Nanofrustulum fogedii sp. nov., a new araphid diatom (Staurosiraceae, Bacillariophyta) from Spitsbergen (Svalbard archipelago)

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Abstract

Nanofrustulum fogedii sp. nov. is described based on a historic sample from Spitsbergen collected by Niels Foged. The new species, originally identified by Foged in 1964 as *Nanofrustulum* (*Melosira) cataractarum*, can be separated from the latter by its larger valve diameter, longer striae composed of 1–6 transapically elongated areolae and a higher valve mantle. The species was observed in several samples collected from thermal springs in the Arctic Svalbard Archipelago. Based on its major morphological features, such as the quasifract girdle bands, the small valve dimensions and the serrated linking spines, the transfer of another small-celled araphid species, formerly described as *Pseudostaurosira bardii* Beauger et al. to the genus *Nanofrustulum* is justified.

Key-words: Foged collection, morphology, *Nanofrustulum*, new species, Spitsbergen

Introduction

The genus *Nanofrustulum* Round *et al.* (1999: 345) was described in 1999 for a very small, rounded araphid marine diatom, *Fragilaria shiloi* J.J.Lee *et al.* (1980: 43). The genus is characterised by its very small valve dimensions, uniseriate striae and typical quasifract copulae (Morales *et al.* 2019). The past few years, several new *Nanofrustulum* species were described whereas a few others were transferred from different genera (including *Melosira*, *Fragilaria*, *Serratifera*) to the genus. According to Guiry & Guiry (2024) the genus now contains 11 accepted species names and one that is considered a synonym of *Pseudostaurosira wachnickianum* (Chunlian Li *et al.* in Li *et al.* 2018: 50) E.Morales *et al.* (in Morales et al. 2019: 280).

One of the species that was recently transferred to *Nanofrustulum*, was described in 1937 by Hustedt from the Indonesian island of Java as *Melosira cataractarum* Hustedt (1937: 142). Its initial position within the genus *Melosira* was not surprising, giving its almost entirely rounded valve outline and the marginal striae, extending as short series of areolae from the margin to the valve center. The species was therefore first transferred to the genus *Aulacoseira* as *A. cataractarum* (Hustedt 1937: 142) Simonsen (1979: 57) and in 2013 to the genus *Pseudostaurosira* (Wetzel *et al.* 2013), despite the obvious presence of quasifract copulae. It was only in 2019 when the importance of these quasifract copulae as defining feature for the genus *Nanofrustulum* became clear, that the species was finally transferred to *Nanofrustulum* as *N. cataractarum* (Hustedt 1937: 142) C.E.Wetzel *et al*. (in Morales *et al.* 2019: 275).

Wetzel *et al.* (2013) discussed the worldwide distribution of the species, stating that most of its records originate from the northern hemisphere, whereas the type population was located in the southern hemisphere. Grana *et al.* (2015) added valuable data regarding distribution and ecology

based on the analysis of several European (Czech Republic) and South American (Argentina, Bolivia) populations. Two additional European populations from France were illustrated in Beauger *et al.* (2018) in comparison with the newly described *Pseudostaurosira bardii* Beauger, C.E.Wetzel & Ector in Beauger *et al.* (2018: 5) from the Massif Central in France.

Two forms of *N. cataractarum* were separated in the past. In 1942 *Melosira cataractarum* f. *laevis* Manguin (1942: 119) was described from the Azores (Manguin 1942) and more than 20 years later, Foged (1964) separated *M. cataractarum* f. *ovata* Foged (1964: 50) based on a population he observed in a hot spring on Spitsbergen, the main island of the Arctic Svalbard archipelago. The latter form could be distinguished by its slightly more oval shape, contrary to the typical rounded valve outline of *M. cataractarum*. The forma *ovata* was only observed in two samples, Foged had collected in August 1958 from the Trollsprings in the Bockfjord area in northern Spitsbergen. Apart from these two localities, Foged (1964) had observed the nominate *M. cataractarum* in seven samples from the Jotunsprings and the Trollsprings, illustrating his findings with 4 line drawings, one representing the nominate *M. cataractarum* (Foged 1964, plate 1, fig. 1) and three others the more oval looking forma *ovata* (Foged 1964, plate 1, figs 2–4). In 2014, Keller & Straub (2014) reported a *Pseudostaurosira cataractarum* population from the same locality in Spitsbergen.

