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ORIGINAL ARTICLE

Siphodinarella costata n. gen., n. sp., a new benthic foraminifer from the Coniacian of the Adriatic Carbonate Platform (Slovenia, Croatia)

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Abstract A new benthic foraminifer is described as *Siphodinarella costata* n. gen., n. sp. from Coniacian shallow-water platform-interior carbonates of Slovenia and Croatia. The new foraminifer is found in skeletal wackestone in association with small benthic foraminifera, thaumatoporellaceans, and calcimicrobes (*Decastronema*, *Girvanella*-type tubes). The existence of an internal siphon in *Siphodinarella* n. gen. is interpreted as an entosolenian tube and discussed in terms of its generic and suprageneric importance.

Keywords Benthic foraminifera · Entosolenian tube · Coniacian · Microbialites · Adriatic Carbonate Platform

Introduction

The Upper Cretaceous Turonian-Santonian shallow-water limestones of the Periadriatic region (Adriatic, Apenninic, and Apulian carbonate platforms) contain a rich fauna of large-sized miliolids and other benthic foraminifera (e.g., Torre 1966; Luperto Sinni 1965, 1976; De Castro 1971, 1974a, b; Cvetko Tešović et al. 2001; Korbar and Husinec 2003; Velić 2007; Checconi et al. 2008; Pomoni-Papaioannou and Zambetakis-Lekkas 2009). A characteristic microfacies of peritidal carbonates consists of skeletal-peloidal wackestones and packstones with an assemblage of *Thaumatoporella parvovesiculifera* (Raineri) and *Decastronema* (former *Aeolisaccus*) *kotori* (Radoičić), occasionally associated with small benthic foraminifera such as *Montcharmontia apenninica* (De Castro), *Robertinella scarsellai* Torre, or *Stensioeina surrentina* Torre (Gušić and Jelaska 1990; Moro and Jelaska 1994; Carannante et al. 2000; Buonocunto et al. 2002; Ruberti and Toscano 2002; Golubic et al. 2006; Jeź et al. 2011; Simone et al. 2012; Spalluto 2012). In the Croatian part of the Adriatic platform, this facies is known as the Gornji Humac Formation and was originally described from the island of Brač (Gušić and Jelaska 1990); similar deposits are known from the islands of Cres (Korbar and Husinec 2003), Dugi Otok (Fuček et al. 1990), and Ist and Olib (Moro and Jelaska 1994). In Slovenia (Trieste-Komen plateau), it corresponds to the Upper Turonian-Santonian Sežana Formation (Jurkovšek et al. 1996). Similar facies with *Decastronema* is found in the Paleocene (Danian) and Early Eocene (Cuisian) deposits both in Slovenia (Kras) and Croatia (Istria, Cres Island, Ravni Kotari) (e.g., Ćosović et al. 2008). The present paper deals with an up-to-now undescribed foraminifer that seems to be a characteristic constituent of *Thaumatoporella*- and *Decastronema*-bearing carbonates of Coniacian age in Slovenia and Croatia (Fig. 1).

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Geological setting

Croatia

Island of Mljet

The backbone of the Island of Mljet consists of a ~1,800-m-thick succession of Upper Jurassic (Tithonian) to

Fig. 1 Satellite image showing the Adriatic Sea with outline of Slovenia and Croatia (based on Google Earth) with occurrences of *Siphodinarella costata* n. gen., n. sp. (*red asterisk*)

mid-Cretaceous (Cenomanian) shallow-water, platform-interior limestone, dolostone, and intraformational breccia (Husinec and Jelaska 2006). The ~190-m-thick Upper Cretaceous (Coniacian) shallow-water limestone (Gornji Humac Formation; Gušić and Jelaska 1990) occurs exclusively along the northeastern coast and adjoining islets, where it is separated from the Cenomanian limestones (Milna Formation; Gušić and Jelaska 1990) by a reverse fault (Husinec 2002) (Fig. 2).

The Coniacian Gornji Humac Formation in the study area consists of a thin- (20 cm) to thick-bedded (170 cm), predominantly mud-rich limestone. The dominant lithofacies are lime mudstone and skeletal wacke-/mudstone, skeletal wacke-/packstone, and rudist floatstone; microbial laminite is subordinate and occurs only in the uppermost part of the studied succession. The former three are interpreted as shallow subtidal facies and are characterized by variable amounts of lime mud, foraminifera (*Montcharmontia apenninica, Scandonea samnitica, Murgella lata, Acordiella conica, Dicyclina* cf. *schlumbergeri,* and various indeterminable miliolids, ataxophragmiids, rotaliids), thaumatoporellaceans (*Thaumatoporella parvovesiculifera*), calcimicrobes (*Decastronema*), rudist (Radiolitidae) fragments, ostracods, peloids, and irregular fenestrae (rare); mudstone is sporadically dolomitized in the upper part of the succession. Intertidal deposits are preserved as microbial laminites that commonly alternate with thin beds of mud-supported limestone.

The foraminifer *Siphodinarella costata* n. gen., n. sp. occurs in the upper third of the studied succession at Rt Stupa (MSR; Fig. 3) in association with *Moncharmontia apenninica*, *Scandonea samnitica*, *Thaumatoporella parvovesiculifera*, and *Decastronema kotori* (Fig. 4a–c). Based on findings of the foraminifer *Murgella lata* lower in the section, the strata can be assigned a (middle?) Coniacian age (Husinec 2002; cf. Steuber et al. 2005).

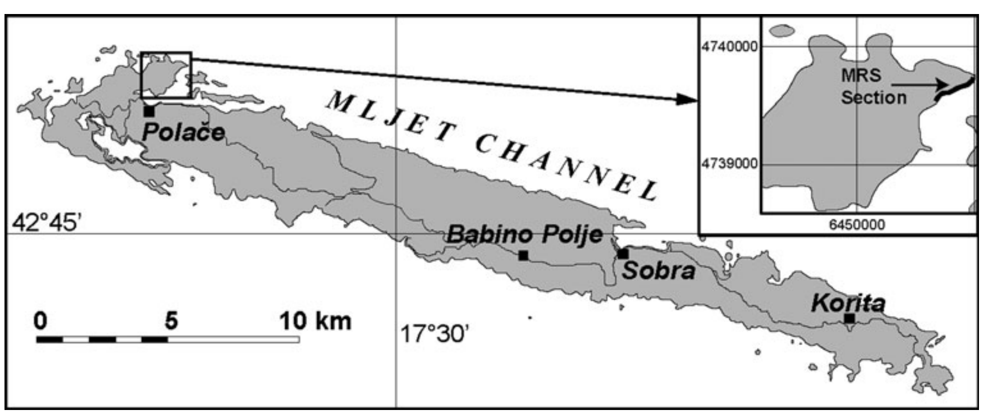


Fig. 2 Detailed location map of study area on the island of Mljet, Croatia, showing location of the Rt Stupa (MRS) section, type locality of *Siphodinarella costata* n. gen., n. sp

