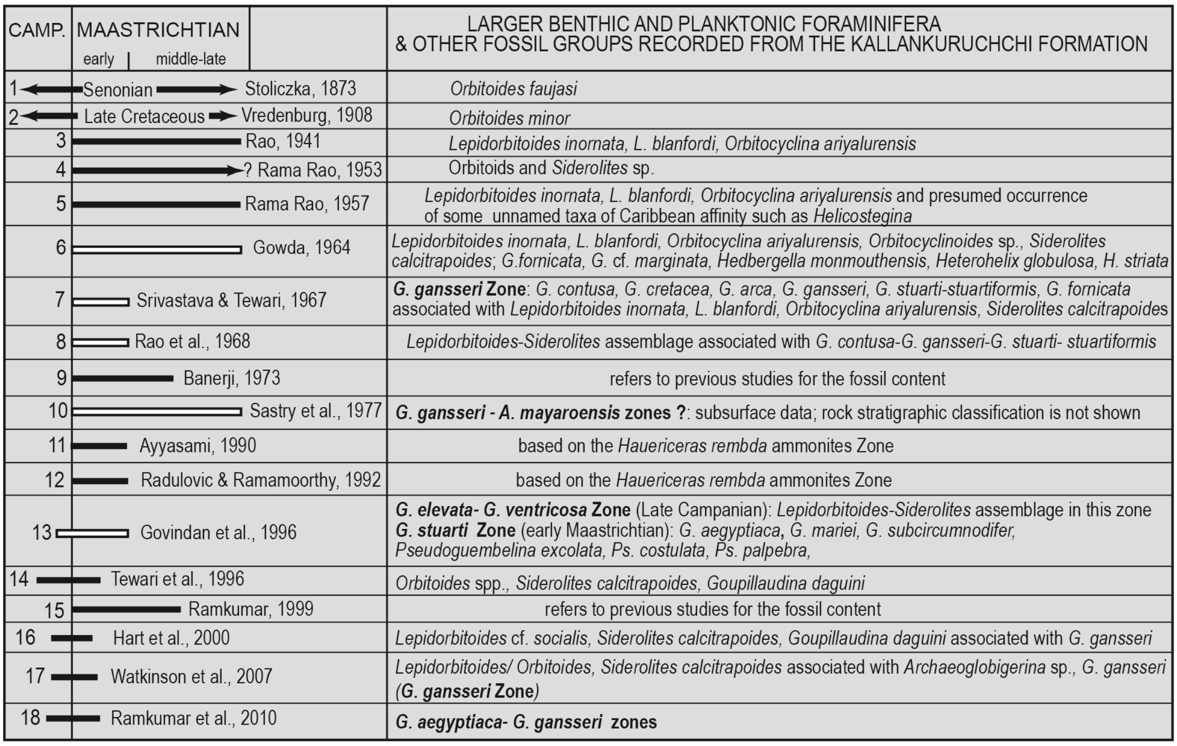
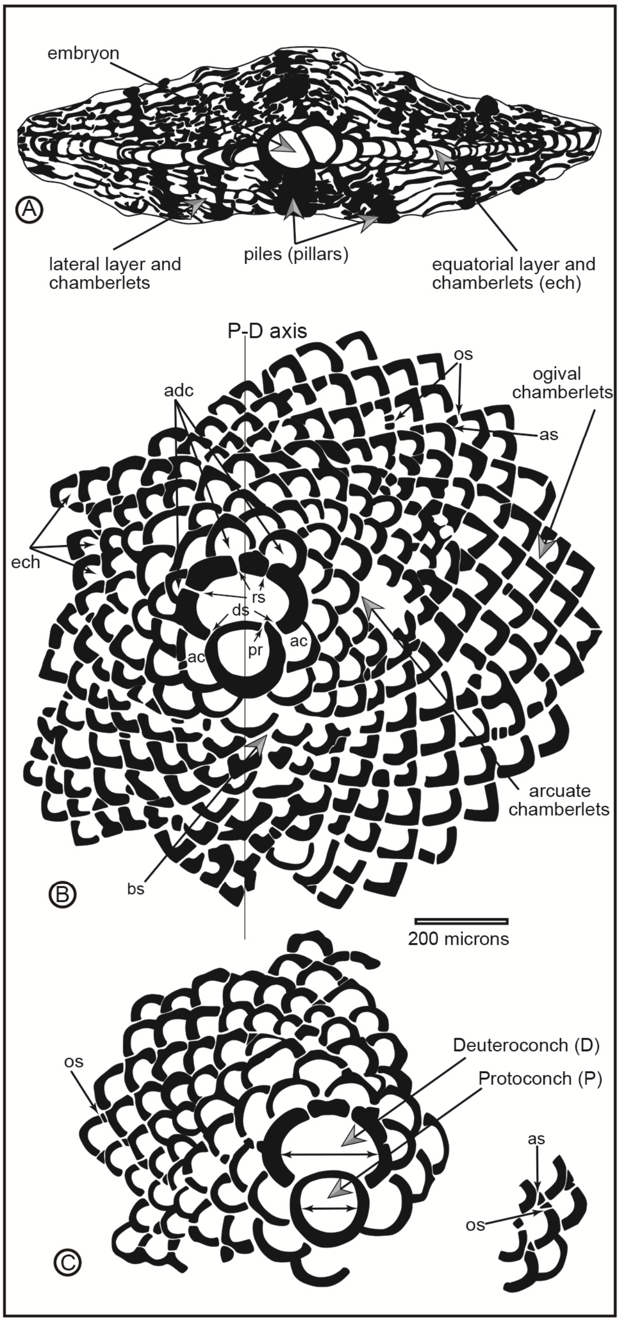


CAMP.	MAASTRICHTIAN early | middle-late	LARGER BENTHIC AND PLANKTONIC FORAMINIFERA & OTHER FOSSIL GROUPS RECORDED FROM THE KALLANKURUCHCHI FORMATION
1	Senonian Stoliczka, 1873	*Orbitoides faujasi*
2	Late Cretaceous Vredenburg, 1908	*Orbitoides minor*
3	Rao, 1941	*Lepidorbitoides inornata, L. blanfordi, Orbitocyclina ariyalurensis*
4	? Rama Rao, 1953	Orbitoids and *Siderolites* sp.
