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A new record of larger benthic foraminifera from Jeju Island (South Korea)

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Larger benthic foraminifera (LBF) are a group of marine organisms that inhabit oligotrophic subtropical-tropical photic zones, commonly possess relatively large shells (i.e., tests) with a complex internal structure and host photosynthetic endosymbionts. In this study, we provide a new report of a LBF species belonging to the genus *Sorites* Ehrenberg, 1839, with a brief description and images of the test. The sediment samples were collected by SCUBA diving from the east coast of Jeju Island (South Korea). The discoidal test shape and annular series of chamberlets with a single row of apertures surrounded by rim indicate that these specimens belong to the genus *Sorites*, and this is the first record of the genus in Korea. The arrangement of early chamberlets, septular disposition, and the aperture details suggest that the specimens can be assigned to *Sorites orbiculus* (Forsskål in Niebuhr, 1775). Only three LBF species, including the present species, have been reported from Korean waters. The present study provides additional information for the evaluation of foraminiferal diversity including LBF in Korea and suggests the necessity of continuous investigations to understand the diversity of *Sorites* species in Korea.

Keywords: biogeography, diversity, protist, *Sorites*, Soritidae, taxonomy

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Introduction

Modern benthic foraminifera are one of the most dominant meiobenthic unicellular eukaryotes and occupy an important position in the marine food web because of their wide range of feeding strategies such as grazing, suspension feeding, deposit feeding, carnivory, parasitism and symbiosis (Boltovskoy and Wright, 1976). The symbiont bearing taxa are commonly referred to as larger benthic foraminifera (LBF), a polyphyletic functional group that is highly adapted to oligotrophic conditions and mostly distributed in subtropical-tropical photic zone between latitudes 40°N and 31°S (Langer and Hottinger, 2000; Langer, 2008). Overall, 68 valid LBF species belonging to 26 genera and six families (Alveolinidae, Amphistigenidae, Calcarinidae, Nummulitidae, Peneroplidae, Soritidae) have been recorded from the Indo-Pacific Ocean (Förderer *et al*., 2018). One of the LBF families, Soritidae Ehrenberg, 1839, is characterized by: i) planispiral test at least in the early stage and a tendency to uncoiled, flaring, fusiform, or cylindrical at later stage; ii) numerous chambers subdivided by interseptal pillars or septula; and iii) multiple apertural row, of circular, elongate or crescentic form (Loeblich and Tappan, 1987; Gudmundsson, 1994). Within the family Soritidae, a total of nine species and five genera (i.e., *Amphisorus hemprichii*, *A. kudakajimaensis*, *A. sauronensis*, *Cyclorbiculina compressa*, *Marginopora vertebralis*, *Parasorites orbitolitoides*, *Sorites marginalis*, *S. orbiculus*, and *S. variabilis*) are recorded in the Indo-Pacific, and five of them (i.e., *A. hemprichii*, *A. kudakajimaensis*, *M. vertebralis*, *P. orbitolitoides*, and *S. orbiculus*) have been reported in the Northwest Pacific waters close to the Korean Peninsula, such as East China Sea (Table 1 and Fig. 1). In the case of Korea, a total of five LBF species are reported in the national list of species of Korea (NIBR, 2022). Among them, only two species (*A. radiata* and *M. vertebralis*) from Jeju Island are valid extant species based on the scientific literature (Kim *et al*., 2016; Lee *et al*., 2021). In this study, we have a new report of a LBF species, *Sorites orbiculus* from Jeju Island (South Korea), with description, scanning electron microscopy (SEM) and photomicrographs.

Materials and Methods

Sediments were sampled from Seongsan-eup, Seogwipo-si, Jeju Island (South Korea) in August 2020 by SCUBA divers (Fig. 1 and Table 2). Bottom sediments at the Seomyeo diving site were collected by using acrylic corers and plastic bottles. Immediately after collection, samples were sieved through 63 μm mesh, fixed with 99% ethanol, and transported to the Biodiversity Laboratory in Hanyang University, Seoul. In the laboratory, foraminiferal individuals were isolated under a stereomicroscope (Olympus SZX12, Tokyo, Japan) using a fine brush. Photomicrographs were taken at multiple focal points using digital cameras (Olympus PEN Lite E-PL3, Canon EOS 90D, Tokyo, Japan) attached to a stereomicroscope (Olympus SZX12, Tokyo, Japan), and the images were stacked using Helicon Focus 7.6.4 software (Helicon Soft). Detailed morphological characters were examined using SEM. The specimens were mounted on a SEM stub with carbon tape attached, and coated with Au ion under 4 mA, for 240 s, in a vacuum ion coater (COXEM SPT-20, Daejeon, Korea). The coated sample was examined using a tabletop SEM (COXEM EM-30, Daejeon, Korea). Species identification was conducted based on the morphological characteristics of the specimens observed and the following relevant literatures such as: Lehmann (1961), Cheng and Zheng (1978), Hatta and Ujiié (1992), Hottinger *et al*. (1993), Gudmundsson (1994), Debenay (2012), Merkado *et al*. (2013), Förderer and Langer (2018), and WoRMS (2023). The voucher specimen was preserved on a micropaleontology slide and deposited to the National Institute of Biological Resources (NIBR), Incheon, Korea.

