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USE OF X-RAY MICRO-COMPUTED TOMOGRAPHY ON SELECTED UPPER TRIASSIC (RHAETIAN) FORAMINIFERA FROM THE WESTERN BLACK SEA SHELF, OFFSHORE ROMANIA

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Abstract. Upper Triassic (Rhaetian) foraminifera belonging to the species *Glomospira charoides* (Jones & Parker), *Gaudryinopsis kelleri* (Tappan), *G. triadica* (Kristan-Tollmann), *Ammobaculites zlambachensis* Kristan-Tollmann, *Verneuilinoides racema* (Trifonova), and *Trochammina* cf. *jaunensis* Brönnimann & Page were investigated using X-ray micro-computed tomography. Foraminifera were recovered from the drill core CM31 of the 817 Lebăda Vest borehole, located off the coast of Romania on the western Black Sea shelf, from depths of 2623 m to 2625 m. Tomographic data was used to generate digital models, which were then virtually sectioned in desirable ways. The acquired transects can be used for comparison with specimens viewed in thin sections, providing a better connection between specimens recovered from residues and those observed in thin sections using transmitted light microscopy.

Introduction

Foraminifera are unicellular eukaryotes characterised by a network of granular pseudopodia, with most having an outer cover, usually a test (Loeblich & Tappan 1988; Sen Gupta 1999). Foraminiferal tests are often encountered in thin sections of carbonate rocks, in residues of poorly lithified rocks and sediments, or in residues extracted by cold acetolysis. Determination of fossil taxa can be rather difficult when a specimen from the residue is compared to the type material of a species presented in thin section (or vice-versa). This is often the case with Triassic foraminifera: type specimens are shown either in thin sections or isolated as a residue. However, only a few papers show both the external and internal features of a certain foraminiferal species (e.g. Trifonova 1965, 1967; Langer 1968; Fuchs 1975; Heath & Apthorpe 1986; Kristan-Tollmann 1988; Vettorel 1988; Haig & McCartain 2012). The traditional method of obtaining two-dimensional transects from three-dimensional specimens is to embed the specimen in resin and then cut it in the desirable orientation. This procedure is relative-

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ly cheap, but results in destruction of the specimen, and getting the right transect may sometimes require destroying more than one specimen. In addition, very small specimens are difficult to orient and cut on the desirable plane. The advent of micro-computed tomography (micro-CT) introduced a non-destructive technique for the study of external as well as internal features of foraminifera (Baumgartner-Mora et al. 2006; Speijer et al. 2008; Briguglio et al. 2011; Görög et al. 2012; Briguglio et al. 2013; Gooday et al. 2018; Schmidt et al. 2018; Kellner at al. 2019), as well as many other microfossils (Sutton et al. 2014). Tomographic data obtained through X-ray detection can be used to create virtual models of the specimens, which can then be interactively dissected in any desirable plane (Sutton 2008). The micro-CT scans, however, only show a fossil properly when it is well contrasted (mineralogical or density) with the matrix surrounding and filling it. This condition is often met with geologically young material, but it can present considerable problems in older material (Baumgartner-Mora et al. 2006; Görög et al. 2012).

Tests of agglutinated foraminifera obtained from the Upper Triassic (Rhaetian) limestone on the western Black Sea shelf, off the coast of Romania, are largely composed of quartz grains and are only partly, if at all, filled with internal cement. They are thus suitable for micro-CT investigation. Many of the investigated species were poorly known from both the thin-sections and the residue studies. We created digital models of *Glomospira charoides* (Jones & Parker, 1860), *Gaudryinopsis kelleri* (Tappan 1955), *G. triadica* (Kristan-Tollmann, 1964), *Ammobaculites zlambachensis* Kristan-Tollmann, 1964, *Verneuilinoides racema* (Trifonova, 1962), and *Trochammina* cf. *jaunensis* Brönnimann & Page, 1966, which allow either reliable determinations from thin sections or from the study of their inner architectures. Although the determined taxa have simple architectures, to our knowledge they represent the first Triassic foraminifera investigated in this way.

Geological Setting

The studied material was taken from the drill core CM31 of the 817 Lebăda Vest (817 LV) borehole drilled in the Histria Depression lying in the Romanian sector of the western Black Sea shelf, which structurally belongs to the eastern offshore extension of the North Dobrogean Orogen (Fig. 1).

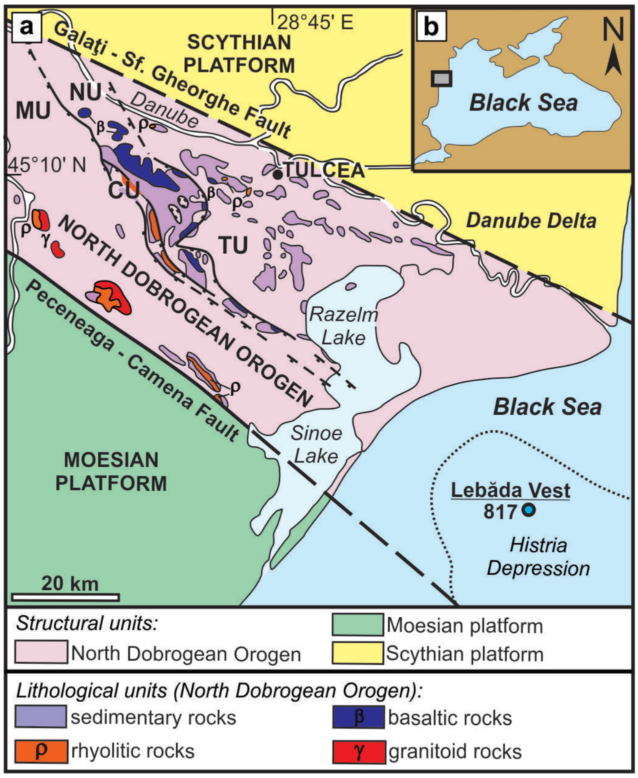

Fig. 1 - Structural position of the studied area. a) Tectonic structure of the North Dobrogean Orogen and its offshore extension in the NW Black Sea margin, with the location of the 817 Lebăda Vest borehole (blue circle). Abbreviations: MU-Măcin Unit, CU-Consul Unit, NU-Niculiţel Unit, TU-Tulcea Unit. b) The geographic position of the North Dobrogean Orogen. The grey rectangle shows area depicted in Figure 1a.

The North Dobrogean Orogen (NDO) is located in the foreland of the Alpine Carpathian Orogen (Săndulescu 1984, 1995), lying in the northern part of Dobrogea, a Romanian province bordered by the Black Sea to the east, and by the Danube Delta to the north. From a structural point of view, the NDO is bounded by the Galaţi-Sf. Gheorghe Fault to the north, and by the Peceneaga-Camena Fault to the south. The two faults separate the NDO from the epi-Caledonian Scythian Platform and the epi-Baikalian Moesian Platform, respectively.

The North Dobrogean Orogen represents the westernmost extension of the Palaeo-Tethyan Cimmerian Orogenic System that also includes the Mountainous Crimea and the Great Caucasus and extends further east to the Asian Cimmerides (Săndulescu 1980, Şengör 1984). The NDO is a fold-and-thrust belt that consists of several tectonic units, a set of thrusts showing a north-eastward vergency (e.g. Visarion et al. 1990; Săndulescu 1995), including the Măcin Unit in the uppermost position, and