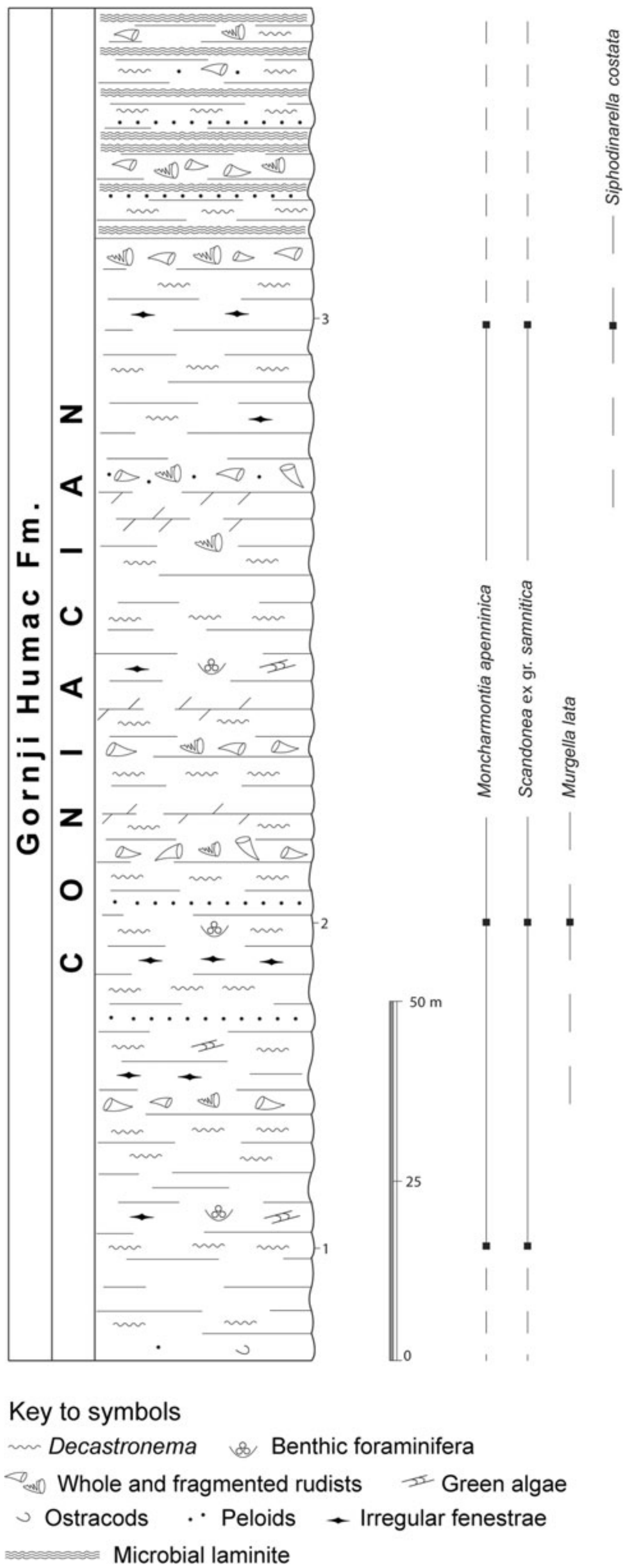


Fig. 3 Stratigraphic column Rt Stupa (MRS), Mljet Island, Croatia, with vertical distribution of index fossils, including the type level of *Siphodinarella costata* n. gen., n. sp

Island of Brač

The Upper Cretaceous carbonate succession of the Island of Brač is composed of a ~1,500-m-thick Cenomanian to Maastrichtian sequence of shallow-marine and pelagic limestones (Gušić and Jelaska 1990). We were able to identify several specimens of *Siphodinarella costata* n. gen., n. sp. from a wackestone with *Murgella lata* and "cyanophyte bundles (of the *Girvanella* type)" on the Island of Brač (Gušić and Jelaska 1990: pl. 8, Fig. 2). The samples containing the new foraminifer were collected from the upper part of the Gornji Humac Formation that is characterized by an alternation of four types of mud-rich limestone: (1) microbial and horizontal laminites; (2) *Thaumatoporella-Decastronema* wackestone; (3) foraminiferal-peloid wackestone; and (4) rudist floatstone with a lime mudstone or fine pellet packstone matrix. Initially, Gušić and Jelaska (1990) suggested a Late Santonian age for the part of the formation with *Murgella lata*. Recently, Steuber et al. (2005) revised the stratigraphy of the island based on numerical ages derived from strontium-isotope stratigraphy of low-Mg calcite rudist shells, and assigned the *Murgella*-bearing strata to the middle Coniacian (older than 87.7 m.a.).

Slovenia

Matarsko Podolje

The investigated area with outcrops of Lower Cretaceous to Paleogene carbonates (Jež et al. 2011) is located near Hrušica Village in the central part of the Matarsko Podolje area, southwestern Slovenia. Tectonically, the area is part of the most external thrust units of the northwestern Dinarides. An approximately 560-m-thick Upper Cenomanian to Coniacian (?Santonian) shallow-marine carbonate succession was sedimentologically studied, while the paleontological material belongs to the 90-m-thick Coniacian (Santonian?) succession. The investigated sequence ends with a regional unconformity that is marked by a prominent paleokarstic surface (Otoničar 2007; Jež et al. 2011). The Upper Cretaceous carbonates were deposited in the northwestern interior of the Adriatic Carbonate Platform.