Results and Discussion

Phylum Foraminifera d'Orbigny 유공충문
Class Tubothalamea Pawlowski, Holzmann & Tyszka, 2013 터보탈라메아강
Order Miliolida Delage & Hérouard, 1896
기장구멍벌레목
Family Soritidae Ehrenberg, 1839
더미유공충과 (신칭)
Genus *Sorites* Ehrenberg, 1839 더미유공충속 (신칭)

***Sorites orbiculus* (Forsskål in Niebuhr, 1775) (Plate 1–5)** 원판더미유공충 (신칭)

Nautilus orbiculus Forsskål in Niebuhr, 1775: 125.
Sorites orbiculus: Ehrenberg, 1840: pl. 3, fig. 2; Lehmann, 1961: 641, text fig. 36; pl. 8, figs. 1–8; Cheng and Zheng, 1978: 198, text fig. 5; pl. 17, figs. 1–9; pl. 31, figs. 1–3; pl. 32, fig. 1; Hatta and Ujiié, 1992: 80, pl. 17, figs. 5, 6; pl. 18, figs. 5, 6; Hottinger *et al*., 1993: 72, pl. 83, figs. 1–13; Gudmundsson, 1994: 122, text figs. 32, 35; pl. 5, figs. 1–3; Debenay, 2012: 131; Förderer and Langer, 2018: 70, pl. 31, figs. 12–16.
Sorites marginals: Hayward, 1999: 108, pl. 6, figs. 12, 13.

Material examined. Seomyeo diving point, Seongsan-eup, Seogwipo-si, Jeju Island, Korea, 33°27′21.54″ N 126°56′3.06″ E, 2 August 2020, by SCUBA diving, collected by Heerin Kim, Jisu Yeom and Wonchoel Lee. Voucher specimen NIBR ID: NIBRPR0000111174.
Description. Test discoidal, with partially fluted, distorted or slightly wrinkled margin, central proloculus, followed

Table 1. The information on the occurrence records of the Soritidae from the waters close to Korean peninsula shown in figure 1(A).

St.	Locality	Lat. (N)	Long. (E)	Species	Reference
●	Ishigaki Island, Ryukyu Islands, Japan	24°24′40.12″	124°5′7.26″	*Amphisorus hemprichii*, *Parasorites orbitolitoides*, *Sorites orbiculus*	Lessard, 1980; Hatta and Ujiié, 1992; Fujita, 2004
●	Sesoko Island and Minna Island, Ryukyu Islands, Japan	26°39′14.04″	127°51′10.56″	*Amphisorus hemprichii*, *Marginopora vertebralis*, *Parasorites orbitolitoides*, *Sorites orbiculus*	Hohenegger, 1994; Hohenegger *et al*., 1999
●	Kudaka Island, Ryukyu Islands, Japan	26°9′51.73″	127°53′32.77″	*Amphisorus kudakajimaensis*	Gudmundsson, 1994
●	Takara Island, Tokara Islands, Japan	29°8′19.06″	129°11′55.26″	*Amphisorus hemprichii*, *Marginopora vertebralis*	Kuwano, 1956
●	Nakano Island, Tokara Islands, Japan	29°49′14.16″	129°53′25.38″	*Marginopora vertebralis*	Kuwano, 1956
●	Kagoshima Bay, Japan,	31°11′9″	130°40′3″	*Marginopora vertebralis*	Oki, 1989
●	Tanabe Bay, Wakayama, Japan	33°44′07.5″ (Rough estimate, st. 98)	135°18′37.1″	*Sorites marginalis*	Chiji and Lopez, 1968
●	Jeju Island, Korea	Not given	Not given	*Marginopora vertebralis*	Kim *et al*., 2016