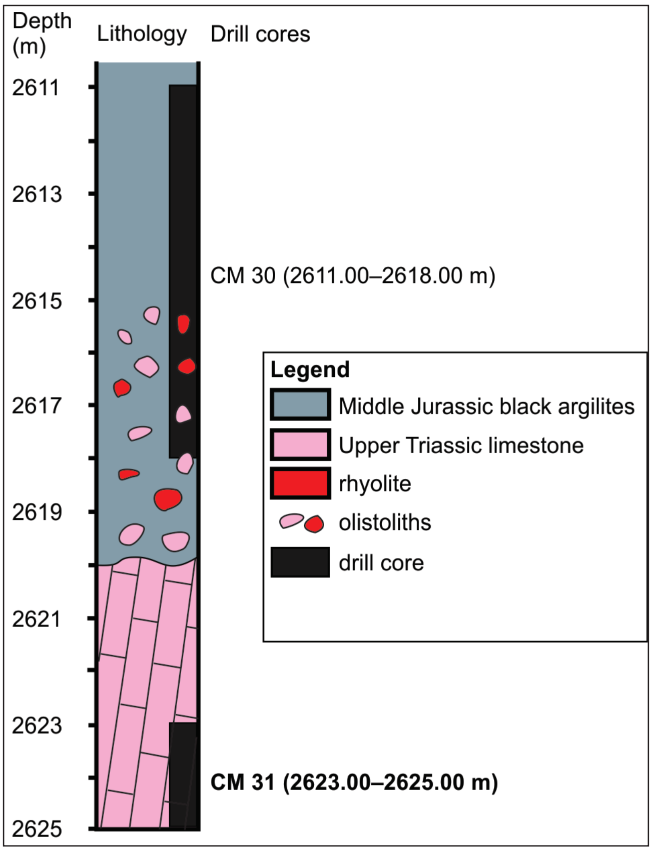

Fig. 2 - Stratigraphic log of the 817 Lebăda Vest borehole, showing the location of the drill core CM31 that delivered the studied Upper Triassic (Rhaetian) foraminifera.

the Consul Unit, the Niculiţel Unit, and the Tulcea Unit in the lower positions (Fig. 1a). The NDO experienced an extensional tectonic regime from the Early Triassic to the mid-Carnian and started to be inverted and telescoped by thrusting during the early Mesozoic Cimmerian orogeny and ending during the mid-Cretaceous Alpine tectonogenesis, being overstepped by the Vraconian-Late Cretaceous sedimentary series of the post-tectonic Babadag Basin (Mirăuţă & Mirăuţă 1964; Burchfiel & Bleahu 1976; Grădinaru 1995, 2004, 2006; Lodowski et al. 2019).

The paleogeographic location of the NDO during the Late Triassic is discussed by Gaetani et al. (2000, 6.1), with the sedimentary area positioned somewhere on the European, northward subducting margin of the Palaeo-Tethys. The Triassic succession has the largest areal extension and the most complete stratigraphic development in the Tulcea Unit. Here, the Triassic rocks unconformably overlie the Variscan basement, and are developed both in basinal and carbonate platform facies (Grădinaru 1995, 2000). The median tectonic unit of the NDO, i.e. the Niculiţel Unit, consists of sub-oceanic Triassic deep-water cherty-carbonate sediments interlayered or pierced by basaltic lava flows, without implying an oceanic spreading steady-state (Savu 1986; Seghedi 2001; Saccani et al. 2004). The Triassic sedimentary cover of the Măcin Unit, which was largely dismantled starting with the inception of its thrusting, is now preserved only on the northern side of the Peceneaga-Camena Fault, along the Cârjelari-Camena Zone (Grădinaru 2006). Besides the Middle Triassic basaltic rocks that characterize the Niculiţel Unit, Lower to Middle Triassic rhyolitic and granitic rocks are also present in most of the internal tectonic units of the North Dobrogean Orogen (Fig. 1b).

While the Triassic rocks are widely represented in the onshore area of the North Dobrogean Orogen (Grădinaru 1995, 2000), these were only sampled offshore in a few of the boreholes drilled in the Romanian sector of the western Black Sea basin (Grădinaru et al. 1989; Cătuneanu & Maftei 1994; Ţambrea et al. 2002; Dinu et al. 2005). The borehole 817 Lebăda Vest (817 LV) is located in the area of the Histria Depression rimmed by the so-called Euxinic threshold, i.e. the shelf break of the Paleogene continental shelf (e.g. Dinu et al. 1989, 2005). After drilling through Cretaceous carbonates and Middle Jurassic black argillites, a Triassic limestone was reached at a depth of 2620 m (Fig. 2). A three-meter core drill, CM31, was sampled at the bottom of the borehole (2623.00 to 2625.00 m). As suggested by the numerous Triassic limestone clasts found in the drill core CM30 (Fig. 2), the Triassic limestone drilled in the drill core CM31 most likely represents an olistolith embedded in Middle Jurassic black argillites (Grădinaru, unpublished data). The limestone is light brownish grey in colour, compact and hard, with splintery cracking and thin veins of calcite or black clay. The limestone is homogenous throughout the core's length and does not display any sedimentary structure, implying that it was drilled more or less along bedding. The ostracod assemblage recovered from the limestone contains some typical Rhaetian species (Forel & Grădinaru 2020). Other fossils, such as brachiopods, also constrain the Rhaetian age (Grădinaru et al. 1989; Forel & Grădinaru 2020).

Material and methods

Triassic limestone from the 817 LV borehole has been sampled from a two-meter-thick drill core (metres 2623 to 2625; sample CM31 on Fig. 2). Foraminifera were obtained from residue by cold acetolysis with buffered 5% acetic acid in the Laboratory of Palaeontology, University of Bucharest. Specimens were photographed using the JEOL JSM 6490LV Scanning Electron Microscope at the Geological Survey of Slovenia. The specimens were mounted on a sample holder by double-sided carbon tape. A thin coating of carbon was applied to the surface of the specimens prior to scanning.

The mineral composition of the wall was determined in the backscattered electron (BSE) mode in a high vacuum using the Oxford INCA Penta FETx3 Si(Li) detector and INCA Energy 350 processing software, at 20 kV accelerating voltage, spot size 50- and 10 mm-working distance. The chemical composition of minerals was measured using the EDS X-ray point analysis with an acquisition time of 60 s. Minerals were assessed by calculating stoichiometric ratios from atomic % of constituent elements acquired by the semi-quantitative X-ray microanalysis, and a comparison with the atomic proportions of constituent elements in known minerals. The software was calibrated for quantification using premeasured universal standards included in the EDS software referenced to a Co optimisation standard. The EDS data was corrected on the basis of the standard ZAF correction procedure included in the INCA Energy software (Oxford Instruments 2006).

The selected specimens were further investigated using XRadia CT-400 tomography (XRadia, Concord, California, USA) at the Slovenian National Building and Civil Engineering Institute. A spatial resolution of 0.9 µm for 1 pixel was adopted using a ×20 magnification optical lens. The beam energy and the intensity were set to 80 kV and 7 W, respectively. For each specimen, 1600 projection images at an exposure time of 2 seconds per projection were captured through the charge-coupled device (CCD) camera. Digital models were created with Avizo Fire 3D-image analysis software. For comparison, oriented thin sections were made from specimens immersed in resin. For a description of the chamber arrangement and the shape of its aperture we follow the terminology in Hottinger (2006), and Arenillas et al. (2017).

Foraminifera

The species investigated with micro-CT comprise *Glomospira charoides* (Jones & Parker, 1860), *Gaudryinopsis kelleri* (Tappan, 1955), *G. triadica* (Kristan-Tollmann, 1964), *Ammobaculites zlambachensis* Kristan-Tollmann, 1964, *Verneuilinoides racema* (Trifonova, 1962), and *Trochammina* cf. *jaunensis* Brönnimann & Page, 1966. All of the described species have agglutinated walls, made predominantly of quartz grains. Most of the lumen is free of the matrix; some chambers (especially the ones closest to proloculus) are filled with cement (e.g. see Fig. 5). The mentioned taxa are described in the following text. The described species are shown in Figures 3–9.

Subphylum **FORAMINIFERA** d'Orbigny, 1826
Class **Globothalamea** Pawlowski, Holzmann & Tyszka, 2013
Order "**Textulariida**" Delage & Hérouard, 1896
Superfamily Ammodiscacea Reuss, 1862
Family Ammodiscidae Reuss, 1862
Subfamily Usbekistaniinae Vyalov, 1968

Genus *Glomospira* Rzehak 1885, emend. Kaminski & Gradstein, 2005

Glomospira charoides (Jones & Parker, 1860)

Fig. 3 a–i

L 1860 *Trochammina squamata charoides* Jones & Parker, p.304.
? 1975 *Glomospira* sp. - Gaździcki et al., pl. 12, fig. 3, 11-12.
cf. 1991 *Glomospira charoides* (Jones & Parker, 1860) - Samuel, p.19, pl. 15, fig. 1-2.
2005 *Glomospira charoides* (Jones & Parker, 1860) - Kaminski & Gradstein, p.168, fig. 22, pl. 22, fig. 1-16.