5	Rama Rao, 1957	*Lepidorbitoides inornata, L. blanfordi, Orbitocyclina ariyalurensis* and presumed occurrence of some unnamed taxa of Caribbean affinity such as *Helicostegina*
6	Gowda, 1964	*Lepidorbitoides inornata, L. blanfordi, Orbitocyclina ariyalurensis, Orbitocyclinoides* sp., *Siderolites calcitrapoides*; *G.fornicata, G.* cf. *marginata, Hedbergella monmouthensis, Heterohelix globulosa, H. striata*
7	Srivastava & Tewari, 1967	***G. gansseri* Zone**: *G. contusa, G. cretacea, G. arca, G. gansseri, G. stuarti-stuartiformis, G. fornicata* associated with *Lepidorbitoides inornata, L. blanfordi, Orbitocyclina ariyalurensis, Siderolites calcitrapoides*
8	Rao et al., 1968	*Lepidorbitoides-Siderolites* assemblage associated with *G. contusa-G. gansseri-G. stuarti- stuartiformis*
9	Banerji, 1973	refers to previous studies for the fossil content
10	Sastry et al., 1977	***G. gansseri - A. mayaroensis* zones ?**: subsurface data; rock stratigraphic classification is not shown
11	Ayyasami, 1990	based on the *Hauericeras rembda* ammonites Zone