During a revision of several *Fragilaria* and *Synedra* species described by Foged from Greenland (Foged 1958) and Spitsbergen (Foged 1964), a population of *M. cataractarum* was observed in one of the historic hotspring sample from the Foged collection in Copenhagen (Denmark) (Foged 462/1958) from Jotunsprings in the Bockfjord area. Comparison with the type population of the species from the spray water zone of the Tjurug Tjibeureum waterfalls in West Java, several morphological and morphometric differences could be noted that justified the separation of both

taxa as independent species. As the observed valves were not oval, but perfectly rounded, the former *M. cataractarum* population from Spitsbergen is described as a new species, named in honor of Niels Foged (1906–1988): *Nanofrustulum fogedii* Van de Vijver, Beauger, Pottiez & C.E.Wetzel, sp. nov. The current contribution describes the new species and compares it with new illustrations of the original Hustedt type material of *Nanofrustulum cataractarum* and one of the French populations (Zagat) discussed in Beauger *et al.* (2018). Additionally, the morphology of *Pseudostaurosira bardii* is been re-evaluated and the species is transferred to the genus *Nanofrustulum*.

Material & Methods

Four samples containing various *Nanofrustulum* populations were (re)analysed in this paper:

- Foged sample 462: Spitsbergen, Bockfjord Area, Jotunspring 1, leg. Niels Foged, coll. date 13.viii.1958
- Hustedt sample AS1524: Tjibeureum Wasserfall, Java TJ2.III.c.
- Zagat spring at Ardes-sur-Couze (France) (E 744209.91/N 6516138.53) leg. A. Beauger, coll. date 28.xii.2016.
- CLF104885 : Bard 2 spring at Boudes (Puy-de-Dôme, Department, Auvergne-Rhône-Alpes region, France) (E 713631.82/N 6483209.55) leg. A. Beauger, coll. date 11.xii.2015.

The material was prepared for LM and SEM observations following the method described in van der Werff (1955). Small amounts of each sample were cleaned by adding 37% H_2O_2 and heating to 80°C for about 1 h, after which the reaction was completed by addition of saturated $KMnO_4$. Following digestion and centrifugation (three times for 10 minutes at 3700 × rpm), the resulting

cleaned material was diluted with distilled water to avoid excessive concentrations of diatom valves on the slides. Cleaned diatom material was mounted in Naphrax (refraction index 1.73) and analysed using an Olympus BX53 microscope at 1000x magnification (N.A. 1.30), equipped with Differential Interference Contrast (Nomarski) optics and the Olympus UC30 Imaging System, connected to the Cell Sense Standard program. For each taxon, the number of specimens, measured at random on the slide, is indicated (n=X). An ecological characterisation of the new species is added based on the accompanying diatom flora.

For SEM, part of the suspension was filtered through 5-µm Isopore™ polycarbonate membrane filters (Merck Millipore), pieces of which were fixed on aluminum stubs after air–drying and coated with a platinum layer of 20 nm, and studied using a JEOL-JSM-7100F field emission scanning electron microscope at 2 kV. Slides, samples and stubs are stored at the BR-collection (Meise Botanic Garden, Belgium). Plates were prepared using Photoshop CS5.

Terminology used in the description of the various structures of the siliceous cell wall is based on Morales *et al.* (2019, *Nanofrustulum* genus features). For taxonomic comparisons, the following papers were consulted: Wetzel *et al.* (2013), Grana *et al.* (2015), Beauger *et al.* (2018), Li *et al.* (2018), Morales *et al.* (2023)

For typification of the species, we chose to use the entire slide as the type, following article 8.2 of the International Code of Nomenclature for algae, fungi, and plants (Turland *et al.* 2018). Diatoms show a broad variability along their cell cycle making the choice for the entire population on the slide more obvious, but because of admixtures, one valve was indicated to best illustrate the taxon (see Figures). All novelties are registered proactively according to Art. 42.3 (Turland *et al.* 2018).