Description. The test is isometric, circular in shape, consisting largely of an undivided half-tube chamber. The proloculus is poorly visible. It could be first encircled by one volution of the deuteroloculus, which then changes direction of coiling by 90°, or is directly enveloped by the deuteroloculus, winding from one side of the test to the other. After the proloculus (and/or the first coil of the deuteroloculus?) follow three complete and one partially complete volution phases. During each phase the deuteroloculus covers the test from one pole to the other, so that successive coils run parallel and closely touch (partly cover) each other until the opposite pole is reached. The coiling then continues in the same fashion, but in the opposite direction. The first of these phases counts four coils, the second comprises 4–5 coils, and the third 5 or 6 coils. The partially complete phase (Fig. 3d) comprises only one and a half coils.

The half-tube diameter is 0.042–0.055 mm. The wall is nonlamellar, unperforated, 0.013 mm (or several grains) thick. It is composed of clay- to silt-size grains of quartz, smoothly finished on both the inner and outer side. The entire test is 0.21 mm in diameter.

Remarks. According to Loeblich and Tappan (1988), the agglutinated wall, the simple structure of the test (proloculus followed by undivided tubular second chamber) and the described way of coiling well coincide with the definition of the genus *Repmanina* Suleymanov in Arapova and Suleymanov, 1966. According to Loeblich and Tappan (1988), the latter genus differs from *Glomospira* Rzehak, 1885 in terms of coiling, which is in *Glomospira* streptospiral to irregular. However, Kaminski and Gradstein (2005) emended the description of *Glomospira* so that the diagnosis of the genus reads that the tubular second chamber is initially coiled trochospirally about a common axis. The genus *Rep-*

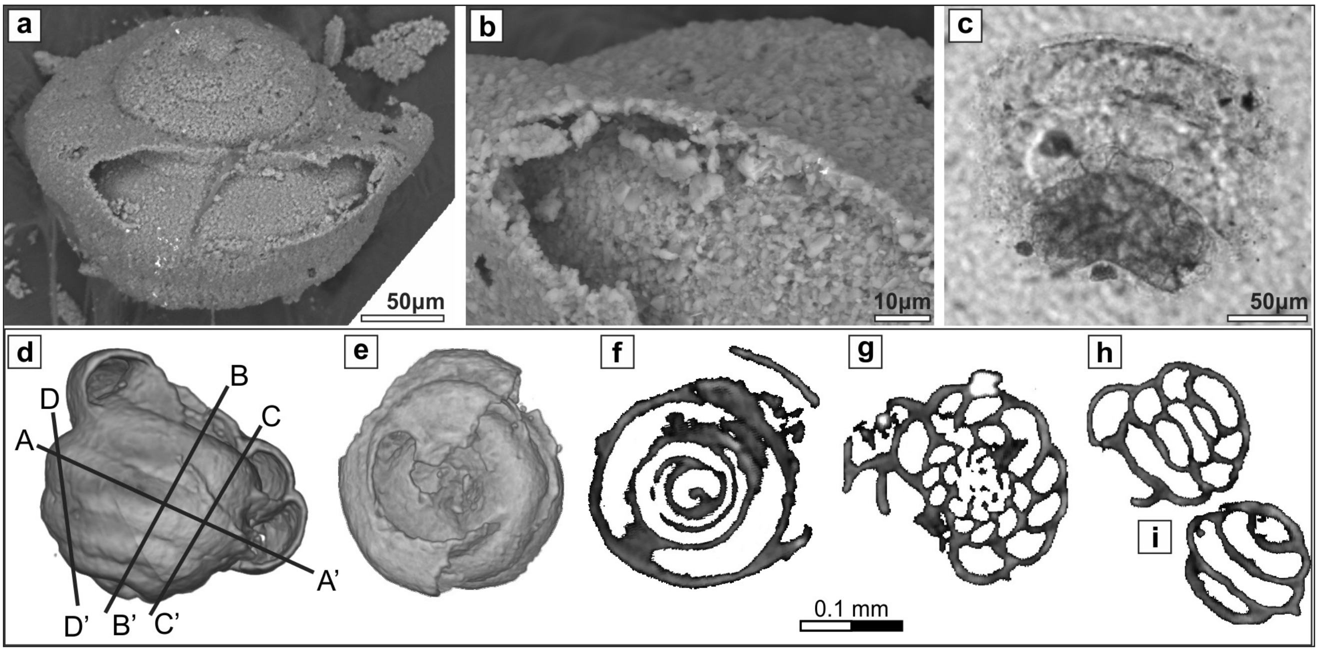

Fig. 3 - *Glomospira charoides* (Jones & Parker, 1860). a) SEM image of the exterior of the test. BEC mode. b) Close-up view on the wall. Note its granular texture. BEC mode. c) Oblique section through the test in a thin section. d–i - Images obtained through micro-CT scans. d) Digital "side" view of the exterior. Lines indicate orientations of virtual transects figured in f–i. e) "Polar" view on the test. f: Transect A–A'. g: Transect B–B'. h: Transect C–C'. i: Transect D–D'.

manina was thus considered to be a junior synonym of *Glomospira*, and the latter was transferred to the subfamily Usbekistaniinae Vyalov, 1968.

The holotype of *G. charoides* measures 0.4 mm in diameter, and the lectotype 0.27 mm (Kaminski & Gradstein 2005). Kaminski and Gradstein (2005) argue that this species shows a wide range of ontogenic phases and sizes, which results in a long list of synonyms or possible synonyms described from Jurassic rocks to recent samples. The size of the specimens from the 817 Lebăda Vest borehole is almost half of the size of the original type specimen, but very close to the size of the lectotype, and the specimens clearly fit into the genetic variability of *G. charoides* illustrated by Kaminski and Gradstein (2005). Specimens of *Glomospira* sp. in Gaździcki et al. (1975) from Anisian show up to three almost planispiral coils in the last part of the test. The specimens illustrated by Samuel (1991) are also only 0.09–0.2 mm in diameter, but show less coils on the outside. The interior of the specimens illustrated by Gaździcki et al. (1975) and Samuel (1991), however, is not visible.

Today, *Glomospira charoides* is present in most deep-sea environments, but it can also be found on shelf areas. It can also tolerate oxygen-deficient environments (Kaminski & Gradstein 2005).

Distribution and age. The current stratigraphic range of *Glomospira charoides* is from Jurassic to Recent according to Kaminski and Gradstein (2005). Besides the specimens from the Rhaetian limestone from the 817 Lebăda Vest borehole, this species was also reported from Anisian by Gaździcki et al. (1975), and from the Upper Triassic by Samuel (1991), respectively. The stratigraphic range of *G. charoides* should therefore be extended to the Rhaetian, and possibly to the Anisian.

Superfamily Lituolacea de Blainville, 1827
Family Lituolidae de Blainville, 1827
Subfamily Ammomarginulinae Podobina, 1978
Genus *Ammobaculites* Cushman, 1910

Ammobaculites zlambachensis Kristan-Tollmann, 1964

Fig. 4a–o

1964 *Ammobaculites zlambachensis* Kristan-Tollmann, p.36, pl. 4, fig. 5-7.
? 1983 *Ammobaculites alveolatus* n. sp. - Salaj et al., p.73, pl. 17, fig. 2.
1990 *Ammobaculites zlambachensis* Kristan-Tollmann, 1964 - Kristan-Tollmann, fig. 8.11-8.16; Pl. 1, fig. 11-13, 17-18.
2014 *Ammobaculites* cf. *zlambachensis* Kristan-Tollmann - Nagy et al., fig. 7.15.