12	Radulovic & Ramamoorthy, 1992	based on the *Hauericeras rembda* ammonites Zone
13	Govindan et al., 1996	***G. elevata- G. ventricosa* Zone** (Late Campanian): *Lepidorbitoides-Siderolites* assemblage in this zone ***G. stuarti* Zone** (early Maastrichtian): *G. aegyptiaca*, *G. mariei, G. subcircumnodifer, Pseudoguembelina excolata, Ps. costulata, Ps. palpebra,*
14	Tewari et al., 1996	*Orbitoides* spp., *Siderolites calcitrapoides, Goupillaudina daguini*
15	Ramkumar, 1999	refers to previous studies for the fossil content
16	Hart et al., 2000	*Lepidorbitoides* cf. *socialis, Siderolites calcitrapoides, Goupillaudina daguini* associated with *G. gansseri*
17	Watkinson et al., 2007	*Lepidorbitoides/ Orbitoides, Siderolites calcitrapoides* associated with *Archaeoglobigerina* sp., *G. gansseri* (***G. gansseri* Zone**)
18	Ramkumar et al., 2010	***G. aegyptiaca- G. gansseri* zones**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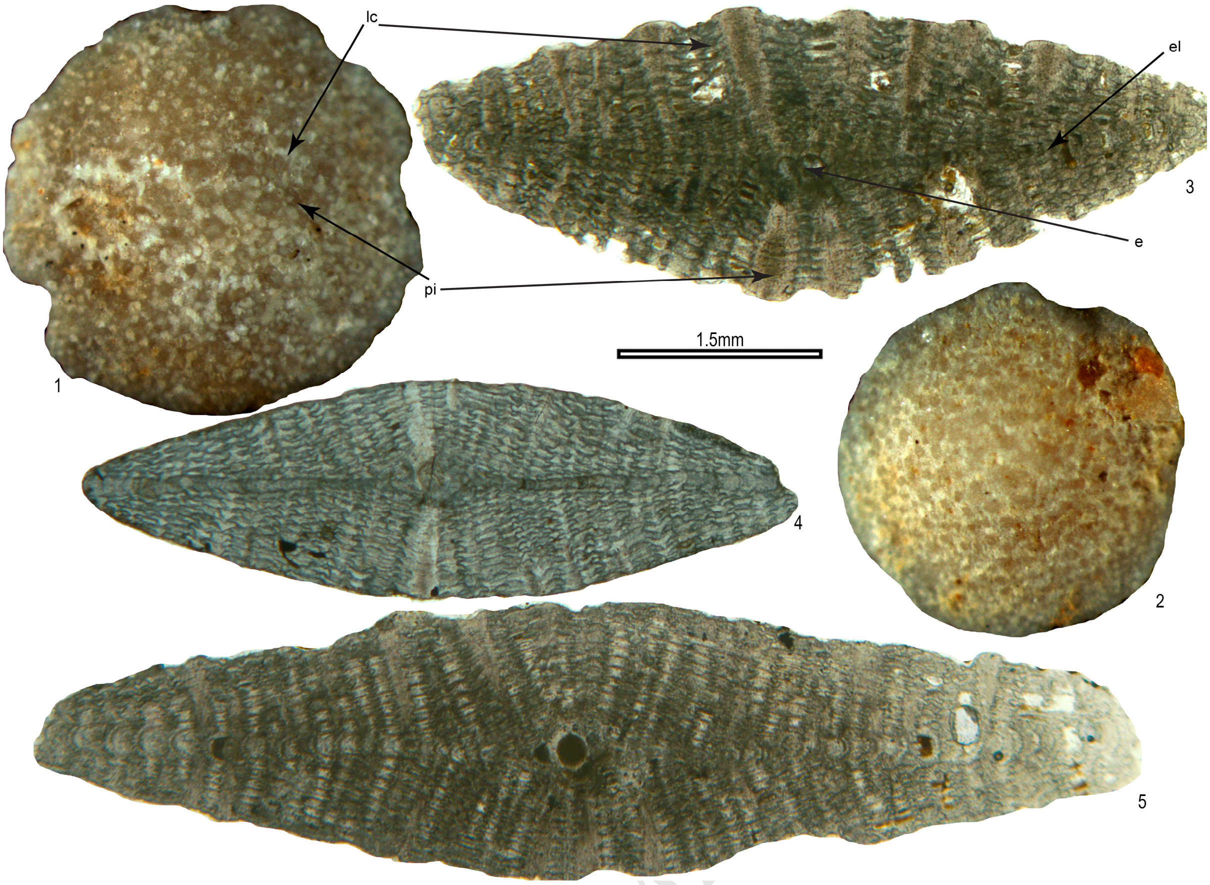
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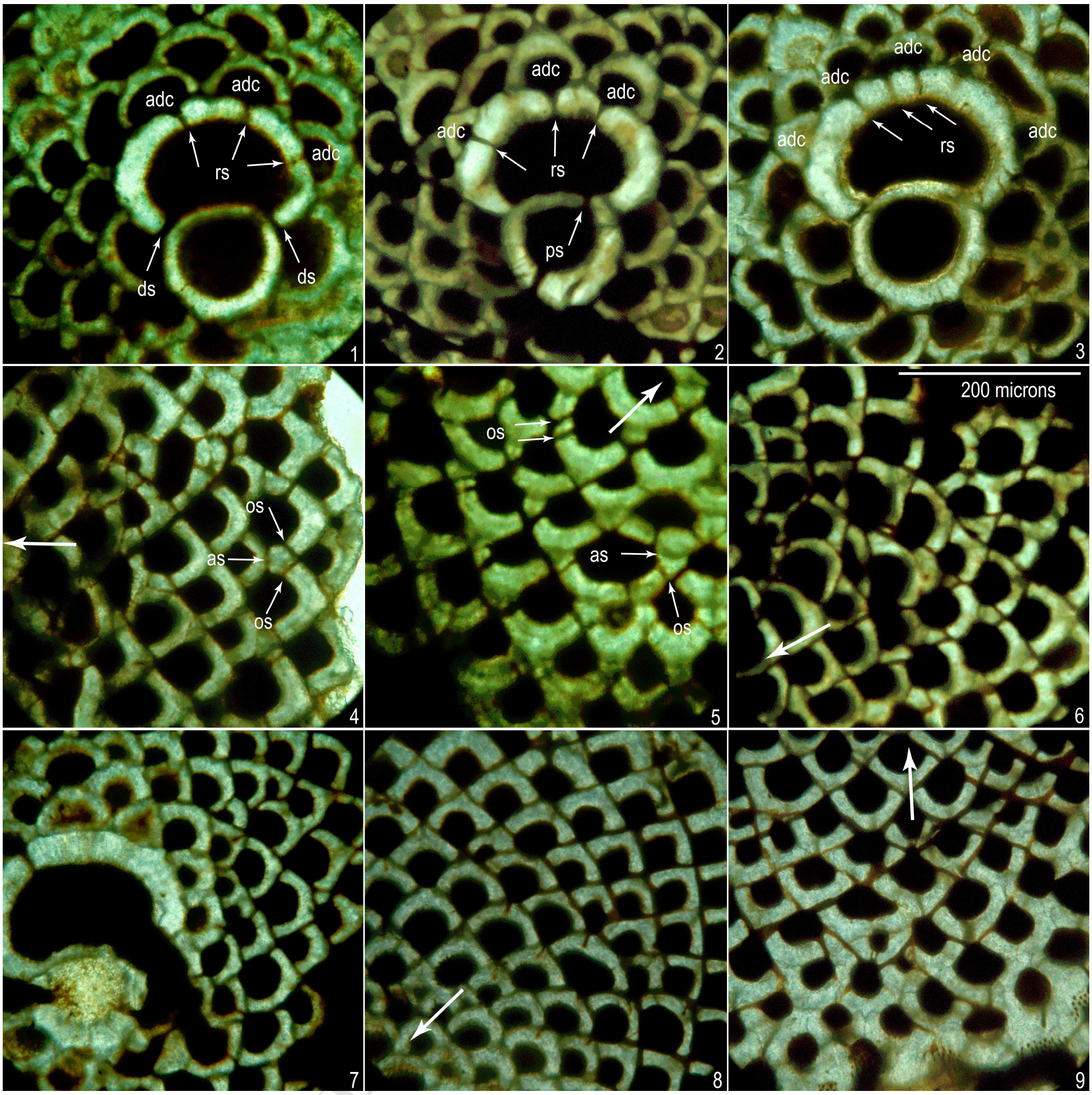
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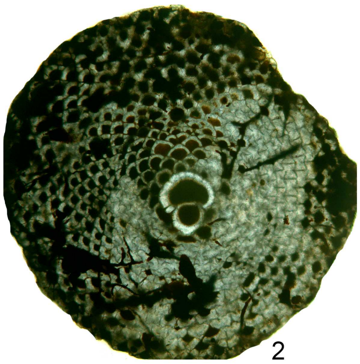