The studied Hrušica section is characterized by an alternation of predominantly lime mudstone/wackestone and skeletal wackestone/packstone; skeletal packstone/grainstone; rarely floatstone occur locally. Thaumatoporellaceans and benthic foraminifers (miliolids, *Scandonea samnitica*, *Scandonea* sp., *Moncharmontia apenninica*,

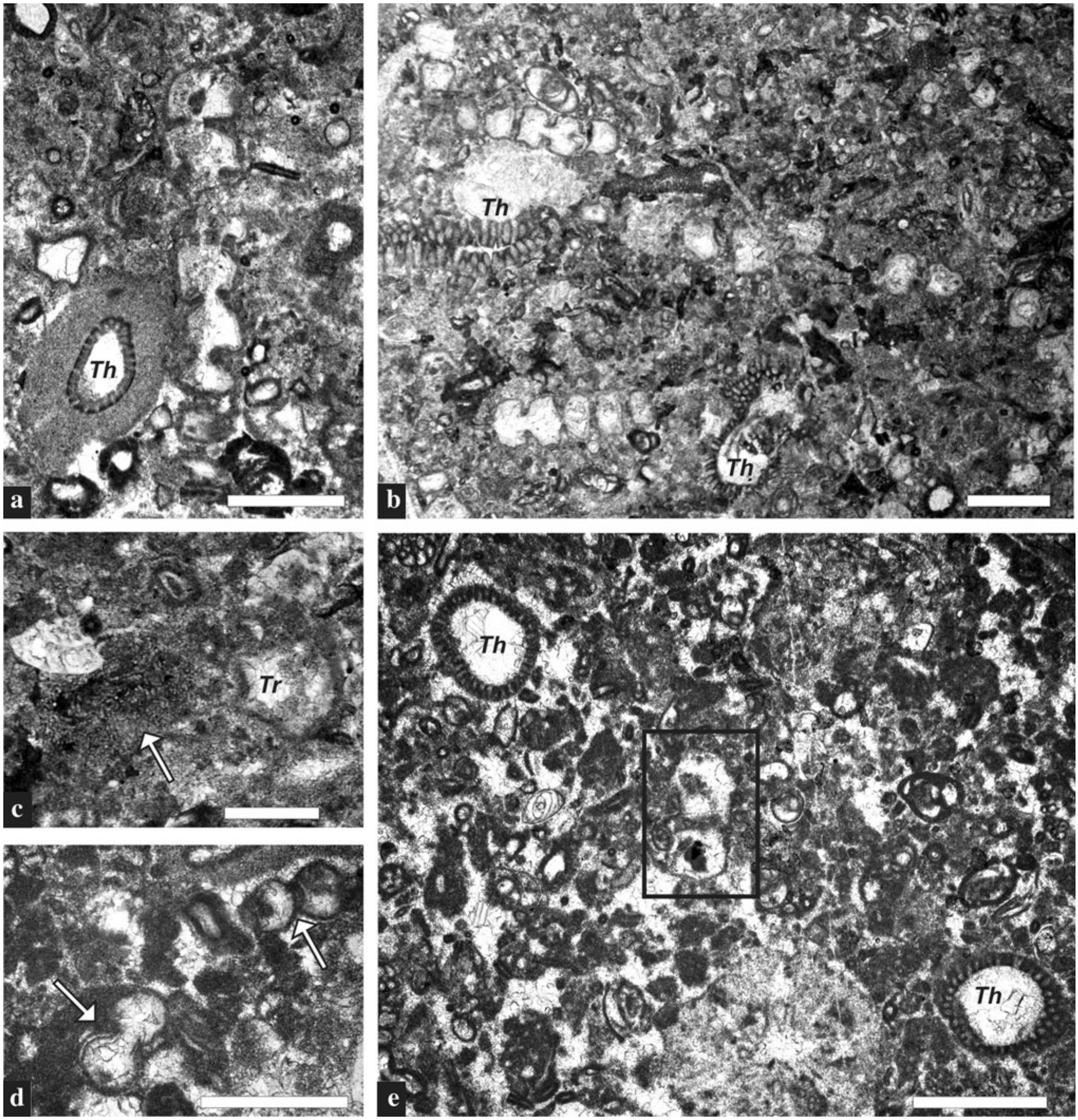


Fig. 4 Microfacies of Coniacian carbonates with *Siphodinarella costata* n. gen., n. sp. from the type-locality, Mljet Island, Croatia (**a**–**c**) and Matarsko Podolje, Slovenia (**d**–**e**). **a**, **b** Wacke-/packstone with *Thaumatoporella parvovesiculifera* (Raineri) (Th), small benthic foraminifera, including miliolids, *Rotorbinella scarsellai* Torre, *Montcharmontia apenninica* (De Castro), and cyanophyts *Decastronema kotori* (Radoičić). Thin-section MRS-3/1 (**a**) and MRS-3 (**b**), *scale bars* 0.5 mm. **c** Detailed view of a wackestone with transverse section of *Siphodinarella costata* (Tr), microbial patch (*Girvanella*-type) (arrow) and a calcareous foraminifer. Thin-section MRS-3, *scale bar* 0.25 mm. **d** Packstone with scattered debris of *Siphodinarella costata* (arrows). Thin-section Hiii-33, *scale bar* 0.5 mm. **e** Packstone with benthic foraminifera (mostly miliolids), thaumatoporellaceans (*Th*) and fragment of *Siphodinarella costata* (*black rectangle*). Thin-section Hiii-33, *scale bar* 0.5 mm

M. compressa, (?)*Nummofallotia apula*, *Nezzazatinella picardi*, *Murgella lata*, *Dicyclina schlumbergeri*, *Cuneolina* sp. and *Rotorbinella* sp.) are the most common microfossils. In addition, rudists, rudist bioclasts, ostracods, and microbial products (bacinellid crusts, *Decastronema*) were also found. Non-skeletal grains are represented by peloids and micrite intraclasts. *Siphodinarella costata* n. gen., n. sp. is rare, and occurs only as chamber fragments (Fig. 4d, e).

Micropaleontological part

Order Foraminiferida Eichwald
? Superfamily Hormosinacea Haeckel
? Family Hormosinidae Haeckel
Genus *Siphodinarella* n. gen.

Derivatio nominis: Combined name referring to the internal siphon interpreted as entosolenian tube and the Dinaric Mountains along the Adriatic Sea.

Type species: *Siphodinarella costata* n. gen., n. sp.

Diagnosis: Test-free, uniserial, rectilinear to slightly bent consisting of numerous spaced-out chambers connected by short stolon-like tubes. Surface of test with longitudinal costae. Wall thin, very finely agglutinated. Aperture simple, terminal, provided with a centrally placed siphon interpreted as entosolenian tube.

Comparisons: The most characteristic feature of *Siphondinarella* is the central siphon. Such a structural element is relatively rare in benthic foraminifera. An entosolenian tube, also known as endosolen or entosiphon, is “a tube-like internal skeletal structure extending from the aperture in a proximal direction” (Hottinger 2006, p. 14). For example, it is present in monothalamous (unilocular) calcareous Lagenidae or the proteinaceous Allogromiinae (e.g., Patterson and Richardson 1987; Mikhalevich 2004; Popescu and Crihan 2004) (Fig. 5). Commonly, the entosolenian tube is broken or dissolved (e.g., Mello 1969), and we argue that that explains its absence in many centered longitudinal sections of *Siphodinarella costata*.