Description. The test is elongated, compris-

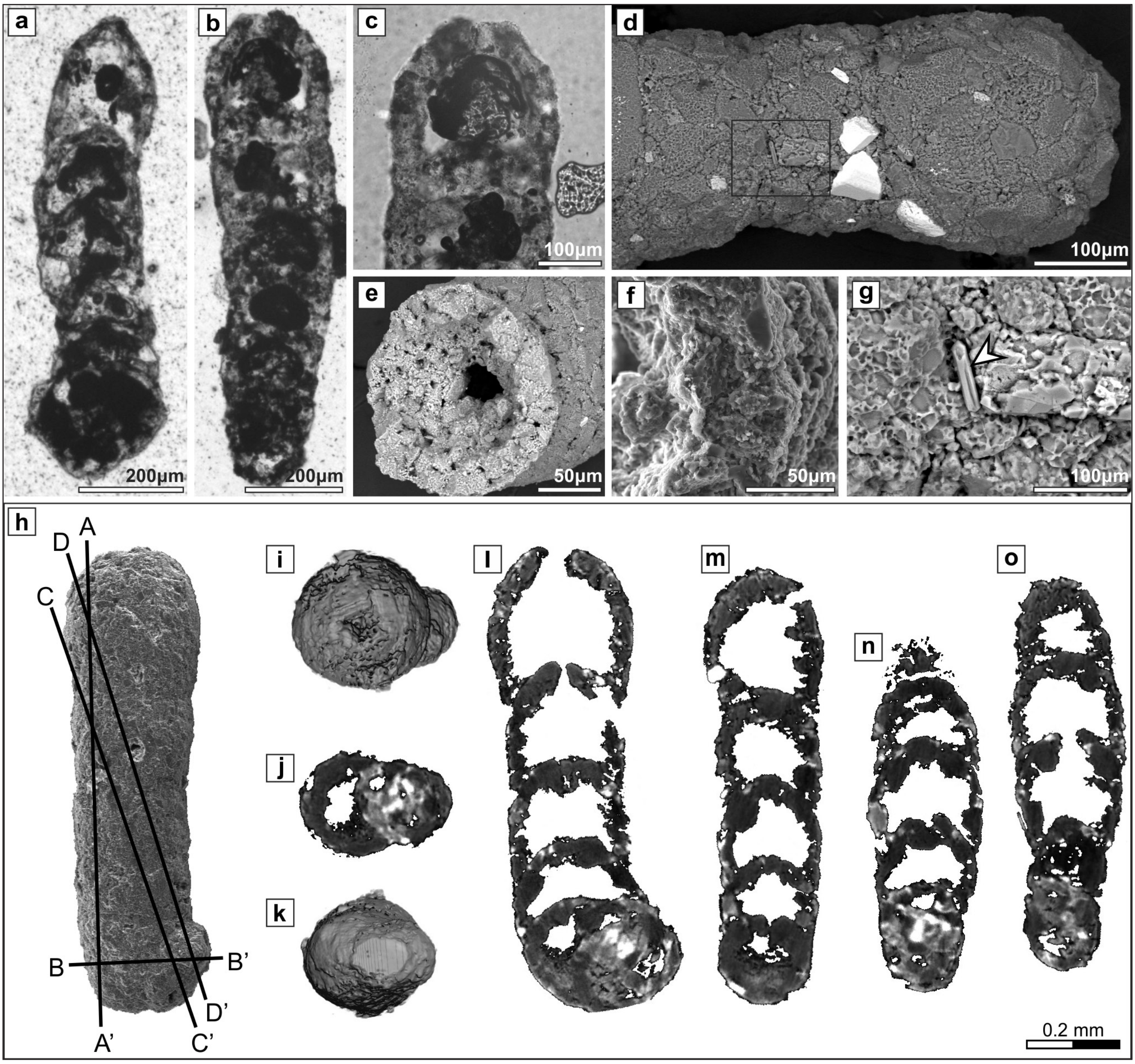

Fig. 4 - *Ammobaculites zlambachensis* Kristan-Tollmann, 1964. a) Longitudinal transect in thin section. Part of the chambers is filled by pyrite. b) Tangential transect in thin section. c) The last chamber with a central position of the aperture. Thin section. d) SEM image of the coarsely agglutinated wall. The rectangle shows the position of Fig. 4g. BEC mode. e) View on the distal part of the chamber, with a foramen at the centre. Note the openings in the wall, considered to be unfilled space between ill-fitting larger grains. SEM image, BEC mode. f) Transect perpendicular through the wall. SEM image, SEI mode. g) Grain of zircon (arrowhead) incorporated in the wall. SEM image, BEC mode. h) SEM image of the exterior of the test, SEI mode. Lines indicate orientations of virtual transects figured in 4j, l–o. i) Apertural view from the digital model. j) Axial/transverse transect B–B'. k. Bottom (proximal) view from the digital model. l) Equatorial/longitudinal transect. m) Tangential transect A–A'. n) Oblique transect C–C'. o) Oblique transect D–D'.

ing an initial planispiral part made of four chambers (only one whorl is clearly visible), and a uniserial second part consisting of two to five chambers. Chambers in the planispiral part are wedge-like, and later cylinder-shaped. The last chamber is distinctly longer than the preceding ones, almost equidimensional (lumen height 0.202 mm; width 0.196 mm). The ratio between the height and the width in the last three chambers decreases from 1.5 to 1.26 and to 0.92 for the last chamber. Chamber sutures are shallow, yet easily distinguished. The apertural face is wide and well-rounded. The aperture is in the last part centrally located, damaged, but probably simple rounded. The test wall is nonlamellar, coarsely agglutinated, 0.053 mm thick, in transect composed of a single layer of large grains, or of a multitude of smaller particles (in the space between larger particles). Zircon, undetermined aluminosilicate, rutile, and quartz grains were determined among larger grains. They are held in place by smaller, silt-size grains of quartz. On the outer side of the wall, the grains are oriented in such a way that they form a smooth surface. In contrast, on the inner side the grains are randomly oriented, which results in a more uneven inner wall surface. On the SEM images, relatively large openings can be seen, especially on the inner side of the wall. They vary in size, shape, and length. They are relatively widely and probably irregularly spaced. At least some are connected within the wall, and most do not reach the outer surface. Based on their size, the openings could be alveolae, but due to the wide spacing between them, they are currently considered to be unfilled space between larger grains on the more uneven inner side of the wall (the result of the absence of an inner organic layer in fossil specimens; see Mendelson 1982). No perforations are visible in the thin sections. The planispiral part is 0.22 mm high and measures 0.30 mm in diameter. The rectilinear part is up to 0.55 mm long. The entire test is slightly wider in the planispiral part than in the rectilinear one. The total test height is 0.39–1.17 mm.

Remarks. The specimens from the 817 Lebăda Vest borehole are indistinguishable from those illustrated in Kristan-Tollmann (1990). Specimens illustrated in Kristan-Tollmann (1990) have between three and seven chambers in the uniserial part. A very characteristic feature of the species is the slightly elongated last chamber with a well-rounded apertural face, which can be seen also in thin sections (e.g. Salaj et al. 1983; Nagy et al. 2014). This, together with dimensions and the number of chambers, allows this species to be distinguished from other species of *Ammobaculites* in thin sections. The species differs from species of the genus *Endotebanella* Vachard, Martini, Rettori & Zaninetti, 1994 in the coarsely agglutinated wall (seen also in thin sections; e.g. see the specimen in Nagy et al. 2014). A possible junior synonym of *A. zlambachensis* is *Ammobaculites alveolatus* Salaj, Borza & Samuel, 1983 from the Carnian of the Carpathians. The species was illustrated in a single oblique section.

Distribution and age. Ladinian of the Topolca Basin, western Hungary (Nagy et al. 2014), Carnian of the Western Carpathians (Salaj et al. 1983), Rhaetian of Northern Calcareous Alps, Austria (Kristan-Tollmann 1964), Papua New Guinea (Kristan-Tollmann 1990), Early Jurassic of Northern Calcareous Alps, Austria (Ebli 1993).

Superfamily Verneuilinacea Cushman, 1911
Family Verneuilinidae Cushman, 1911
Subfamily Verneuilinoidinae Suleymanov, 1973
Genus *Gaudryinopsis* Podobina, 1975

Gaudryinopsis triadica (Kristan-Tollmann,1964)

Fig. 5a–m

1964 *Gaudryina triadica* Kristan-Tollmann, p.47, pl. 7, fig. 12.
non 1983 *Gaudryina triadica* Kristan-Tollmann, 1964 - Salaj et al., p.78, pl. 25, fig. 1-3; pl. 26, fig. 5.
?non 1984 *Gaudryina triadica* Kristan-Tollmann - Kristan-Tollmann, pl. 15, fig. 5.
?non 1987 *Gaudryina* cf. *triadica* Kristan - Oravecz-Scheffer, pl. 66, fig. 6.
?non 1987 *Gaudryina triadica* Kristan - Oravecz-Scheffer, pl. 85, fig. 5-7.
?non 1996 *Gaudryina triadica* Kristan-Tollmann - Pronina & Vuks, pl. 1, fig. 11.
?non 1996 *Gaudryina* cf. *triadica* Kristan-Tollmann - Kobayashi, fig. 4.23-4.24.
?non 2005 *Gaudryina triadica* Kristan-Tollmann - Kobayashi et al., fig. 8.56-8.58.
?non 2006 *Gaudryina triadica* Kristan-Tollmann - Kobayashi et al., fig. 4.33-4.36.