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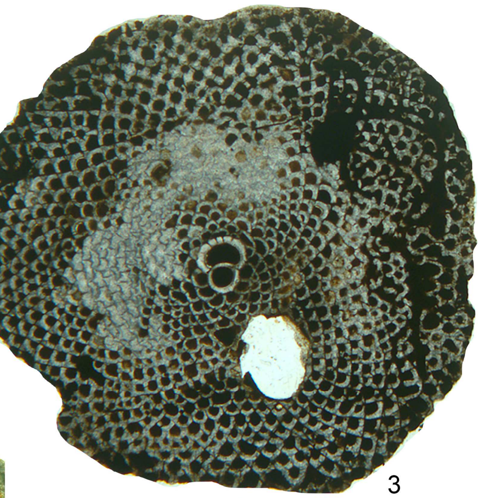
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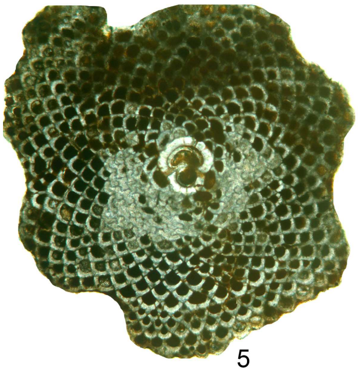
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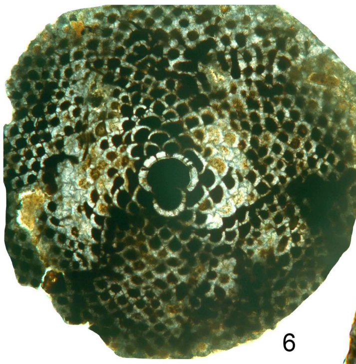
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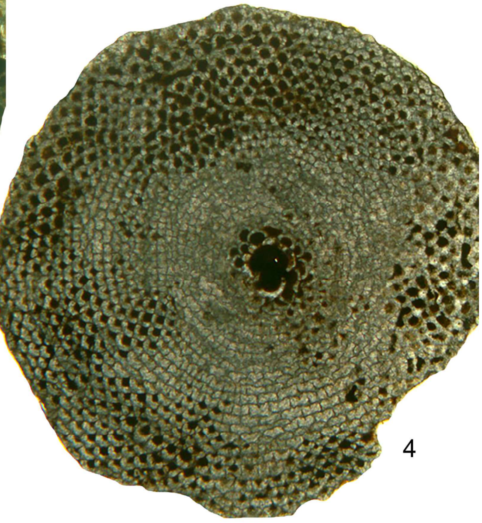
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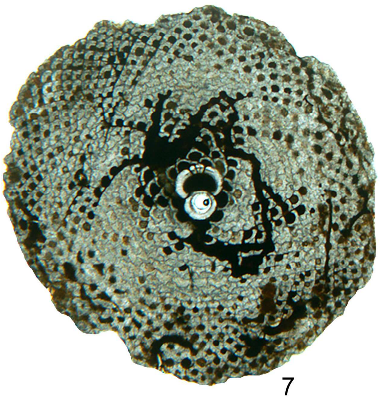
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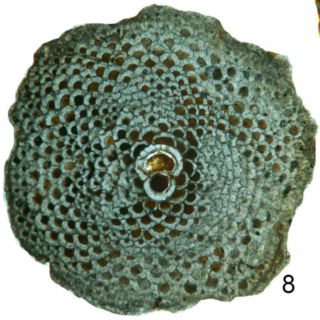
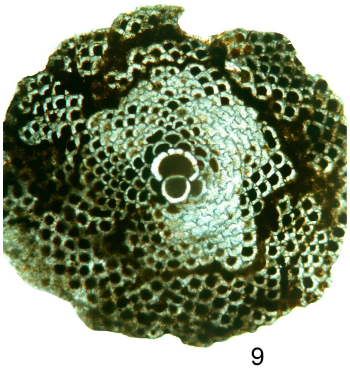

8

200 microns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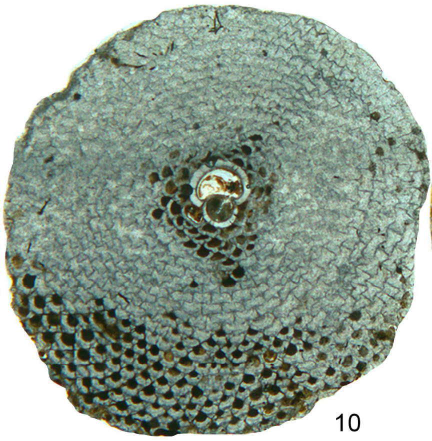
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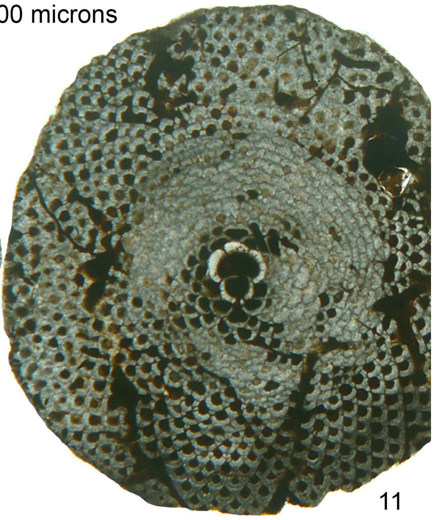
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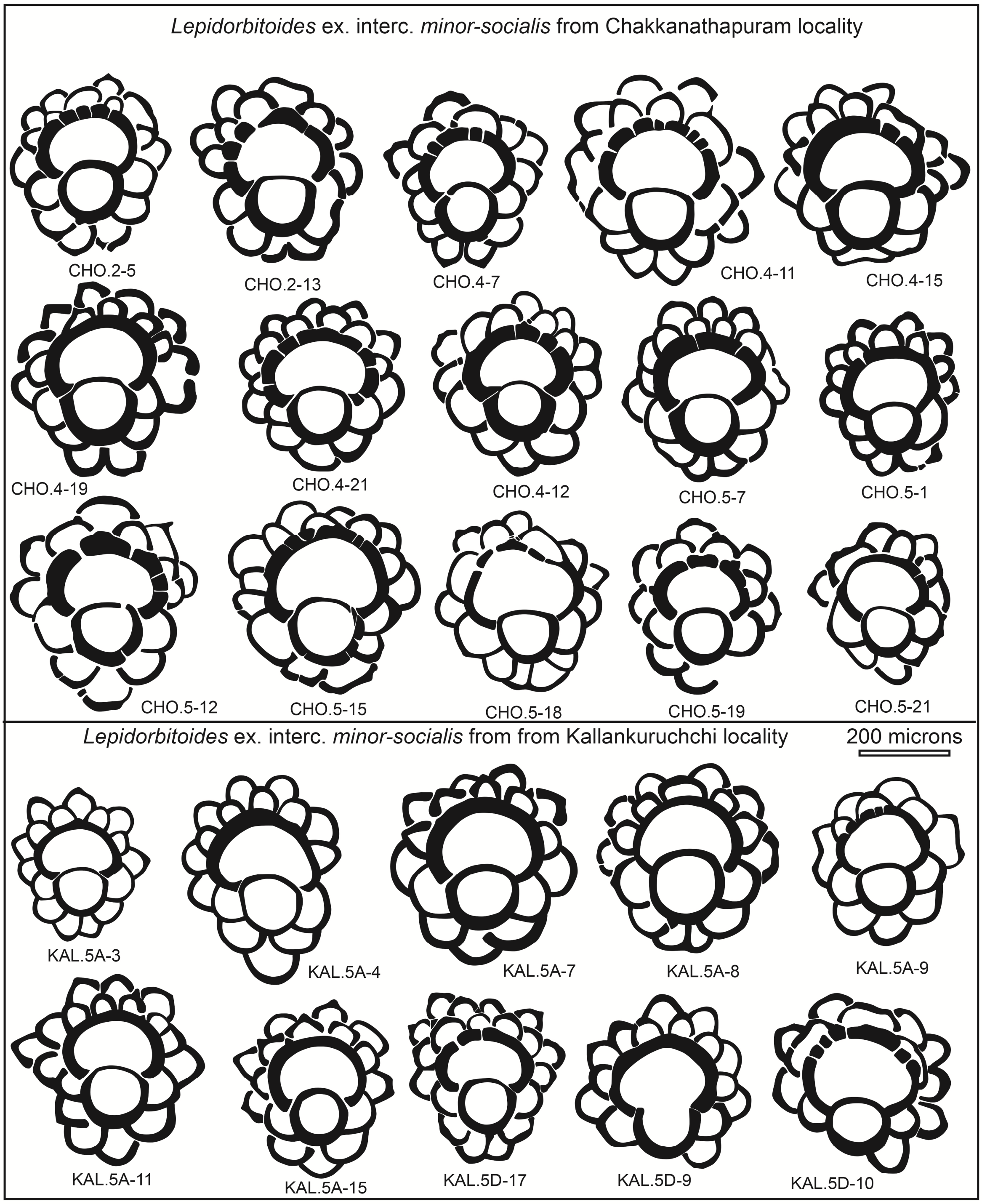
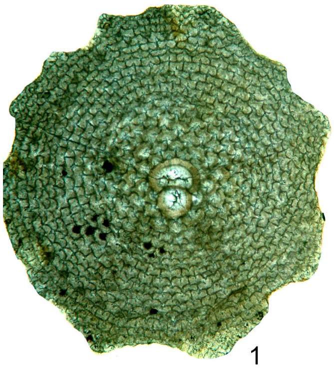
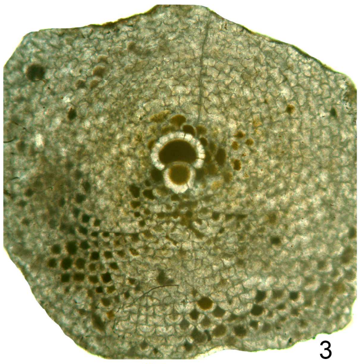

Lepidorbitoides ex. interc. *minor-socialis* from Chakkanathapuram locality