According to the suprageneric foraminiferal classification of Loeblich and Tappan (1987), the presence of an entosolenian tube in the subfamilies Oolinae Loeblich and Tappan (including 13 genera) and the Ellipsolageninae Silvestri (including five genera) represents a suprageneric feature. In the subfamily Sipholageninae Patterson and Richardson, the presence/absence of an entosolenian tube is considered a diagnostic generic criterion. This feature has been included in the identification key of unilocular lagenids provided by Clark and Patterson (1993). In multilocular foraminifera with entosolenian tube, e.g., representatives of the family Glandulinidae Reuss (see Loeblich and Tappan 1987, p. 431), the tube is often associated with the final chamber only. In addition to calcareous benthic foraminifera, a reputed entosolenian tube was also described from the Upper Triassic

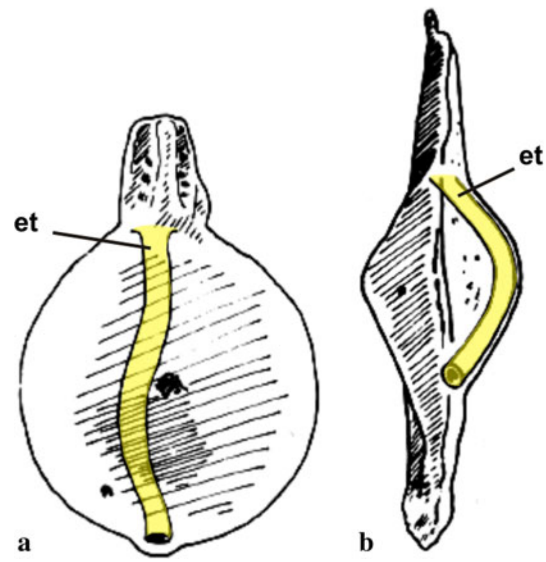


Fig. 5 Examples of unilocular Lagenidae with entosolenian tube (et, *yellow filling*). Without scale. **a** *Prislinosceptrella hispida* Patterson and Richardson, Quaternary of the Atlantic Ocean (modified from Patterson and Richardson 1987, pl. 5, Fig. 7); entosolenian tube slightly bent and reaching down to the chamber base. **b** *Wiesnerina carinata* Taylor, Quaternary of the Pacific Ocean (modified from Patterson and Richardson 1987, pl. 5, fig. 13); entosolenian tube attaching to the chamber wall and terminating at the chamber base

agglutinated genus *Agglutisolena* attributed to the Ataxophragmiidae (Senowbari-Daryan 1984). This interpretation, however, was disputed by Loeblich and Tappan (1987, p. 141).

An entosolenian tube-like structure is also present in the Holocene agglutinating hormosinid genus *Ginesina* Bermudéz and Key. In *Ginesina*, the aperture is “produced on a long cylindrical neck, the successive chambers added closely, so that the distal interior wall of the new chamber rests against the preceding neck, successive tubular necks forming a continuous connection between succeeding chambers” (Loeblich and Tappan 1987, p. 61). In this case, the tubiform necks are extensions of the wall and thus an integral part of it, whereas the tube of *Siphodinarella* is sticking in a telescope-like manner inside the stolons connecting the chambers. Therefore, it cannot be interpreted as a neck around the chamber aperture and the intercameral apertures but is considered an entosolenian tube. The attribution of the new genus to the family Hormosinidae Haeckel is, however, uncertain and tentative because the occurrence of such a structural element has not yet been reported from this group. In any case, the combination of an entosolenian tube in a uniserial foraminifer exhibiting tubiferous chamber connections does not permit closer comparisons of *Siphodinarella* with other genera.

All specimens exhibit a slightly yellowish fibrous-calcitic cement rim along the inner side of chamber walls.