Description. Specimens are robust and laterally slightly compressed. A short triserial part of the test (taking 26% of the test height, 2 whorls?) is followed by a biserial part. The triserial part (0.185 mm long) consists of three series of chambers. The sides diverge at 60° (Fig. 6a). The biserial part is 0.5 mm long, comprising four pairs of chambers. The sides of the test here diverge at 25°. Chamber sutures are perpendicular to the outer margin (but slightly oblique to the central axis). In a side view, each succeeding pair of chambers covers one half of the height of the previous chamber. The last chamber lumen is approximately 0.116 mm high and 0.200 mm wide. The aperture is a moon-like lateral slit (see Arenillas et al. 2017). The wall is coarsely agglutinated, one or several grains thick, comprising larger particles of aluminosilicates, rutile, and quartz, and clay- to silt-sized grains in the intermediate space. The outer surface is smoothly finished, whereas the inner side is rough, with spaces left between the larger particles (as in *A. zlambachensis*, described above). No perforations are present. The largest thickness of the wall is 0.04 mm. The total test height is 0.7 mm. The width in the last part is 0.42 mm.

Remarks. The holotype of this species is an isolated specimen recovered from the residue (Kristan-Tollmann 1964). Several authors determined this species in thin sections, but these determina-

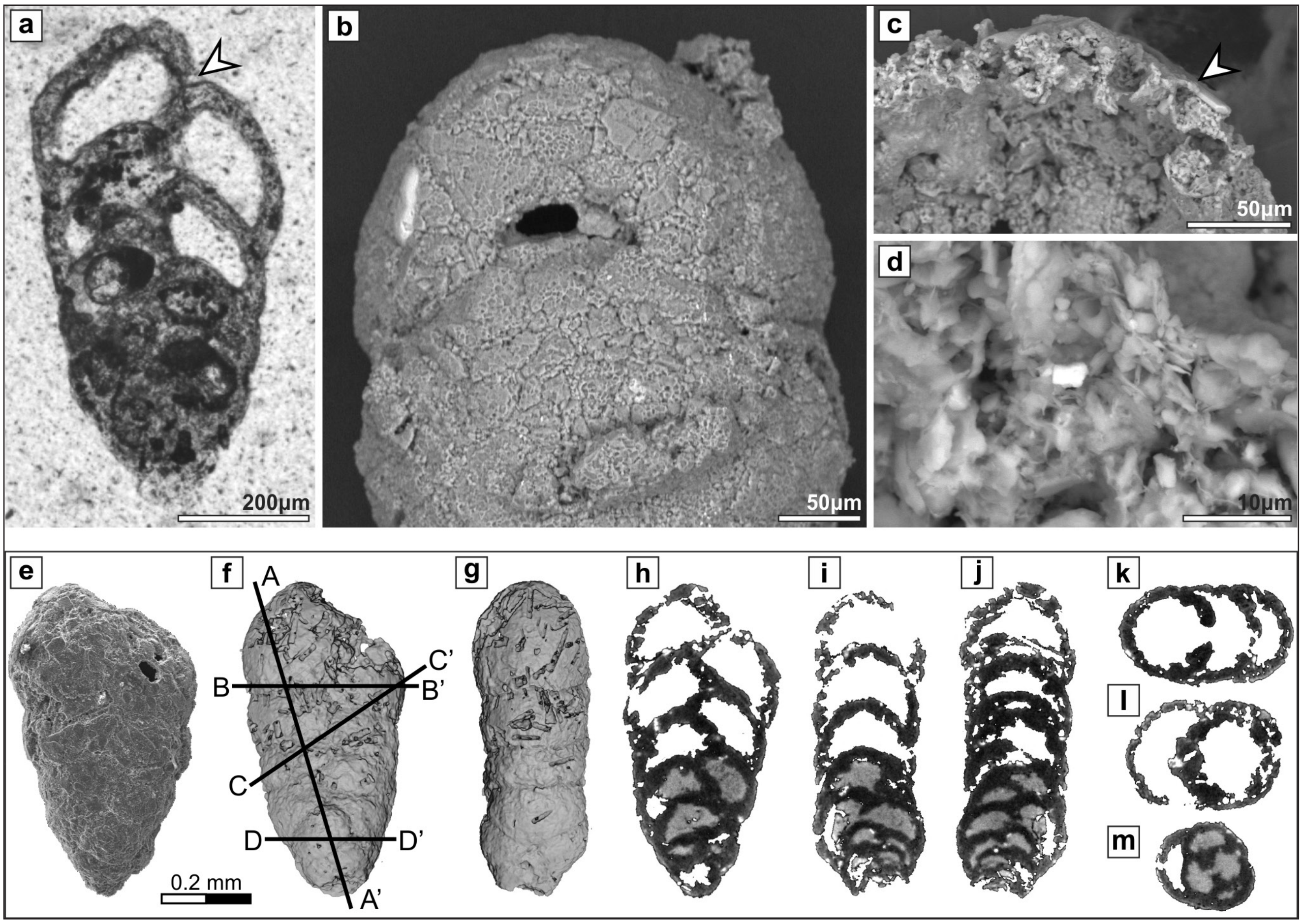

Fig. 5 - *Gaudryinopsis triadica* (Kristan-Tollmann, 1964). a) Axial transect in thin section. Arrowhead points at the aperture. b) Apertural view. The aperture is a moon-like slit. SEM image, BEC mode. c) Transect of the wall. Arrowhead points at a large aluminosilicate grain, placed parallel to the surface. Note also the highly irregular inner side of the wall. SEM image, BEC mode d) Detail of the wall, composed of different mineral grains. SEM image, BEC mode. e) SEM image of the exterior, SEI mode. f) Longitudinal view from the digital model. Lines indicate orientations of virtual transects figured in h–m. g) Side view from the digital model. h) Frontal longitudinal transect. i) Side-view longitudinal transect. j) Transect A–A'. k) Transect B–B'. l) Transect C–C'. m) Transect D–D'. Note the cement-filled chambers in the lower part of the test (light-grey infill in figures h–j, m).

tions are not reliable (e.g. Kristan-Tollmann 1984; Oravecz-Scheffer 1987; Kobayashi 1996; Kobayashi et al. 2005, 2006). Helpful criteria could be the outline of the test, with less diverging sides in the later stage of growth, and the shape of lumen in the longitudinal section (see Figs. 5a, h). Specimens figured in Salaj et al. (1983) have a long biserial part and nearly parallel sides of the test, and are not considered here to belong to *G. triadica*. The specimen illustrated by Pronina and Vuks (1996) has too many chambers in the biserial part.

Distribution and age. Carnian of Kumaun, Himalaya, India (Kristan-Tollmann 1984), Norian and/or Rhaetian of Sambosan Accretionary Complex, Japan (Chablais et al. 2010), and Transdanubian Range, Hungary (Oravecz-Scheffer 1987), Upper Norian or Rhaetian of Crimea (Kotlyar et al. 1999) and Western Caucasus, Russia (Vuks 2004), Rhaetian of the Northern Calcareous Alps, Austria (Kristan-Tollmann 1964).

Gaudryinopsis kelleri (Tappan, 1955)

Fig. 6a–i

1955 *Gaudryina kelleri* Tappan, n. sp. - Tappan, p.47, pl. 13, fig. 19.
pars 1962 *Gaudryina triassica* n. sp. - Trifonova, p.169, pl. 3, 14-17 [non fig. 18].
1990 *Gaudryina kelleri* Tappan, 1955 - Kristan-Tollmann, fig. 9.10-9.14; pl. 2, fig. 6-9, 11; pl. 3, fig. 3.
?non 2010 *Gaudryinopsis kelleri* (Tappan, 1955) - Haig & McCartain, p.381, Fig. 6.28-6.31.
2010 *Gaudryinopsis triassica* (Trifonova, 1962) - Haig & McCartain, p.382, Fig. 6.32-6.34.