CHO.2-5
CHO.2-13
CHO.4-7
CHO.4-11
CHO.4-15
CHO.4-19
CHO.4-21
CHO.4-12
CHO.5-7
CHO.5-1
CHO.5-12
CHO.5-15
CHO.5-18
CHO.5-19
CHO.5-21
Lepidorbitoides ex. interc. *minor-socialis* from from Kallankuruchchi locality
200 microns
KAL.5A-3
KAL.5A-4
KAL.5A-7
KAL.5A-8
KAL.5A-9
KAL.5A-11
KAL.5A-15
KAL.5D-17
KAL.5D-9
KAL.5D-10


1


2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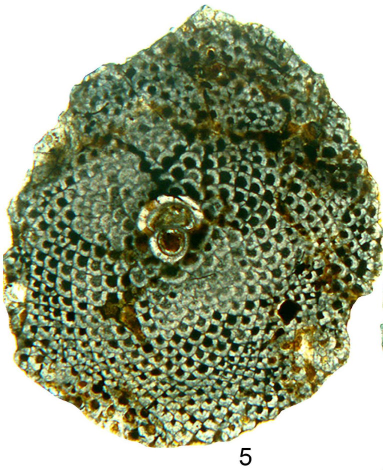
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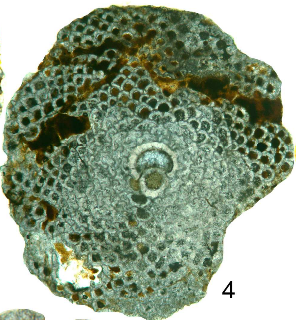
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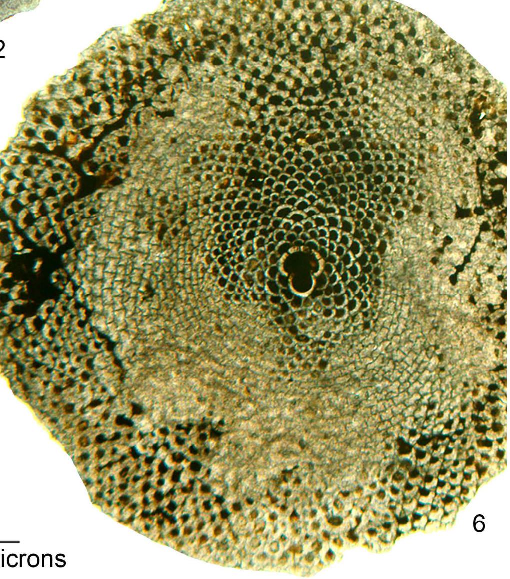
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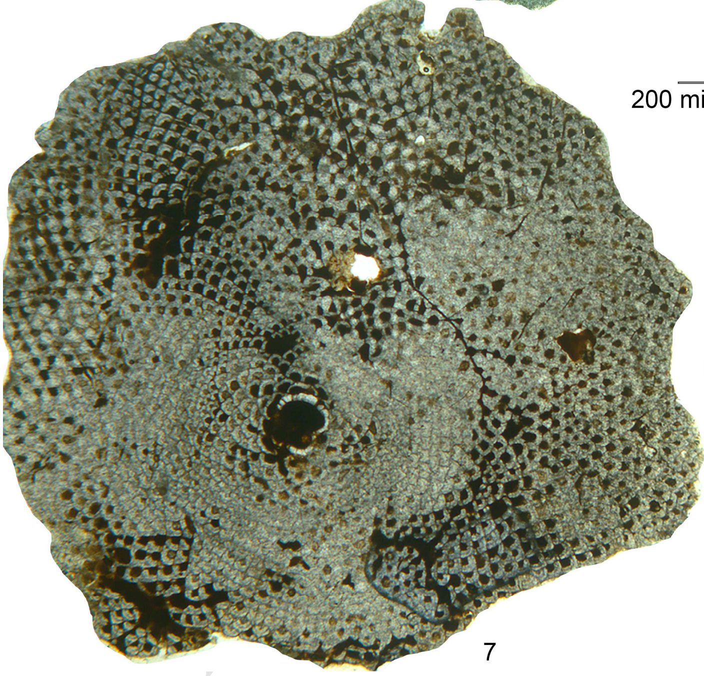
200 microns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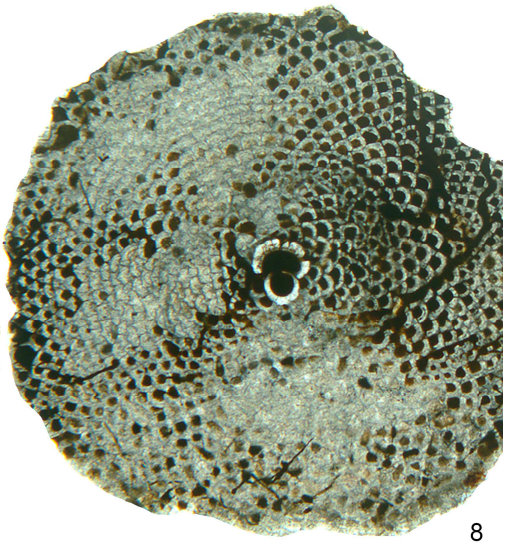
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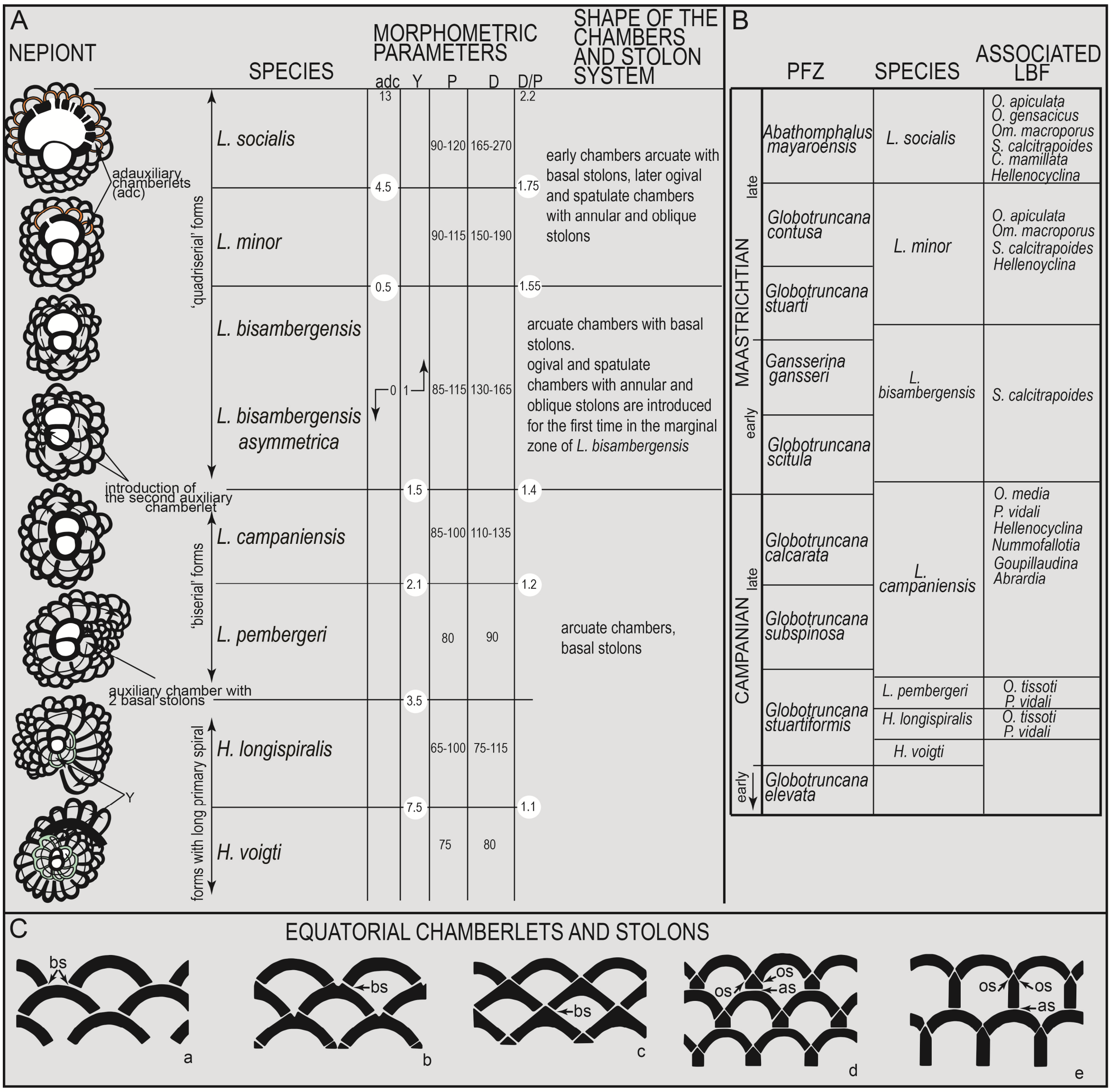
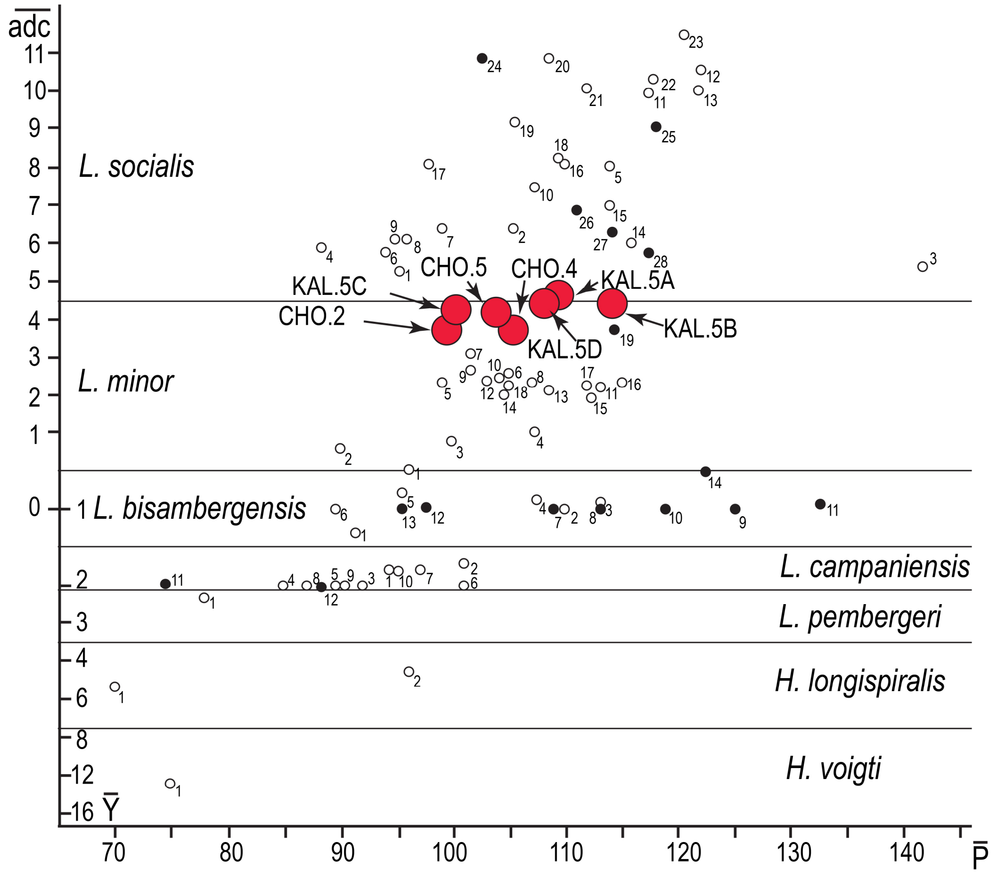
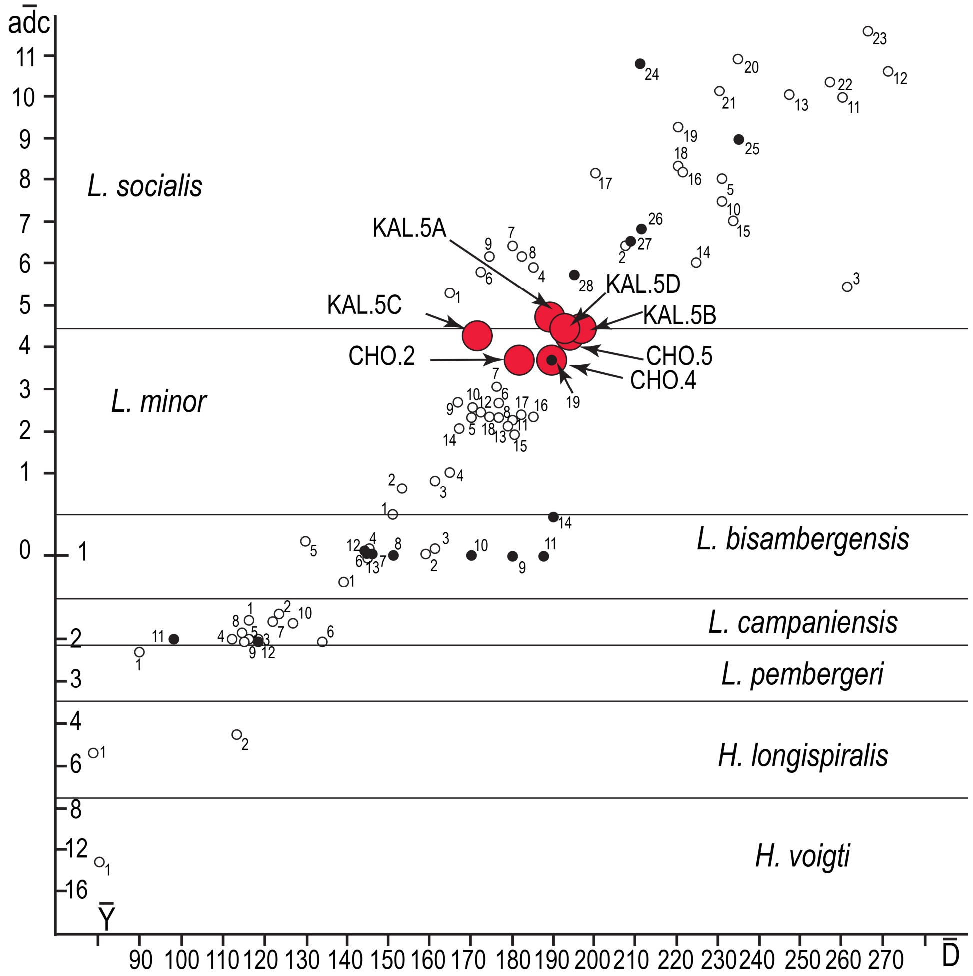
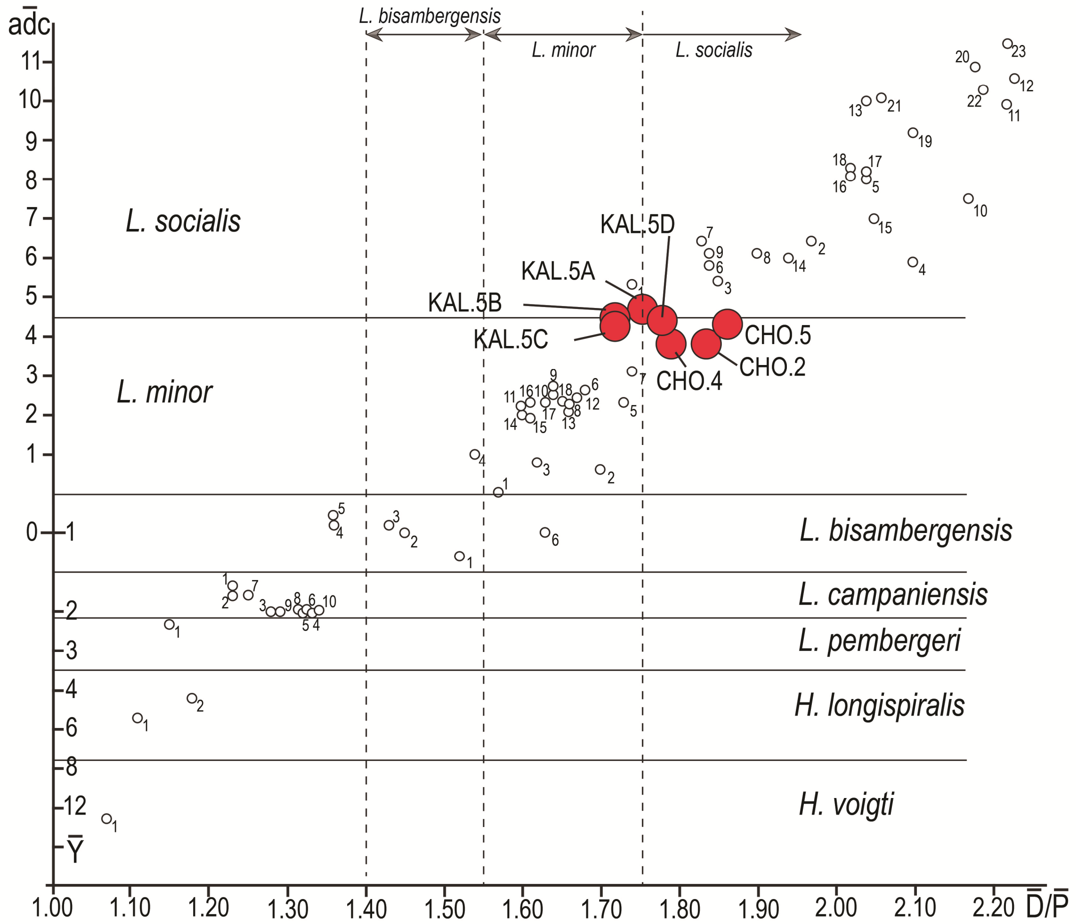
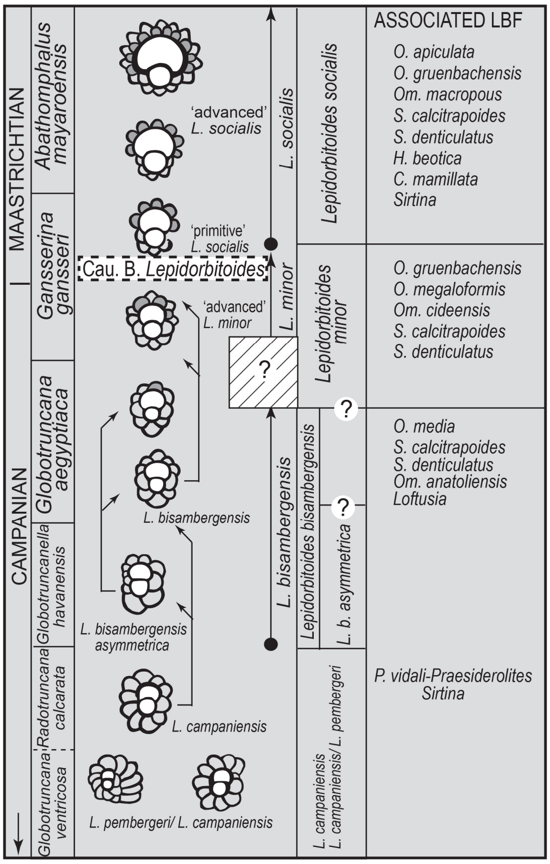

A
NEPIONT
SPECIES