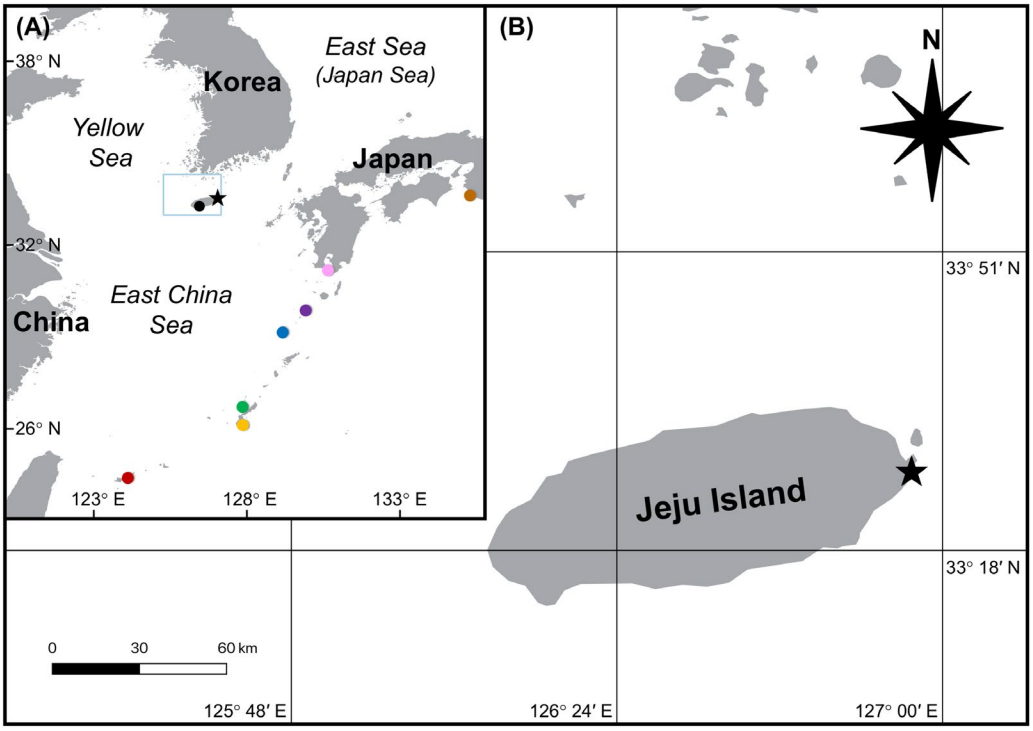


Fig. 1. Map of the occurrence records of Soritidae from waters close to Korean Peninsula (A), and the magnified sampling site of present study (B). The collection site of newly recorded *Sorites* in this study is marked with a star symbol (★), and the sites of occurrence records of Soritidae in waters close to Korea are marked with dot symbols (●) (see Table 1 for additional information). The map was generated using QGIS software v. 3.16.13 and the free vector and raster map data at Natural Earth (naturalearthdata.com).

Table 2. Information of the *Sorites orbiculus* sample collection from the Jeju Island.

St.	Locality	Date	Lat. (N)	Long. (E)	Depth	Method
★	Seomyeo diving point, Seongsan-eup, Seogwipo-si, Jeju Is., Korea	2020-08-02	33°27′21.54″	126°56′3.06″	18.3 m	SCUBA diving

by flexostyle and then with a few, about five to eight evolute planispiral chambers arranged in early stage. Later stage with annular series of small, slightly elongated ovate chamberlets that are symmetrical with respect to the equatorial plane, separated by a median annular passage that appears circular in section, crosswise-oblique stolon system connects chamberlets with two chambers of the preceding series and two chambers of the following series, stolons in a single plane, annular sutures wave-shaped due to depressions of lateral walls above the septulum forming septulum-sutures; wall calcareous, porcelaneous, smooth; aperture a single row of ovate openings surrounded by protruding rims and few of openings with eight shaped outline due to shell material, bridge the narrow part of the aperture. Test diameter about 1.3 mm and test thickness about 160 μm.

Remarks. *Sorites orbiculus* is the type species of the genus *Sorites*, and there are two congeners: *S. marginalis* (Lamarck, 1816) and *S. variabilis* Lacroix, 1940. Referring to WoRMS (2023), *S. duplex* (Carpenter, 1883), which was originally described as *Orbitolites duplex* Carpenter, 1833, is listed as a valid species of *Sorites*. However, this species has been synonymized with *Amphisorus hemprichii* by some previous studies including Carpenter (1883), Loeblich and Tappan (1987), Gudmundsson (1994), and Förderer *et al*. (2018). *Sorites duplex* can be distinguished from *S. orbiculus* in that the former has marginal apertures arranged in two series, commonly alternating in position, separated by elevated ridges as *Amphisorus*, whereas the latter has apertures of ovate or 8-shaped or separated two ovate openings arranged in a row, without separation by elevated ridges.

Sorites orbiculus can be distinguished from *S. variabilis* morphologically by the apertural rim detail, and they

are also genetically separated (Merkado *et al*., 2013). According to their study, *S. orbiculus* has prominent apertural rim, while *S. variabilis* has faint or no rim around the aperture. Additionally, they can be also separated genetically by using partial SSU rDNA sequences.