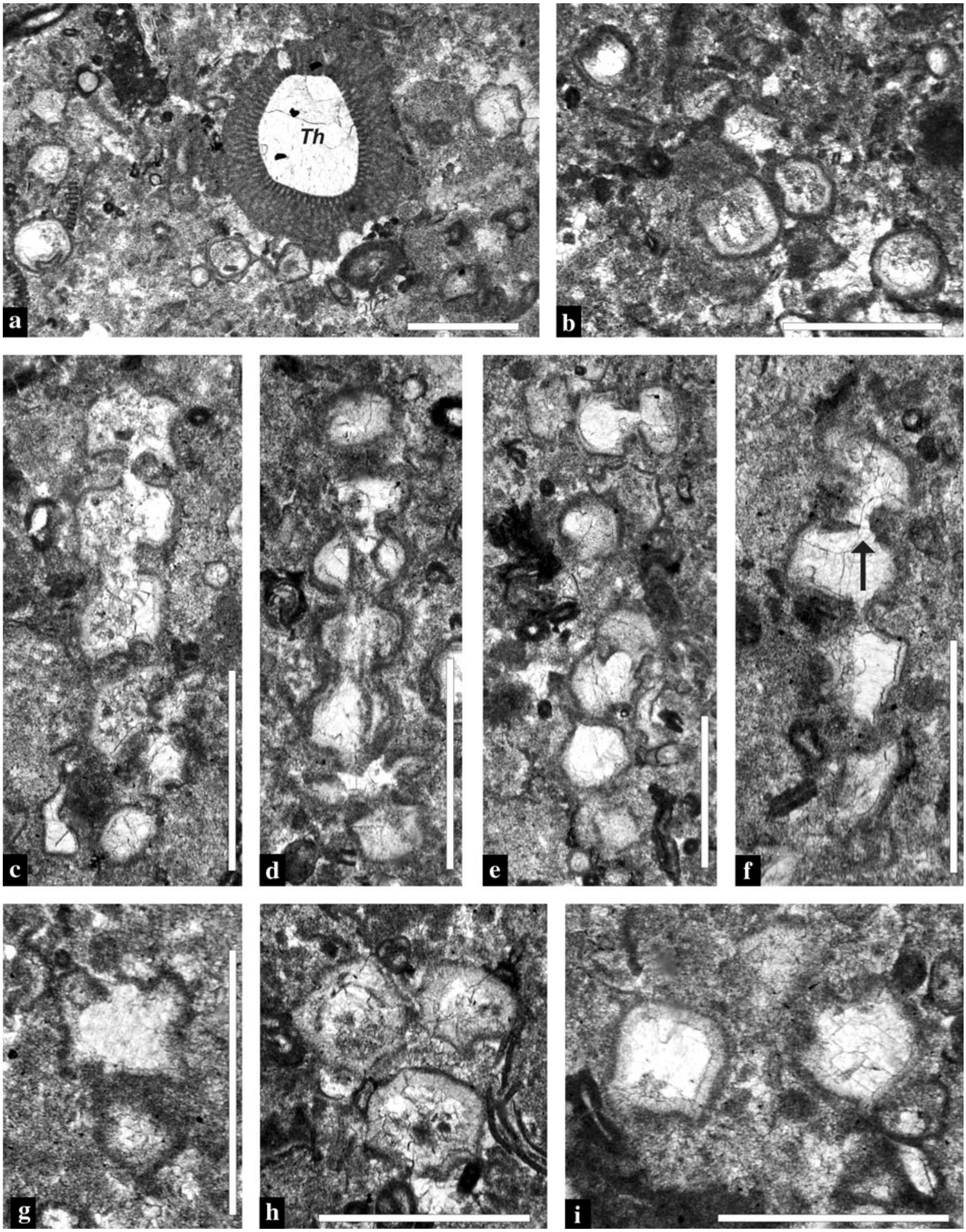
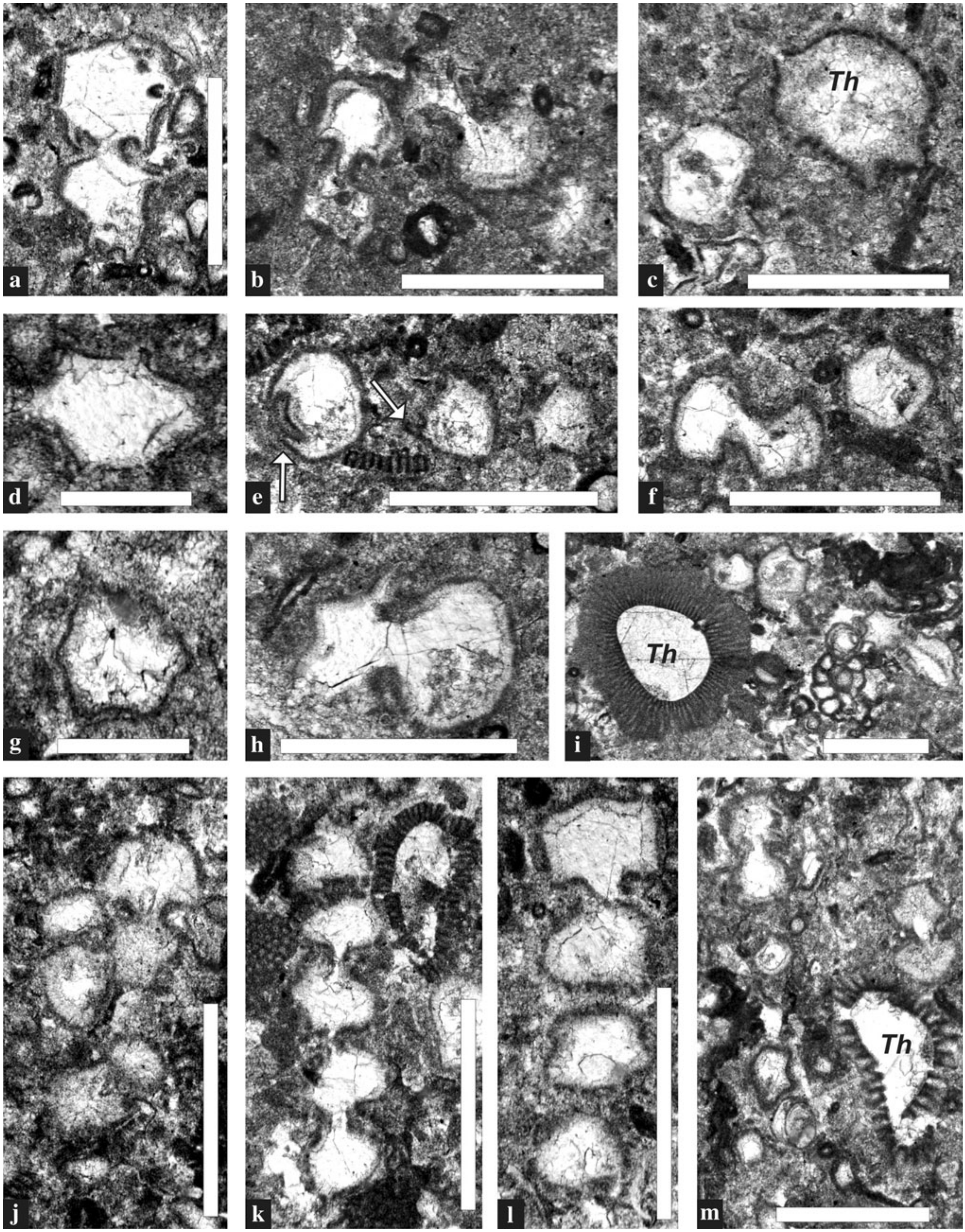


Fig. 6 *Siphodinarella costata* n. gen., n. sp. from the Coniacian of the Island of Mljet, Croatia. **a** Wacke-/packstone with scattered broken chambers and a thick-walled specimen of *Thaumatoporella* (Th). **b**, **g–i** Different chamber sections, mostly oblique. **c–f** Longitudinal sections. Note the wide chamber spacing connected by stolon-like necks. Individual chambers may be irregular arranged with respect to the test axis resulting in an eccentric foramen (*arrow* in f). Thin-section MRS 3.1. *Scale bars* 0.5 mm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◀ **Fig. 7** *Siphodinarella costata* n. gen., n. sp. from the Coniacian of the Island of Mljet, Croatia. **a–c**, **e**, **f**, **h** Different sections of broken specimens with 1–2 chambers. Note acute lower margin of the chamber (*arrows* in **a** and **e**). **d**, **g** Slightly oblique transverse sections showing polygonal chamber outline resulting from concave longitudinal furrows and ridges. *Th* = *Thaumatoporella* specimen in **c**. **i**, **m** Fragments co-occurring with *Thaumatoporella parvovesiculifera* (Raineri) (*Th*) and a trochospiral benthic foraminifer (*?Montcharmontia*) in **i**. Note also the variability of *Thaumatoporella* with respect to wall thickness and pore width. **j–l** Partly oblique longitudinal to tangential sections. Note the comparable wide chamber spacing. Thin-sections MRS-3 (**a**, **d**, **f**, **g**, **i–m**) and MRS 3.1 (**b**, **c**, **e**, **h**). *Scale bar* 0.2 mm for **d**, **g**, 0.5 mm for all others

Since this rim is interpreted as cement and not an integral part of the test wall (i.e., inner layer), this observation was not included into the diagnosis of *Siphodinarella*.