MORPHOMETRIC PARAMETERS
adc
Y
P
D
D/P
SHAPE OF THE CHAMBERS AND STOLON SYSTEM
L. socialis
13
2.2
90-120
165-270
adauxiliary chamberlets (adc)
early chambers arcuate with basal stolons, later ogival and spatulate chambers with annular and oblique stolons
4.5
1.75
L. minor
90-115
150-190
'quadriserial' forms
0.5
1.55
L. bisambergensis
arcuate chambers with basal stolons.
ogival and spatulate chambers with annular and oblique stolons are introduced for the first time in the marginal zone of L. bisambergensis
0
1
85-115
130-165
L. bisambergensis asymmetrica
introduction of the second auxiliary chamberlet
1.5
1.4
L. campaniensis
85-100
110-135
'biserial' forms
2.1
1.2
L. pembergeri
80
90
arcuate chambers, basal stolons
auxiliary chamber with 2 basal stolons
3.5
H. longispiralis
65-100
75-115
Y
forms with long primary spiral
7.5
1.1
H. voigti
75
80
B
PFZ
SPECIES
ASSOCIATED LBF
MAASTRICHTIAN
late
early
CAMPANIAN
late
early
Abathomphalus mayaroensis
L. socialis
O. apiculata
O. gensacicus
Om. macroporus
S. calcitrapoides
C. mamillata
Hellenocyclina
Globotruncana contusa
L. minor