Description. A highly elongated, small and slender foraminifera. A very short triserial initial part (12% of the total test height; length 0.037 mm; three whorls) is followed by approximately eight pairs of biserial chambers. The test is laterally

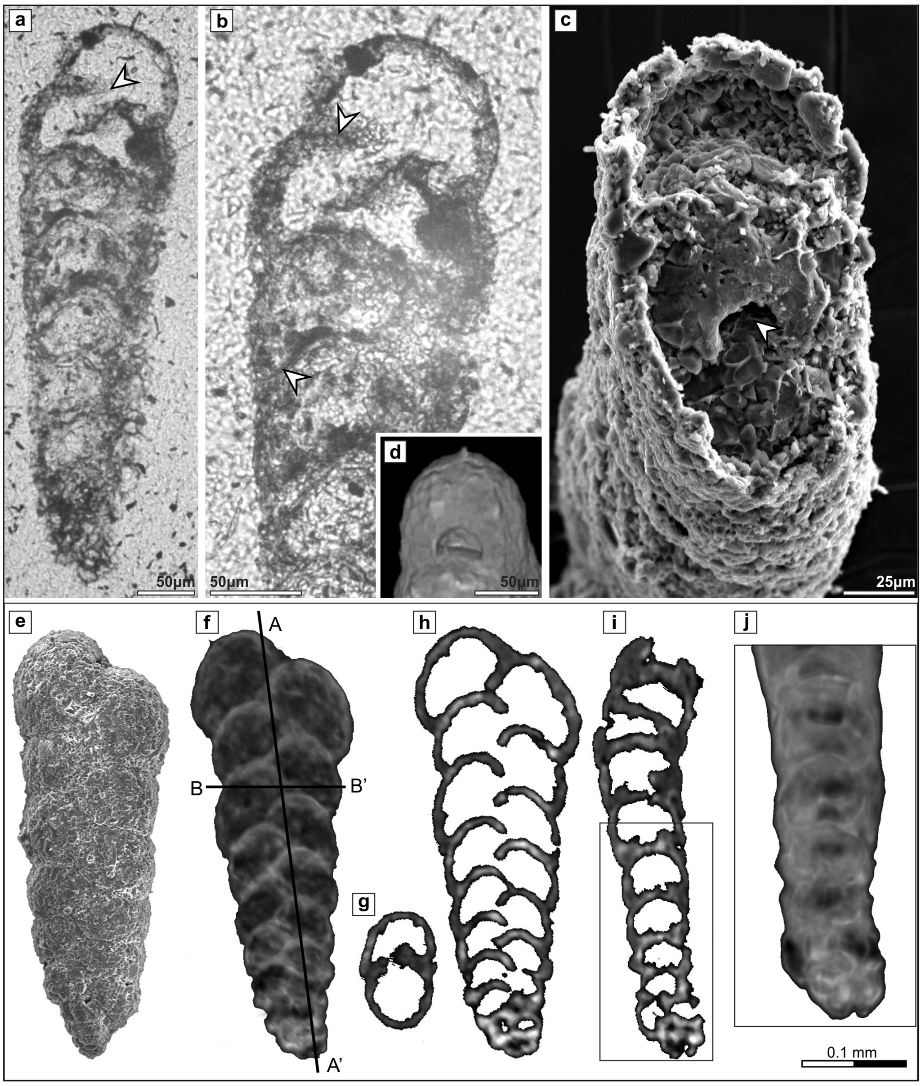

Fig. 6 - *Gaudryinopsis kelleri* (Tappan, 1955). a) Side longitudinal transect in thin section. The arrowhead points at the foramen (lateral – see Arenillas et al., 2017). b) Close-up of the distal part of the test in a side longitudinal view. Arrowheads point to dark linings within the wall. c) View towards the apertural face of the chambers. Arrowhead points to the half-circular foramen. Note the agglutinated nature of the wall (one or several grains thick, depending on the size of the grains). SEM image, SEI mode. d) The half-circular aperture. Micro-CT image. e) View of the exterior. SEM image, SEI mode. f) Transparent micro-CT scan of the specimen; frontal view. Lines indicate orientations of virtual transects figured in g and i. g) Transverse section B–B'. h) Longitudinal section, frontal view. i) Longitudinal section, side view A–A'. j) Partly transparent side view of the proximal part of the specimen (see fig. h for position of the image).

compressed. Its sides first diverge at 65°, but later become almost parallel-sided. The apertural face is rounded. The aperture is lateral, half-circular. The wall is coarsely agglutinated, 0.010 mm thick, and probably unperforated. It consists of larger, silt-size quartz and aluminosilicate mineral grains that span the entire thickness of the test, as well as clay-sized particles of the same mineralogy in the intermediate space. The total test height is very variable. The figured specimen is 0.465 mm high. It is 0.18 mm wide in the final part, and 0.10 mm thick (side view). The lumen of the last chamber is 0.066 mm high, 0.079 mm wide, and 0.074 mm thick.

Remarks. The type specimens of *G. kelleri* are 0.39–0.73 mm long and the type specimen is 0.18 mm wide at the apertural end. The test is 0.13 mm thick (Tappan 1955). Tappan (1955) described the wall as finely agglutinated, with the addition of some larger grains. Compared to the wall of *A. zlambachensis*, described above, the wall indeed looks relatively fine grained. According to Kristan-Tollmann (1970), part of the specimens described as paratypes of *G. triassica* (Trifonova, 1962) also belong to *G. kelleri*. We agree with this opinion. Trifonova (1992) later wrote that *G. triassica* differs from *G. kelleri* in having less globular chambers, a longer test, a shorter triserial part, and a narrower test at the apertural end. The holotype of this species indeed shows more parallel-sided test in its biserial part.

Distribution and age. Upper Triassic of Northern Calcareous Alps (Kristan-Tollmann 1990), Carnian and Norian of Bulgaria (Trifonova 1962, 1992), Rhaetian of Papua New Guinea (Kristan-Tollmann 1990), Lower Jurassic of Alaska (Tappan 1955).

Family Verneuilinidae Cushman, 1911
Subfamily Verneuilinoidinae Suleymanov, 1973
Verneuilinoides Loeblich & Tappan, 1949