Results

***Nanofrustulum fogedii* Van de Vijver, Beauger, Pottiez & C.E.Wetzel, sp. nov.** (Figs 1–35)

LM (Figs 1–27): Frustules solitary or arranged in long colonies, connected valve face to valve face. Valves elliptical to rounded, showing a bipolar (not a radial) symmetry. Valve dimensions (n=50): diameter 5–8 µm. Sternum very broad, lanceolate, at its broadest point up to almost 40 % of the total valve diameter, narrowing towards the apices. Striae radiate, of irregular length, becoming shorter and more radiate at the apices, 20–24 in 10 µm). SEM (Figs 28–35): Frustules showing a complex cingulum structure containing multiple quasifract copulae (Figs 28, 29). Valvocopula very large consisting of several broad, plate-like scales of variable width, overlapping with each other (Fig. 28, white arrows). Copulae including valvocopula unperforated. Numerous copulae progressively and advalvary reduced in size (Fig. 28). Mantle relatively high (up to 2.5 µm) with uniseriate, parallel striae composed of 3–4 small, rounded areolae in the advalvar part and a hyaline abvalvar part (Figs 28, 29, 35), the latter covered with very large mantle plaques (Fig. 35). Entire valve mantle covered with dense pattern of small granules (Figs 29, 35). Valve face flat (Figs 30, 31). Striae uniseriate, composed of 3–6 transapically elongated to rounded areolae (Figs 30, 31). Occasionally shorter striae composed of 1–3 areolae placed between normal striae (Fig. 31, white arrows). Apical pore fields absent. Large, flattened linking spines placed at the valve margin between the striae (Figs 31, 33–35). Spines with serrated tip (Fig. 33). Internally, striae located in grooves between raised virgae. Areolae covered by long, finely branched closing plates (Fig. 32).

Type:—NORWAY. Spitsbergen, Bockfjord Area, Jotunspring 1, Foged sample 462, leg. Niels Foged, coll. date 13.viii.1958 (holotype slide BR-4855= Fig. 4, isotype slide 450 in Collection University of Antwerp, Belgium).

Registration:— http://phycobank.org/105103

Etymology:—The species is named in honor of Niels Foged who collected the sample and initially identified the species as *Melosira cataractarum*.

Ecology & associated diatom flora:—At present only the sample with the type population was examined. The sample was collected from "green granulated masses around the aperture from which the spring flows". The Jotunspring has a very low water level ("poor in water, practically extinct", Foged 1964, p. 45) and was running through 20–30 m thick calcareous tufa deposits. Foged (1964) had noted a pH of 6.3 and a water temperature of 23.0°C). The sample was dominated by *N. fogedii* together with *Fragilaria hoelii* Foged (1964: 58), *Nitzschia* cf. *denticula*, *Caloneis jotunensis* Foged (1964: 82), and *Hygropetra elongata* Krammer & Lange-Bertalot (in Krammer 2000: 240).

Discussion

The presence of the quasifract bands, the small valve size, the internal closing plates on the areolae and the serrated tips of the linking spines, place the new species in the genus *Nanofrustulum* as emended by Morales et al. (2019).

Nanofrustulum fogedii is most similar to *N. cataractarum* and was in the past most likely identified as such. The population from Spitsbergen, however, differs from both the type population from Java (Figs 36–52, Wetzel *et al.* 2013, fig. 1) and the French populations in Beauger *et al.* (2018, figs 57–77) (our Figs 53–71) in having larger valves (most of the population has a valve diameter of >6 µm contrary to max. 5 in *N. cataractarum*), striae composed of more areolae (up to 5 versus max. 3 in *N. cataractarum*), a lack of slit-like areolae near the sternum (see for instance Wetzel *et al.* 2013, fig. 2A), and a higher valve mantle. Grana