O. apiculata
Om. macroporus
S. calcitrapoides
Hellenocyclina
Globotruncana stuarti
Gansserina gansseri
L. bisambergensis
S. calcitrapoides
Globotruncana scitula
Globotruncana calcarata
L. campaniensis
O. media
P. vidali
Hellenocyclina
Nummofallotia
Goupillaudina
Abrardia
Globotruncana subspinosa
Globotruncana stuartiformis
L. pembergeri
O. tissoti
P. vidali
H. longispiralis
O. tissoti
P. vidali
H. voigti
Globotruncana elevata
C
EQUATORIAL CHAMBERLETS AND STOLONS
bs
a
bs
b
bs
c
os
os
as
d
os
os
as
e


adc
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
6
8
12
16
Ȳ
70
80
90
100
110
120
130
140
P̄
L. socialis
L. minor
L. bisambergensis
L. campaniensis
L. pembergeri
H. longispiralis
H. voigti
KAL.5C
CHO.2
CHO.5
CHO.4
KAL.5A
KAL.5B
KAL.5D



adc
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
6
8
12
16
Y
90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270
D
L. socialis
L. minor
L. bisambergensis
L. campaniensis
L. pembergeri
H. longispiralis
H. voigti
KAL.5A
KAL.5C
KAL.5D
KAL.5B
CHO.2
CHO.5
CHO.4


adc
D/P
L. bisambergensis
L. minor
L. socialis
L. socialis
L. minor