Siphodinarella costata n. gen., n. sp.

Figure 4 pars, 6–9

Derivatio nominis: costatus = Latin for ribbed, referring to the longitudinal outer chamber ribs separated by concave depressions.

Holotype: Slightly oblique longitudinal-tangential section of the specimen illustrated in Fig. 8e, thin-section MRS-3.

Paratypes: All specimens appearing in the two thin-sections MRS-3 and MRS-3-1 are illustrated in Figs. 6, 7, and 8.

Depository: The two thin-sections labeled MRS-3 and MRS 3-1 are curated at the Croatian Geological Survey Thin-Section Repository, Sachsova 2, HR-10000 Zagreb, Croatia.

Locus typicus: Rt Stupa Section (WPS 84 System coordinates: start at $X = 6{,}450{,}650$, $Y = 4{,}739{,}500$; end at $X = 6{,}450{,}975$, $Y = 4{,}739{,}725$), Island of Mljet, southern Croatia.

Stratum typicum: (Middle?) Coniacian, Gornji Humac Formation, *Murgella lata* partial-range Zone of Velić (2007).

Diagnosis: See diagnosis of genus.

Description: In the studied thin-sections, the new species is represented by debris of single chambers, or by fragments of mostly two to three chambers and more or less complete specimens (Fig. 6b). The largest test observed has a length of 1.45 mm and is composed of eight chambers (Fig. 8d). There are about three chambers per 0.5 mm in the adult part of the test. The width of the test is within a range of 0.18–0.35 mm. In the juvenile part, the width and height of chambers are approximately equal, later they gradually increase in size as added (width/height ratio reaching up to 1.8). In addition to the changes in width/height ratio, the chamber morphology also changes during ontogeny. In longitudinal sections, the chambers appear subspherical to ovoid in the juvenile part. In the adult test part, the chambers exhibit rectangular shapes with a rounded upper and more acute overhanging lower margin that almost touches the preceding chamber (Figs. 7a, 8c). The external chamber surface shows longitudinal ridges (costae) separated by concave depressions as can be deduced from the polygonal shaped transverse sections (Fig. 7d, g). Whether the longitudinal costae are in continuity between successive chambers is unknown. The chambers are mostly clearly spaced and separated by neck-like stolons with outer diameters of ~0.05 to 0.11 mm (Figs. 6a, c, 7k). A conspicuous feature is the presence of a central, straight to slightly bent siphon (entosolenian tube), whose width equals that of the neck-like stolons (Fig. 9). In some sections it appears that the tube represents an inner longitudinal cylinder (Fig. 9a, d, k). In any case, it passes through the whole chamber length (Fig. 9d, k). The thin wall (thickness: ~0.075 to 0.125 mm) appears to be microcrystalline. Its original nature (finely agglutinating?), is unknown. Noteworthy is the common presence of a yellowish fibrous calcitic layer which is interpreted as cement (thickness 0.01–0.03 mm) that lines the interior side of chambers (e.g., Figs. 5i, 6l, 7j).

Comparisons and remarks: The general shape of the test may be similar to that of the (juvenile) uniserial specimens of *Troglotella incrustans* Wernli and Fookes without irregular final stage (Fig. 10). Adult specimens of *T. incrustans* that lack this branching final stage show a distinct enlarged fistulose chamber (Fig. 10a–d). In *T. incrustans*, the chambers are rather closely spaced, either slightly touching at the external sides or separated by very short stolon-like necks (Fig. 10b). In contrast, the chambers of *Siphodinarella costata* are clearly spaced and separated by occasionally rather thick stolon-like necks. Another difference is a smooth unornamented outer surface in *Troglotella incrustans* contrasting with the ribbed test of *Siphodinarella costata*. Both species exhibit a rather thin wall appearing as dark microcrystalline calcite for which a finely agglutinating habitus was assumed by Schmid and Leinfelder (1996). The endolithic or cryptobiotic way of life of *Troglotella* (Wernli and Fookes 1992; Schmid and Leinfelder 1996; Kolodziej 1997; Schlagintweit 2012) is, however, completely different from that of the free-living *Siphodinarella*.

Paleoenvironment: *Siphodinarella costata* is associated with *Thaumatoporella parvovesiculifera* (Raineri) and *Decastronema kotori* (Radoičić) in algal-foraminiferal wackestones. According to Golubic et al. (2006), the latter species is a cyanobacterium comparable to the modern genus *Scytonema* that on Andros Island, Bahamas,