Sorites orbiculus is most similar to *S. marginalis*; these species have often been misidentified as each other. Accordingly, Gudmundsson (1994) suggested that *S. marginalis* can be considered an eco-type or variation of *S. orbiculus*. He pointed out that the morphological characters noted by Lehman (1961) that have been used to distinguish the two species are unclear and sometimes co-occur in the same species, or even in a single individual such as the number of apertural opening in a row (double in *S. orbiculus*, single in *S. marginalis*), number of early planispiral chambers (five to eight in *S. orbiculus*, 13 in *S. marginalis*) and the chamberlet shape (more elongate in *S. orbiculus*, more ovate in *S. marginalis*). Furthermore, a molecular phylogenetic study on superfamily Soritoidea revealed that *S. orbiculus* and *S. marginalis* are not clearly separated genetically and these species appear to be variants of one species, so that the morphological criteria for the *Sorites* species identification need to be revised (Holzmann *et al*., 2001). The present examined material has somewhat mixed characteristics of *S. orbiculus* and *S. marginalis* in terms of row of peripheral apertures. The apertures are surrounded a by distinct rim, and most of the apertures are single elongate-oval openings, and few are 8-shaped openings. However, other characters, including the number of early planispiral chambers and chamberlet shape, point to *S. orbiculus*. According to Hottinger *et al*. (1993) and Gudmundsson (1994), in the early annular stage of *S. orbiculus*, a single apertural row of a single circular, ovate, or 8-shaped openings may appear, and are retained as far as eighth to fourteenth chamber. Our specimens consist of about nine annular chambers, therefore, represent *S. orbiculus* in early growth stage. As mentioned above, several studies have provided detailed morphological analysis and molecular phylogeny of *Sorites* (Lehmann, 1961; Hottinger *et al*., 1993; Gudmundsson, 1994; Holzmann *et al*., 2001) but these are somewhat fragmentary. Therefore, a comprehensive study including all *Sorites* species is needed to clearly understand *Sorites* diversity.

Sorites species are known to host dinoflagellate symbionts belonging to *Symbiodinium* (Hottinger *et al*., 1993; Hohenegger, 2011). Additionally, diatom symbiont *Nitzschia* sp. and *Nanofrustulum shiloi* were isolated and cultured from living *S. orbiculus* individuals collected from Sesoko Island (Japan) by Mayama *et al*. (2000). In our SEM images, there are some diatoms on the inner wall of the broken chamberlets. Based on the previous studies (Lehmann, 1961; Hottinger *et al*., 1993; Saraswati, 2002), *S. orbiculus* prefers to live attached to the surface of substrate, such as of sea grasses and macroalgae or rocks, very firmly. Such individuals are commonly permanently fixed, and the irregular surface of their substrate affect during growth. Therefore, the test can become much distorted, and the annuli of chamberlets may be somewhat incomplete. These morphological features can be confirmed in the present specimen (Pl. 1, figs. A–E; Pl. 2–5, fig. A). Such ecological feature may also be the reason why few individuals were obtained from the sediment samples in present study. To collect additional *Sorites* individuals for the further study, including molecular analysis, we need to investigate subtidal rocky habitats rich in macroalgae, seagrasses or corals around Jeju Island.

Distribution. *Sorites orbiculus* is widely distributed in circumtropical waters of Indo-Pacific, and the range is expanding into some regions of the Mediterranean and the Caribbean Realm (Langer and Hottinger, 2000; Meriç *et al*., 2014; Förderer *et al*., 2018; Oron *et al*., 2022; WoRMS, 2023). The closest sites to Korea where this species has been reported are Japanese Rukyu Islands in the East China Sea, and Xisha, Zhongsha Islands in the South China Sea (Cheng and Zheng, 1978; Hatta and Ujiié, 1992). The distribution of *S. orbiculus* is reported below:

Indo-Pacific: Korea, Xisha Islands, Zhongsha Islands, Ryukyu Islands, Gulf of Aqaba, Red Sea, Tanzania (Zanzibar), Republic of South Africa, Mozambique, Kenya, Chagos Island, Maldives, Indonesia, Palau, Papua New Guinea, Philippines, Federated States of Micronesia (Chuuk lagoon), Solomon Islands, Australia, New Zealand, New Caledonia, Marshall Islands, Kiribati (Phoenix Islands, Line Islands), Hawaii, Society Islands, Tuamotu Islands, Pitcairn Islands; Atlantic: Israel (Shikmona), Türkiye (Ayvalık, Antalya, Gulf of Kuşadası), Portugal (Selvagens Islands), Gulf of Gabes, Sicily, Brazil, Gulf of Cariaco, Bahamas, Florida Bay.

Conclusion

A *Sorites* species is newly reported from Jeju Island (South Korea). Based on the number of early planispiral chamber, the chamberlet shape, and the apertural details with chamber number, the species have been assigned to *S. orbiculus*. This result contributes to establishing the basic data on Korean LBF species diversity. To improve our understandings of *S. orbiculus* and its congeners, we need to collect more specimens over a wide area and conduct comprehensive research on the morphology, genetic information, and symbionts.

Conflicts of Interest

The author of this paper has no affiliation with any inter-

ests and is solely responsible for the paper.