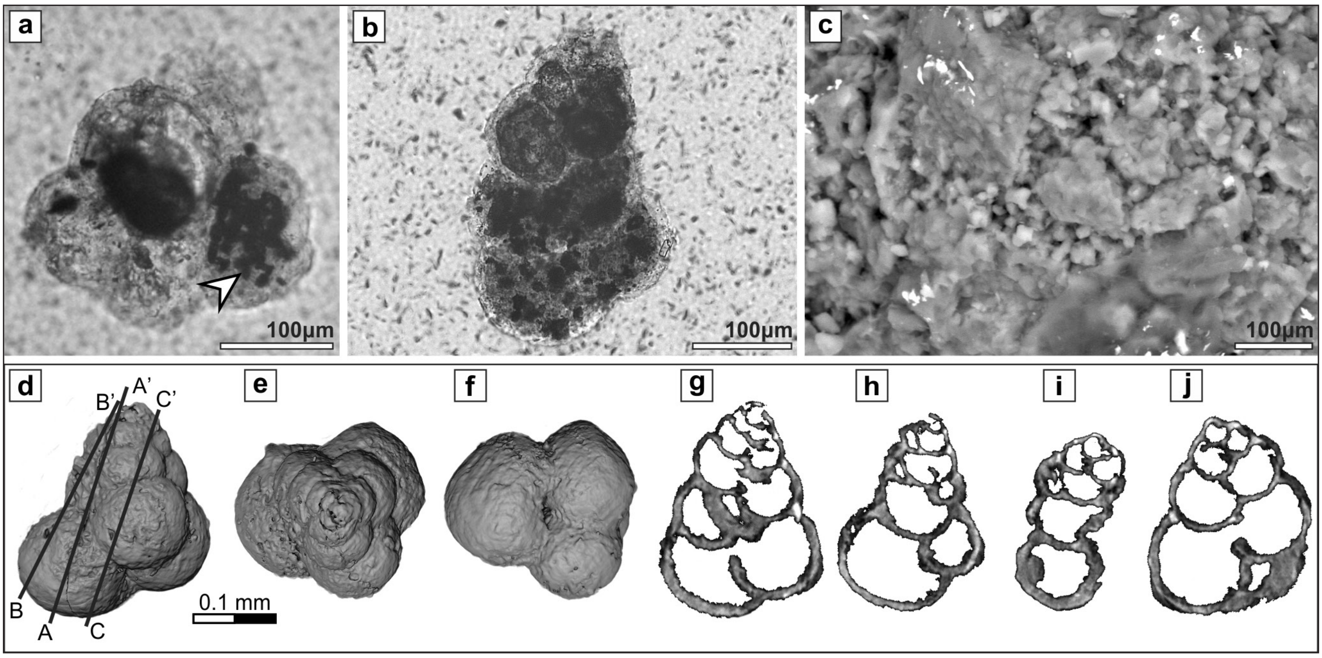

Fig. 7 - *Verneuilinoides racema* (Trifonova, 1962). a) Oblique transect of a specimen partly immersed in resin; thin section. Arrowhead points to framboidal pyrite inside the test. b) Oblique axial transect; thin section. c) Detailed surface view of the wall. Note the variable size of agglutinated particles. SEM image, BEC mode. d–j) Pictures, produced from tomographs. d) External view. Lines indicate orientations of virtual transects figured in g–j. e) Apical view. f) Umbilical view. g) Axial section. h) Transect A–A'. i) Transect B–B'. j) Transect C–C'.

Verneuilinoides racema (Trifonova, 1962)

Fig. 7

cf. 1866 *Verneuilina mauritii* Terquem, 1866, p.448, pl. 18, fig. 18a-b.
?non 1960 *Verneuilinoides mauritii* (Terquem 1866) - Bizon, p.4, pl. 1, fig. 3a-b; pl. 4, fig. 10. [lectotype]
1962 *Gaudryina racema* n. sp. - Trifonova, p.168, pl. 3, fig. 8-11.
cf. 1964 *Verneuilinoides triserialis* n. sp. - Ziegler, p.51, pl. 1, fig. 1-2; pl. 2, fig. 10-11. [jun. syn. to *V. mauritii*]
1988 *Verneuilinoides mauritii* (Terquem, 1866) - Kristan-Tollmann, fig. 1.18-1.22.
1990 *Verneuilinoides mauritii* (Terquem, 1866) - Kristan-Tollmann, fig. 8.17; pl. 6, fig. 5; pl. 7, fig. 1.
non 1990 *Gaudryina racema* Trifonova, 1962 - Kristan-Tollmann, pl. 2, fig. 5.
1992 *Gaudryina racema* Trifonova, 1962 - Trifonova, p.35, pl. 1, figs. 9-11, 13-15.

Description. The test is triserial, counting five to six levels made of three chambers each. The chambers of each successive level are situated one below the other, in the apical view giving the test a symmetrical appearance. The apertural face, however, is below the equatorial plane. Chambers are globular. The aperture is an umbilical-extraumbilical arch-like opening. The diameter of the proloculus is 0.024 mm on the exterior. The test of the figured specimen is 0.21 mm wide at the base and 0.26 mm high. Some specimens, however, appear to be more elongated. The wall is unperforated, agglutinated, built from clay- to silt-sized grains of quartz and aluminosilicate minerals, 0.01–0.015 mm (one or several grains) thick. Quartz and aluminosilicates are incorporated into the matrix, replaced by silica.

Remarks. The wall type, the triserial arrangement of chambers, and the nature of the aperture allow the placement of these specimens into the genus *Verneuilinoides* (Loeblich & Tappan, 1988). The shape and number of chambers, as well as the size of the specimens closely match specimens described as *Gaudryina racema* Trifonova, 1962 (Trifonova 1962, 1992). Trifonova described this species as having only two chambers in the last part of the test in mature specimens, and thus attributed to the genus *Gaudryina*. Some of the specimens from the 817 Lebăda Vest borehole also appear to show only two chambers at the very end of the test, but we believe this is due to an incomplete final coil. Indeed, remarks in Trifonova (1962) show that she herself considered placing this species in the genus *Verneuilinoides*. The specimen in Kristan-Tollmann (1990) is too robust for *V. racema*.

The type material of *V. racema* and the specimens described herein also closely match those specimens illustrated by Kristan-Tollmann (1988) as *Verneuilinoides mauritii* (Terquem, 1866). Terquem's (1866) hand-drawing of the type specimen of *V. mauritii* from the Lower Jurassic of France, however, shows a very elongated form with less globular chambers, and a height of 0.40–0.54 mm. Identical, in our opinion, to Terquem's specimen is *Verneuilinoides triserialis* Ziegler, 1964 from the Rhaetian of Germany (but see a different opinion by Trifonova 1992). Kristan-Tollmann (1988) nevertheless opted for *V. mauritii*, observing the large range in size and shape of her material (length ranging of 0.28 mm and width of 0.21 mm, to specimens 0.46 mm long and 0.31 mm wide). A wide range of size in *V. triserialis* was also described by Trifonova (1992), and the specimens from the 817 Lebăda Vest borehole actually show transitions between short (such as the one illustrated) and long forms. However, pictures and hand-drawings of the lectotype of *V. mauritii* by Bojzon (1960) are somewhat confusing, showing a specimen with a flat ventral side, a flush surface, and more cylindrical chambers, not unlike that of the *Duotaxis* Kristan, 1957. *Verneuilinoides parva* (Ziegler, 1964) is of the same size as the specimens described herein but have less globular chambers. Trifonova (1992) considered it a junior synonym of *V. triserialis*.

Distribution and age. *Verneuilinoides racema* was determined in Ladinian and Carnian of Bulgaria (Trifonova 1962, 1992). It was also reported, but not illustrated, from the Upper Triassic (Norian?) olistoliths in Crimea (Pronina & Vuks 1996; Kotlyar et al. 1999).

Trochamminidae Schwager, 1877
Genus *Trochammina* Parker & Jones, 1859

Remarks. *Trochammina* has a free, trochospiral test with an unperforated agglutinated wall. Its aperture is an interiomarginal, umbilical-extraumbilical arch with a narrow bordering lip. The stratigraphic range of the genus is from Carboniferous to Recent (Loeblich & Tappan 1988). Haig et al. (2007) interpreted the wall of Triassic species *T. alpina* Kristan-Tollmann, 1964 and *T. almtalensis* Koehn-Zaninetti, 1969 as calcareous microgranular, in contrast to the organic-cemented non-calcareous wall of the modern *Trochammina inflata* (Montagu, 1808). Thus, they tentatively suggested that the Triassic species assigned to *Trochammina* should be transferred to *Siphovalvulina* Septfontaine, 1988. However, as pointed out by Gale et al. (2018), the foramina in *Siphovalvulina* do not open directly into the umbilical cavity. *Siphovalvulina* also only has three chambers in the last coil (perhaps it is even triserial), and the wall bears clearly visible parapores (Gale et al. 2018).

Trochammina cf. jaunensis Brönnimann & Page, 1966

Fig. 8a–p

cf. 1964 *Trochammina alpina* Kristan-Tollmann, p.43, fig. 2-3.
cf. 1966 *Trochammina jaunensis* Brönnimann & Page, p.88, pl. 1, fig. 6-8.
cf. 1969 *Trochammina almtalensis* Koehn-Zaninetti, p.38, Figs. 6A-6P; pl. 5, fig. E-F.

Description. The test is very small, with chambers arranged in a low trochospire. The initial part is not clearly visible. The proloculus is followed by three coils. The first coil comprises three chambers, whereas three and a half chambers are needed to close each of the second and the third coil. The chambers are globular and quickly gain in size, so that those in the last coil are much larger than the chambers of the first coil. The aperture is a low arch in umbilical-extraumbilical (umbilical peripheral?) position, bordered by a low lip. The wall is agglutinated from clay- to silt-sized particles, mostly quartz grains and rare aluminosilicate minerals. On the outside it appears homogenous and smoothly finished. In transect it is 0.006 mm (several grains) thick. The diameter of the first coil and the thickness of the entire test is 0.11 mm. The total diameter of the test is 0.30 mm.