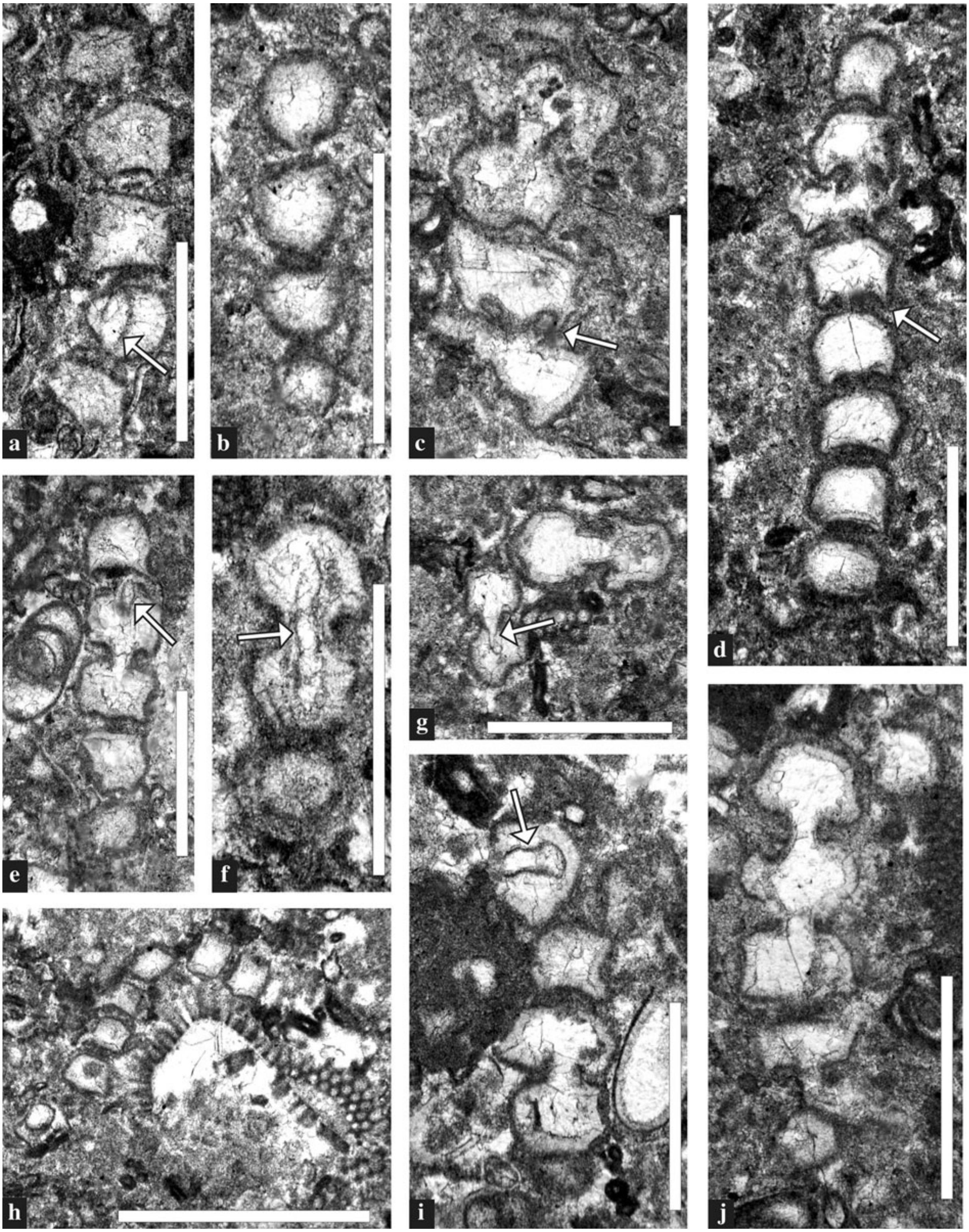


Fig. 8 *Siphodinarella costata* n. gen., n. sp. from the Coniacian of the Island of Mljet, Croatia. **a–j** Different sections, mostly longitudinal to tangential-oblique. Note variable chamber outline from rather regular to more irregular in **c**. The specimen shown in **d** represents the greatest test observed showing also a short initial bend. Note also the offset chamber connection between the third- and second-last chambers. *Arrows* in **c** and **d** display the acute lower margins of some chambers. *Arrows* in **a** and **e–g**, **i** show the entosolenian tube. Thin-section MRS-3. *Scale bars* 0.5 mm

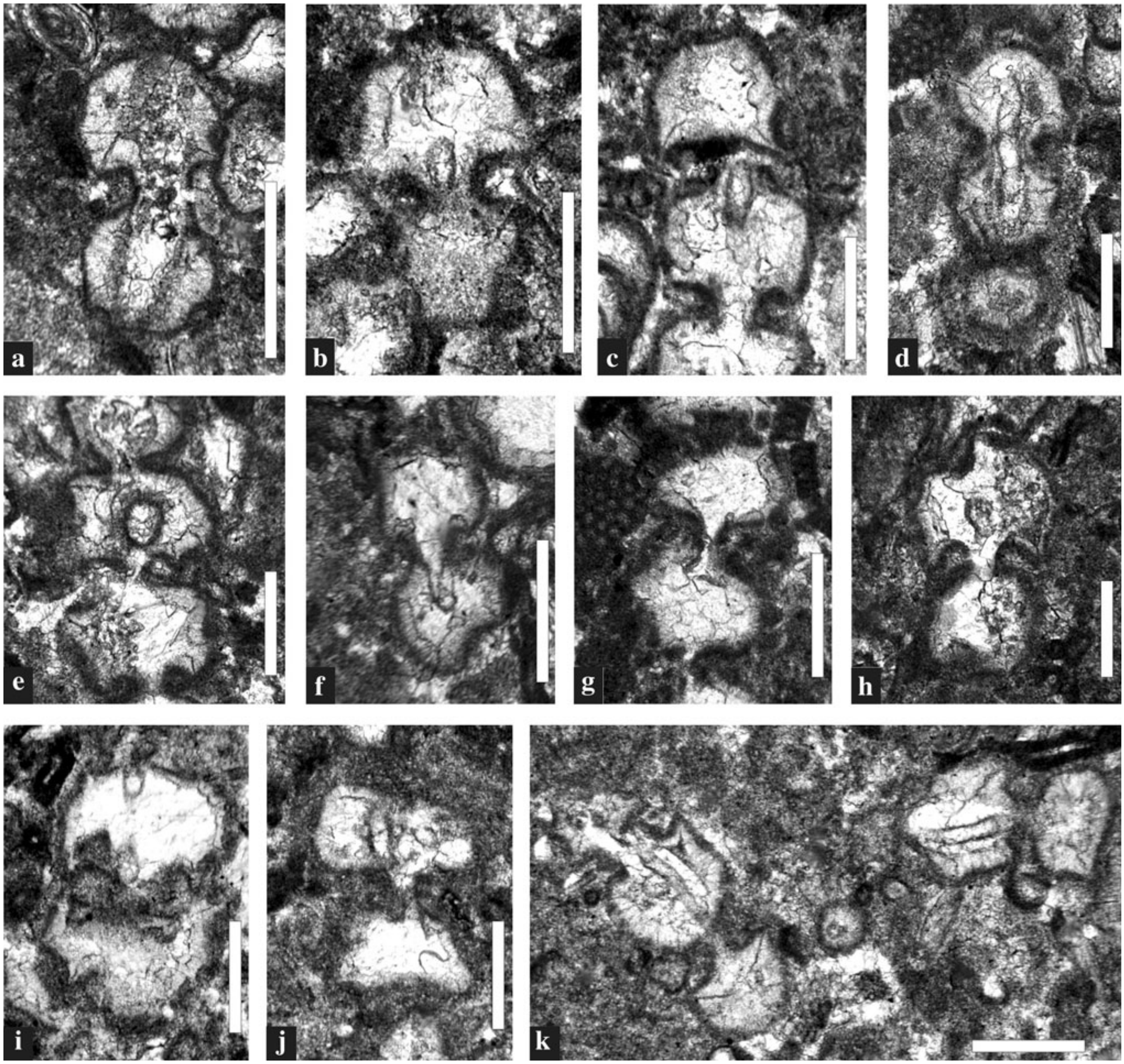
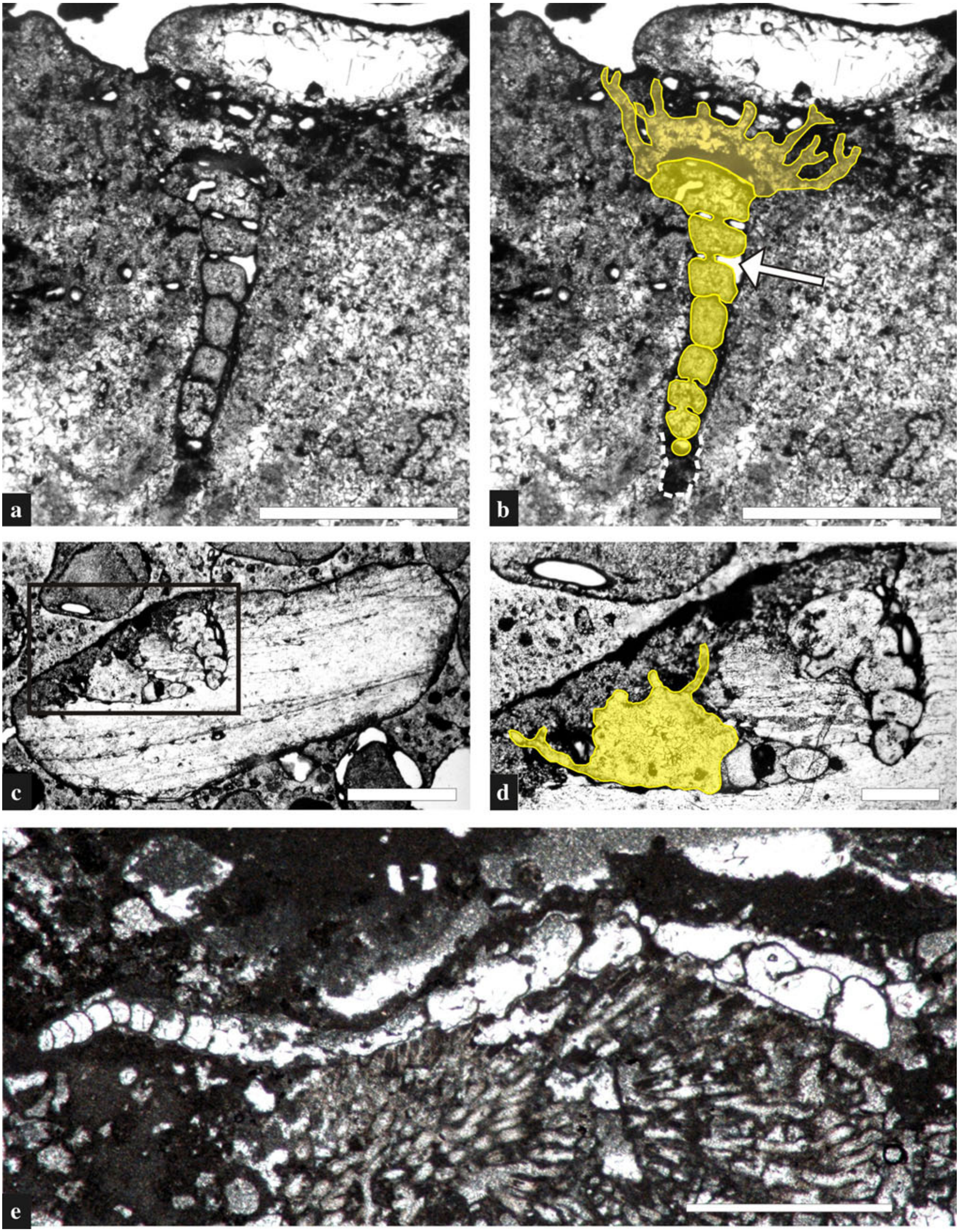