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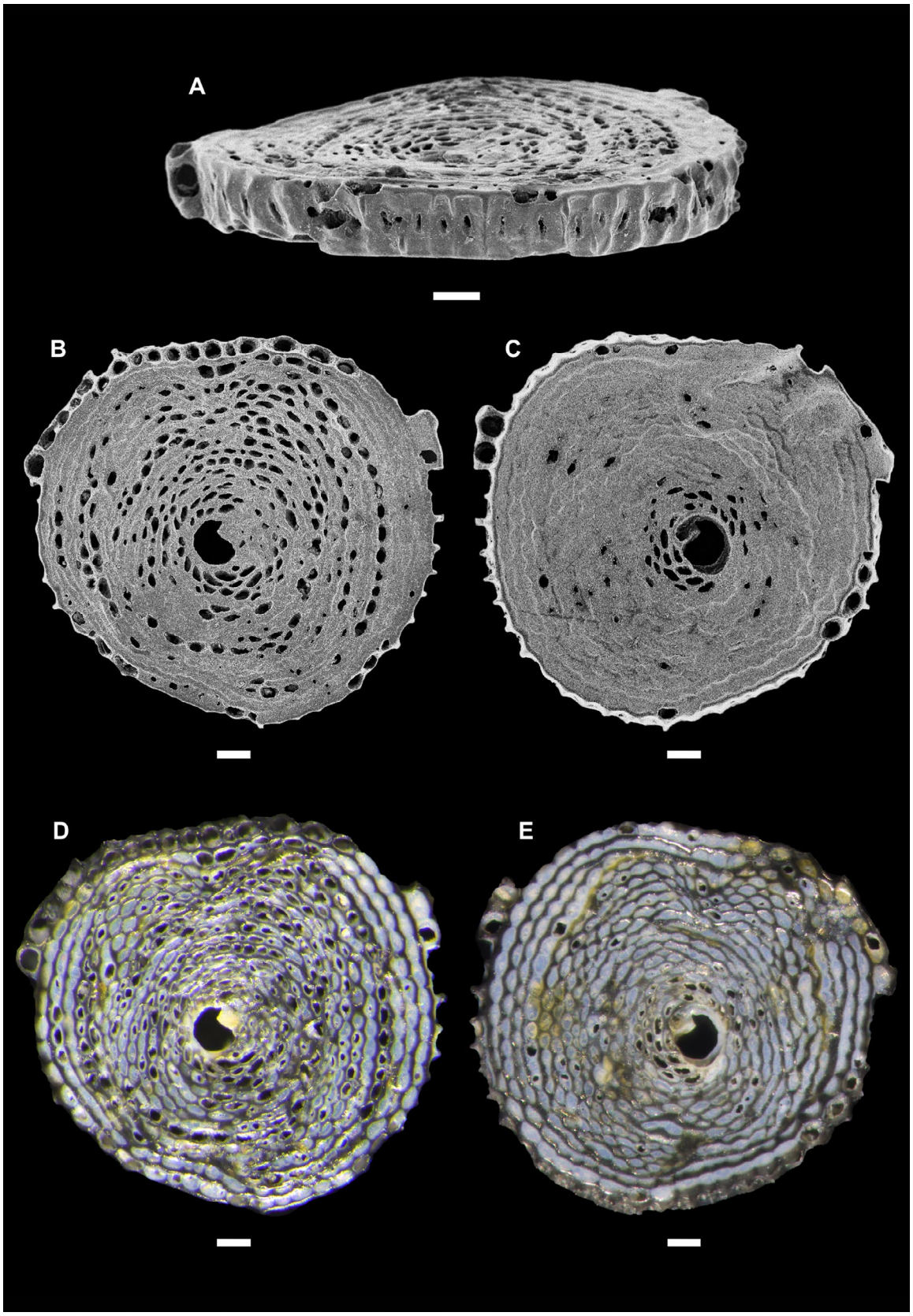


Plate 1. Scanning electron microscope (SEM) images and photomicrographs of *Sorites orbiculus* (Forsskål in Niebuhr, 1775). A–C. SEM image; A. peripheral, apertural view; B, C. lateral view. Scales = 100 μm. D, E. photomicrographs of the lateral view. Scales = 100 μm.