L. bisambergensis
L. campaniensis
L. pembergeri
H. longispiralis
H. voigti
KAL.5D
KAL.5A
KAL.5B
KAL.5C
CHO.5
CHO.2
CHO.4
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-6
-8
-12
Y
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20


MAASTRICHTIAN
CAMPANIAN
Abathomphalus mayaroensis
Gansserina gansseri
Globotruncana aegyptiaca
Globotruncanella havanensis
Radotruncana calcarata
Globotruncana ventricosa
'advanced' L. socialis
'primitive' L. socialis
Cau. B. Lepidorbitoides
'advanced' L. minor
L. bisambergensis
L. bisambergensis asymmetrica
L. campaniensis
L. pembergeri/ L. campaniensis
L. socialis
L. minor
?
L. bisambergensis
Lepidorbitoides socialis
Lepidorbitoides minor
Lepidorbitoides bisambergensis
L. b. asymmetrica
L. campaniensis
L. campaniensis/L. pembergeri
ASSOCIATED LBF
O. apiculata
O. gruenbachensis
Om. macropous
S. calcitrapoides
S. denticulatus
H. beotica
C. mamillata
Sirtina
O. gruenbachensis
O. megaloformis
Om. cideensis
S. calcitrapoides
S. denticulatus
O. media
S. calcitrapoides
S. denticulatus
Om. anatoliensis
Loftusia
P. vidali-Praesiderolites
Sirtina