Remarks. The agglutinated wall, the trochospiral test, and the nature of the aperture characterise these specimens as members of the genus *Trochammina*. This genus is among the most commonly determined taxa from Triassic assemblages (e.g. Chablais et al. 2011). However, the taxonomy of the Triassic species of *Trochammina* is controversial due to the lack of evidence of the bordered aperture (see also above). *Trochammina angulata* and *T. balcanica* were described by Trifonova (1962), but the former is likely identical to *Variostoma coniforme* Kristan-Tollmann, 1960, and the illustrations of the latter fail to support the trochospiral coiling (although different sides of the test are illustrated). Both species also differ from true *Trochammina* in the aperture. Although observed from the residue, the lack of the bordered aperture is also noted in Ziegler's (1964) specimens described as four new

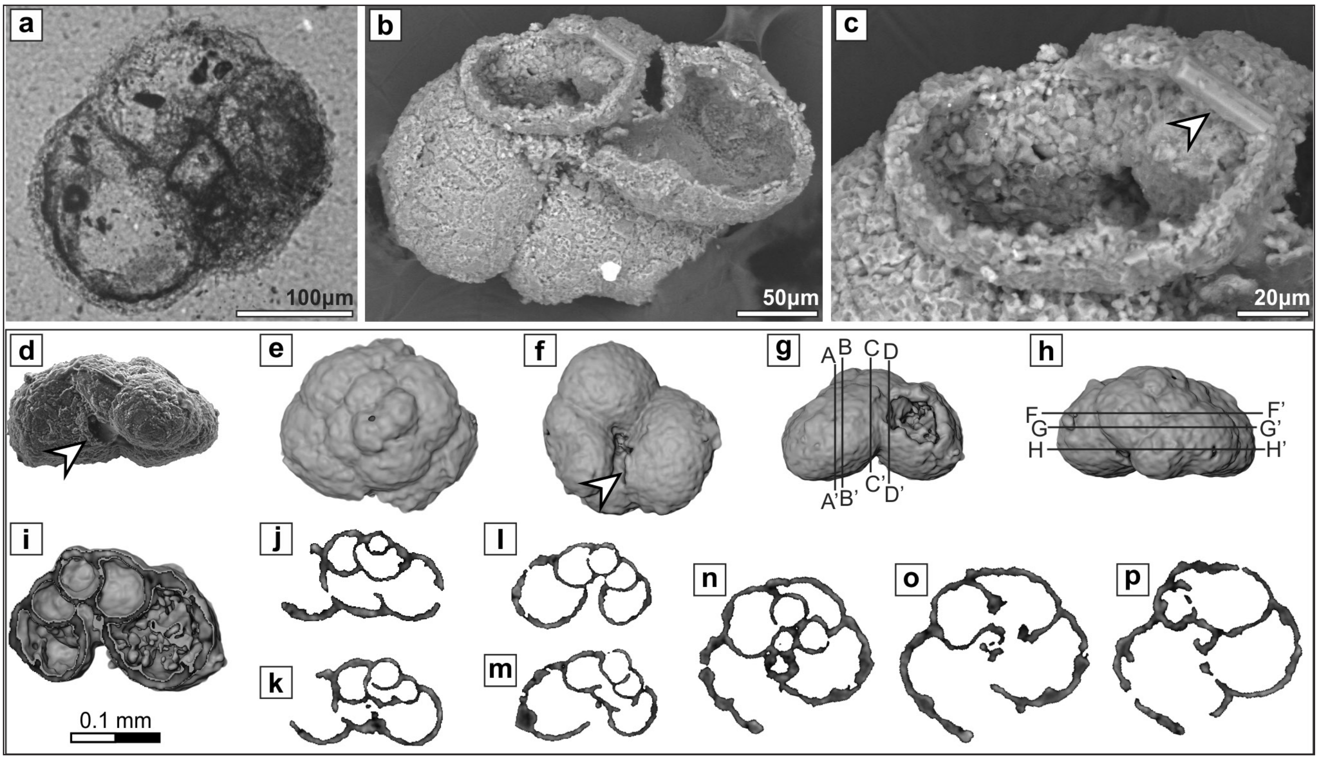

Fig. 8 - *Trochammina* cf. "*Trochammina*" *jaunensis* Brönnimann & Page, 1966. a) Transverse section from thin section. b) Oblique view towards the lower side of the test. Two chambers are partly broken. SEM image; BEC mode. c) Detailed view of the wall. Note rare larger agglutinated grains (arrowhead) among smaller quartz grains, which are more uniform in size. SEM image; BEC mode. d) Side view towards the apertural face. The arrowhead points to the aperture. SEM image; SEI mode. e) Spiral view from the digital model. f) Umbilical view from the digital model. The arrowhead points to the aperture. g) Side view at the distal end of the test. Lines indicate orientations of virtual transects figured in j–m. h) Side and partly top view towards the apertural face. Lines indicate orientations of virtual transects figured in n–p. i) Axial section in the digital model. Note the high umbilical cavity in the middle. j) Transect A–A'. k) Transect B–B'. l) Transect C–C'. m) Transect D–D'. n) Transect F–F'. o) Transect G–G'. p) Transect H–H'.

species: *T. triloculata*, *T. globula*, *T. squamosa*, and *T. rhaetica*. All, except *T. squamosa*, differ from the specimens described herein in having fewer chambers. *Trochammina squamosa* was described with a slit-like aperture. Its size, the number of chambers, and the outline are comparable to the specimens from the 817 Lebăda Vest borehole. Unfortunately, the drawing of the side view introduces some confusion as to the shape of this species, but it is nevertheless interesting to consider its status regarding *T. jaunensis* (see below).

The most commonly reported species of *Trochammina* are *Trochammina alpina* Kristan-Tollmann, 1964, *Trochammina jaunensis* Brönnimann & Page, 1966, and *Trochammina almtalensis* Koehn-Zaninetti, 1969. *Trochammina alpina* was illustrated as a rather large species (height 0.46 mm, diameter 0.58 mm for the holotype), with four to five coils, and four or three chambers per coil. No lip is visible at the aperture (Kristan-Tollmann 1964). *Trochammina jaunensis* was figured in two (eccentric subaxial?) transects from thin sections. This species was described as rather small (diameter of the holotype 0.288 mm, height of the holotype 0.144 mm), with two coils, and four or five chambers in the last coil (Brönnimann & Page 1966). Finally, *Trochammina almtalensis* was described as relatively small (diameter of the holotype 0.30 mm, with the 0.18 mm height of the test), but otherwise similar in form to *T. alpina*. Although the difference in size between *T. alpina* and *T. almtalensis* was acknowledged by Haig et al. (2007), numerous specimens from the literature show intermediate sizes. Moreover, some transects of *T. almtalensis*, illustrated in Koehn-Zaninetti (1969), closely match the type material of *T. jaunensis*. The two species could thus be synonyms. If we consider them identical to the specimens from the 817 Lebăda Vest borehole, the earlier described species, *T. jaunensis*, is correctly placed in the genus *Trochammina*. The distinction from *T. alpina*, described even earlier, and the generic attribution of the latter, remains to be resolved, as does the status of *Trochammina squamosa*.

Distribution and age. *Trochammina squamosa*, *T. alpina* and *T. jaunensis* were all described from Rhaetian beds (Ziegler 1964; Kristan-Tollmann 1964; Brönnimann & Page 1966). *Trochammina almtalensis* was established from the Upper Anisian of the Almtal in Austria (Koehn-Zaninetti 1969). Anisian to Rhaetian age is reported for *T. almtalensis* and *T. jaunensis* in Gale et al. (2012).

Conclusions

The availability of X-ray micro-computed tomography in recent studies of foraminifera gives us the opportunity to bridge the gap between observations made from thin sections and from isolated material. Although the mounting of the specimens is relatively quick and the scanning itself is not destructive, the scanning and the data processing are time-consuming and require powerful computers and special software (Sutton et al. 2014). This method is also applicable only for those specimens meeting certain requirements (e.g. the contrast in density between the fossil and the rock). Micro-CT studies are thus currently no match for traditional methods of determination. However, even though not routinely used, micro-CT investigations play an important part in solving some of the taxonomic issues challenging micropaleontologists.

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