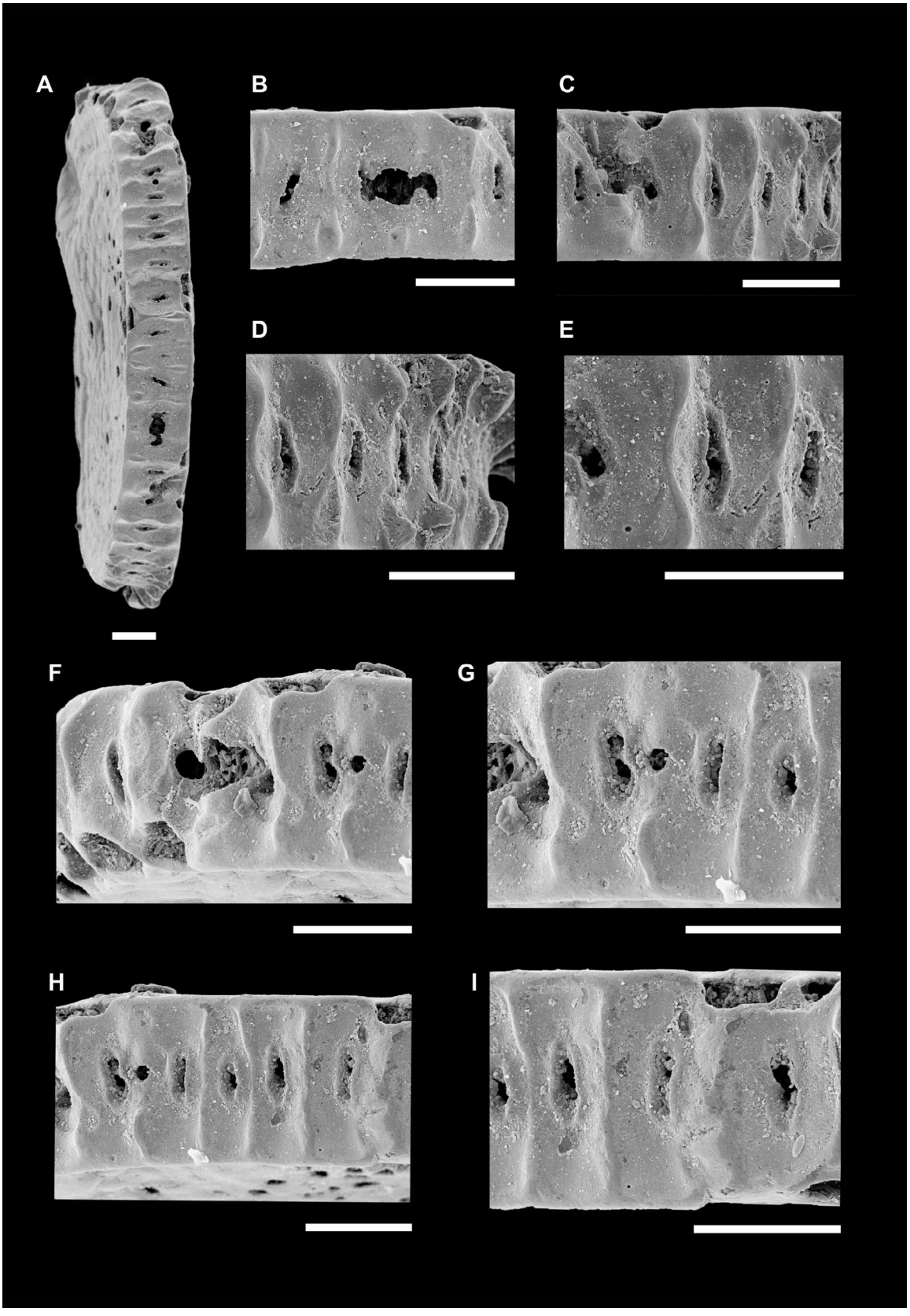


Plate 2. Scanning electron microscope images of the newly recorded LBF, *Sorites orbiculus* (Forsskål in Niebuhr, 1775). A. peripheral, apertural view; B–I. close-up of apertures. Scales = 100 μm.