Fig. 9 Specimens of *Siphodinarella costata* n. gen., n. sp. from the Coniacian of the Island of Mljet showing the presence of an entosolenian tube. All from thin-section MRS-3. *Scale bars* 0.2 mm

occupies supratidal environments, i.e., the freshwater, inland algal marshes (Monty and Hardie 1976). Besides *D. kotori*, patches of tiny *Girvanella*-type filaments (Fig. 3c) are also a common microbial constituent of the Upper Cretaceous material studied. This could be an indication that microalgae and cyanobacteria served as a potential food source for *S. costata* and that it possessed a herbivorous feeding habit. The Adriatic platform facies suggests that *Siphodinarella costata* thrived in a low-energy subtidal to tidal flat environments.

Stratigraphy: The only microfossil with relatively short stratigraphic range that occurs in association with *Siphodinarella costata* is *Murgella lata* (*M. lata* partial-range Zone of Velić 2007). The species has been regarded as index foraminifer for the Late Santonian (Luperto Sinni and Richetti 1978; Fleury 1980; Gušić and Jelaska 1990; Cvetko Tešović et al. 2001). On the Adriatic platform, *Murgella lata* is found within the upper part of the Gornji Humac Formation in Croatia (or its equivalent Sežana Formation in Slovenia). However, based on numerical ages derived from strontium-isotope stratigraphy of low-Mg calcite of rudist shells from the island of Brač (Steuber et al. 2005), the upper, *Murgella*-bearing part of the Gornji Humac Formation is of Coniacian age (87.7 Ma), and thus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◀ **Fig. 10** *Troglotella incrustans* Wernli and Fookes from the type-locality, the Kimmeridgian of St. Germain-de-Joux, southeastern France (re-illustration from Schlagintweit 2012, Fig. 4) (**a**–**d**) and the Tithonian of the Crimea Mountains, S-Ukraine (material M. Krajewski) (**e**). **a**, **b** Specimen with rectilinear chambers inside a bored coral exhibiting a final fistulose chamber with branched terminal projections (from Wernli and Fookes 1992, pl. 2, Fig. 5). Note that the test apex does not reach the base of the boring marked by a *white dotted line* in **b**. The *arrow points* to the neck-like chamber connections. *Scale bar* 1 mm. **c** Two specimens boring into a bivalve shell. The *black rectangle* marks the detail shown in **d**. *Scale bar* 1 mm. **d** Detail from **c** (from Wernli and Fookes 1992, pl. 1, Fig. 15) showing the voluminous last fistulose chamber (*yellow-transparent*). *Scale bar* 0.3 mm. **e** Large test with more than 24 rectilinear chambers lacking an irregular final part. The specimen with a total test length of ~4.5 mm (bent!) is interpreted as boring into a calcimicrobial crust that overgrows a rivulariacean-type alga. Thin-section KE 4c. *Scale bar* 1 mm

older than considered previously. To summarize, *Siphodinarella costata* is recorded so far only from the (middle?) Coniacian deposits of the Adriatic Carbonate Platform. It is likely, however, that its stratigraphic range is much wider given its association with the *Thaumatoporella-Decastronema*-type microfacies.

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