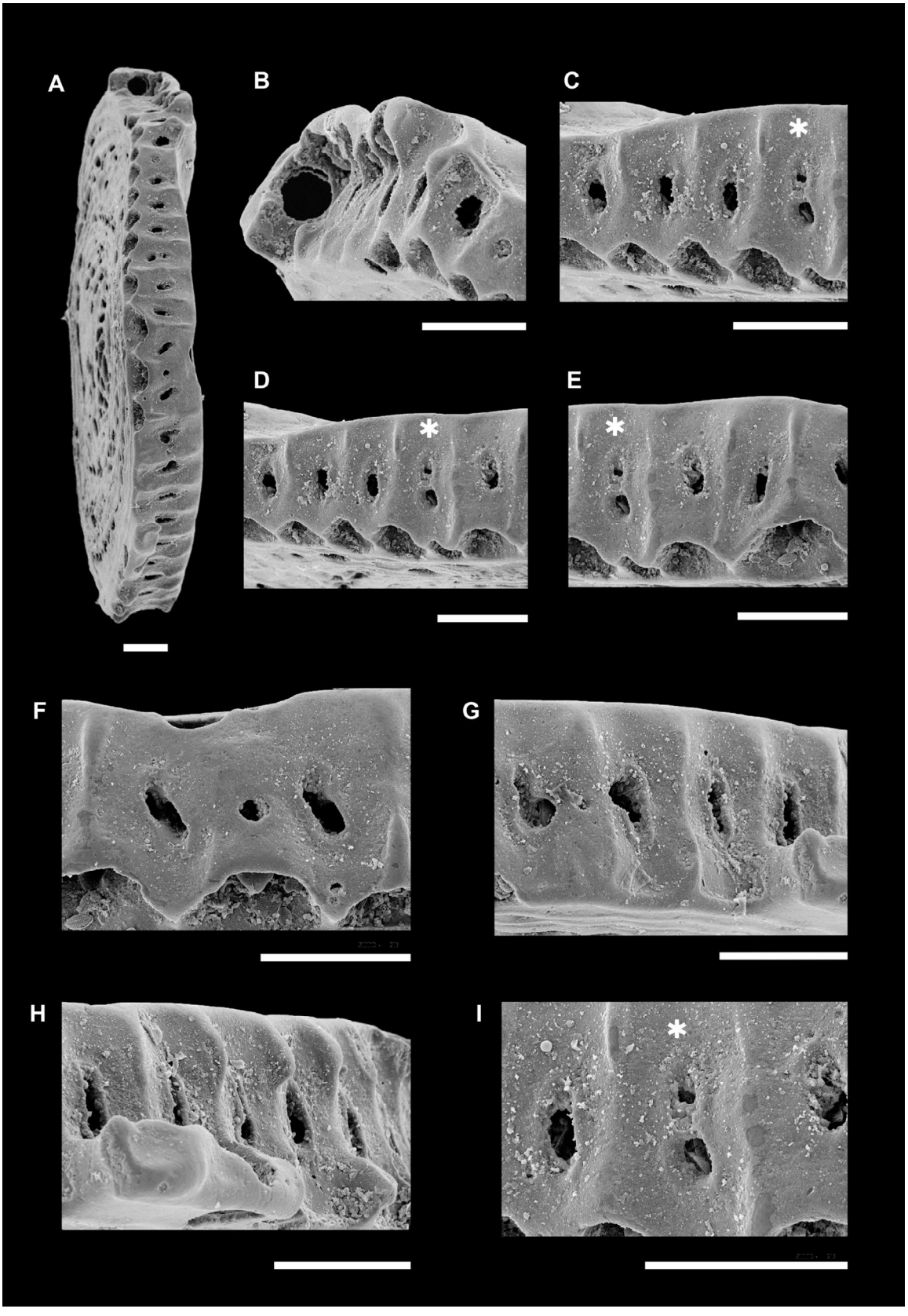


Plate 3. Scanning electron microscope images of the newly recorded LBF, *Sorites orbiculus* (Forsskål in Niebuhr, 1775). A. peripheral, apertural view; B–I. close-up of apertures. The '8' shaped aperture is indicated with * symbol. Scales = 100 μm.

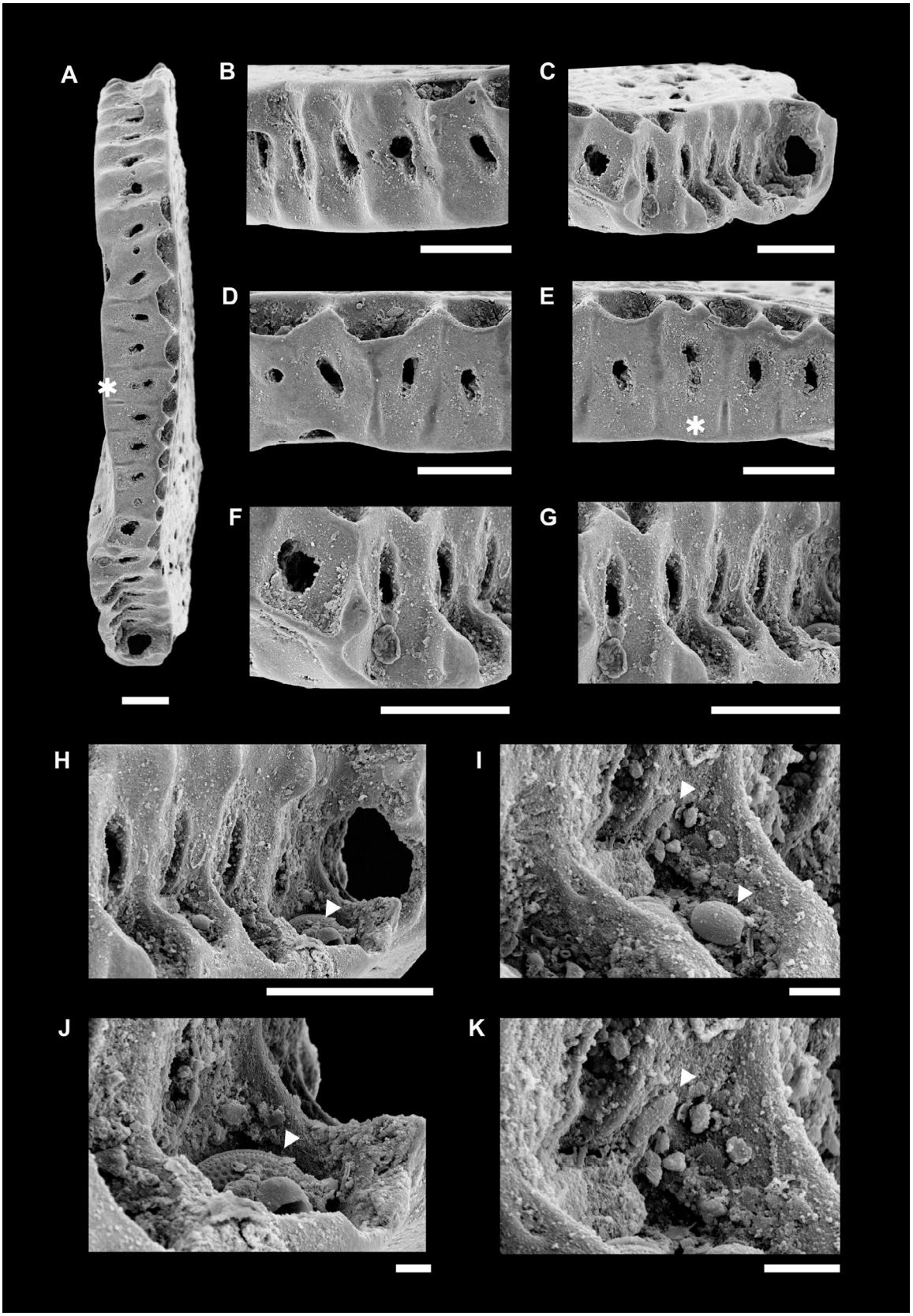


Plate 4. Scanning electron microscope images of *Sorites orbiculus* (Forsskål in Niebuhr, 1775). A. peripheral, apertural view; B–H. close-up of apertural side. The symbol * is indicating the '8' shaped aperture. Scales: 100 μm; I–K. close-up of broken part, some diatoms (white arrowhead) are on the inner surface of chamberlet. Scales = 10 μm.

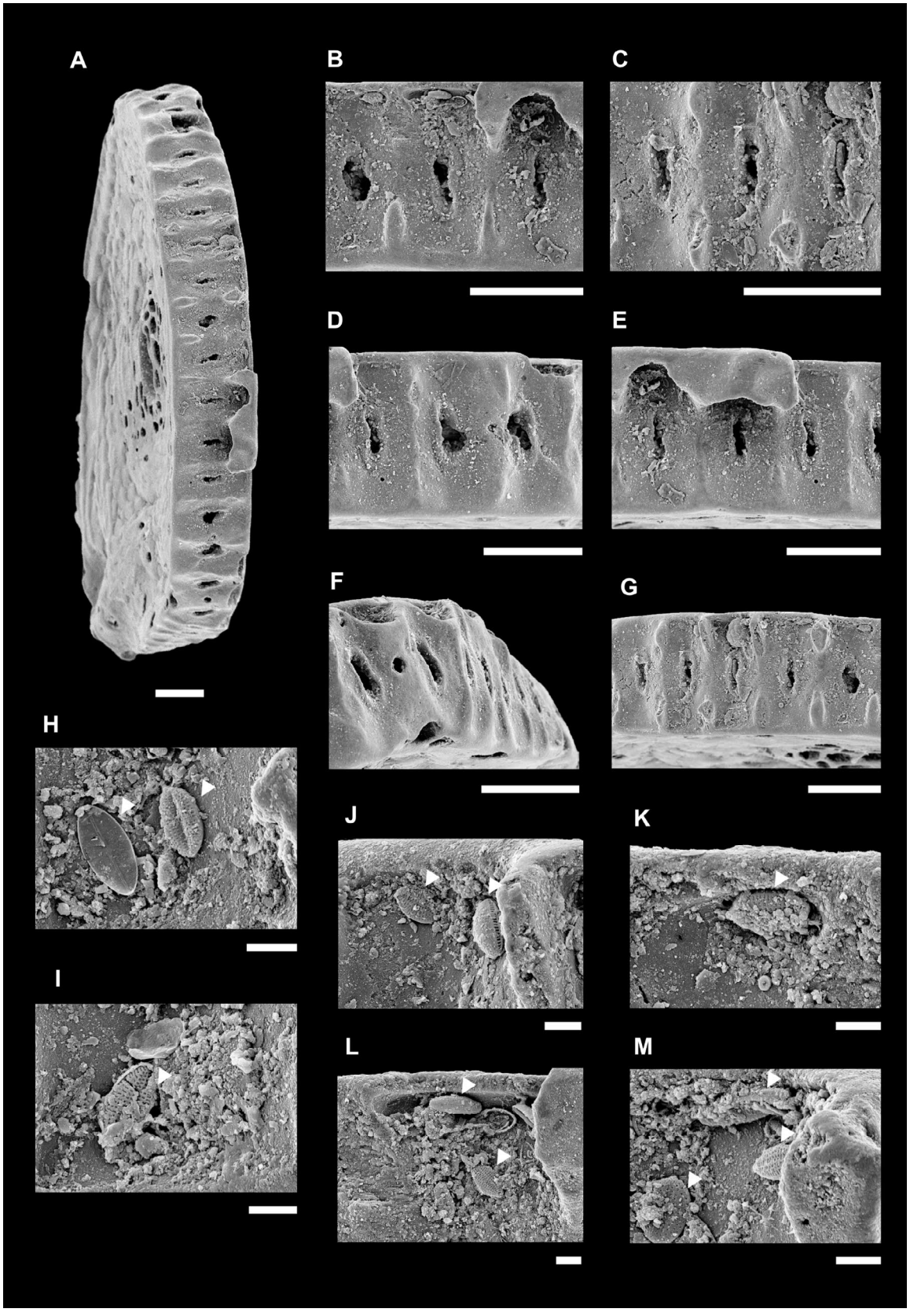


Plate 5. Scanning electron microscope images of *Sorites orbiculus* (Forsskål in Niebuhr, 1775). A. peripheral, apertural view; B–G. close-up of apertural side. Scales = 100 μm; H–M. close-up of broken part, some diatoms (white arrowhead) are on the inner surface of chamberlet. Scales = 10 μm.