et al. (2015, p. 818) reported a maximum valve length of < 6 µm for the populations from the Czech Republic and South America, although in their emended description, the maximum valve length was set on > 8 µm. However, this higher valve length included data from Wetzel *et al*. (2013) who combined all published measurements including Foged (1964) from Spitsbergen. Although these differences may seem subtle, they separate the Spitsbergen population from all others. Especially the French populations of Zagat and Puits, illustrated in Beauger *et al.* (2018) and our Figs 53–71, show valves with very short striae, both on the mantle and the valve face and it is unclear whether they should also be separated from the Javan type as a separate taxon. The drawings Foged (1964, plate 1, fig. 2) added in his book on the diatoms from Spitsbergen to illustrate the valve face of his new variety *ovata*, shows a slightly elongated valve with a length almost 30% more than the width. This contrast with Foged's fig. 1 showing a perfectly rounded valve face, identified as the nominate *M. cataractarum*. Although the original material of the var. *ovata* could not be checked, the clear difference in valve outline, excludes conspecificity with our newly described *N. fogedii*.

Nanofrustulum cataractarum is known to thrive in aerophilic habitats (Wetzel *et al.* 2013, Grana *et al.* 2015) such as waterfalls (type locality in Java for instance, Hustedt 1938), wet rocks (Ando 1978) or temperate springs (Beauger *et al.* 2018). Foged (1964) was the only one to report the species from hot springs in Spitsbergen and this specific habitat may be the reason why the population described now as *N. fogedii*, differes morphologically from the other *N. cataractarum* populations worldwide. Keller & Straub (2014) observed the species in the same hot springs as Foged did, 50 years before, confirming the stability of this population and its morphology as the reported images in Keller & Straub (2014) are identical to the illustrations in the present contribution.

The current morphological analysis justifies the separation of the Spitsbergen population as a new species.

Their chain-forming *Melosira*/*Aulacoseira*-like outlook gives *Nanofrustulum fogedii* and *N. cataractarum* a unique position within the genus *Nanofrustulum* and separates them from other round to elliptical species in this genus. *Nanofrustulum sopotensis* (Witkowski & Lange-Bertalot 1993: 67) E.Morales, C.E.Wetzel & Ector (2019: 275), *N. trainorii* (E.Morales 2001: 113) E.Morales (2019: 275) and *N. ibericum* E.Morales et al. (2023: 79) have a similar rounded valve outline but the stria pattern differs entirely showing a very narrow, linear sternum. *Nanofrustulum shiloi*, also mostly rounded in outline, possesses very large, almost quadratic areolae of variable length but so for without a large sternum separating the striae in the middle. Other *Nanofrustulum* species such as *N. lucectorii* E.Morales *et al.* (2023: 76) have a more elongated elliptical outline. Another small-celled elongated araphid species was described as *Pseudostaurosira bardii* from the Bard spring in the Massif Central in France (Beauger *et al.* 2018). The morphology of this species shows several features that justify the transfer of that species to the genus *Nanofrustulum* (Figs 72–94). The cingulum is entirely composed of quasifract copulae, including a large quasifract valvocopula consisting of large overlapping scales. The areolae are occluded in the valve interior by finely branched closing plates, similar to the ones in *N. cataractarum* and *N. fogedii*. The frustules are linked to each other with thick, platelike spines, each of them possessing a serrated tip. As these features have so far not been seen in the genus *Pseudostaurosira* where the species was originally placed, but have been reported for other *Nanofrustulum* species, the transfer of *P. bardii* to the latter genus is justified.

Nanofrustulum bardii **(Beauger, C.E.Wetzel & Ector) Van de Vijver, Beauger, Pottiez & C.E.Wetzel comb. nov.** (Figs 72–94)

Basionym: —*Pseudostaurosira bardii* Beauger, C.E.Wetzel & Ector in Beauger et al. (2018), Botany Letters 166(1), p. 6, figs 2–56.

Registration:— http://phycobank.org/105104

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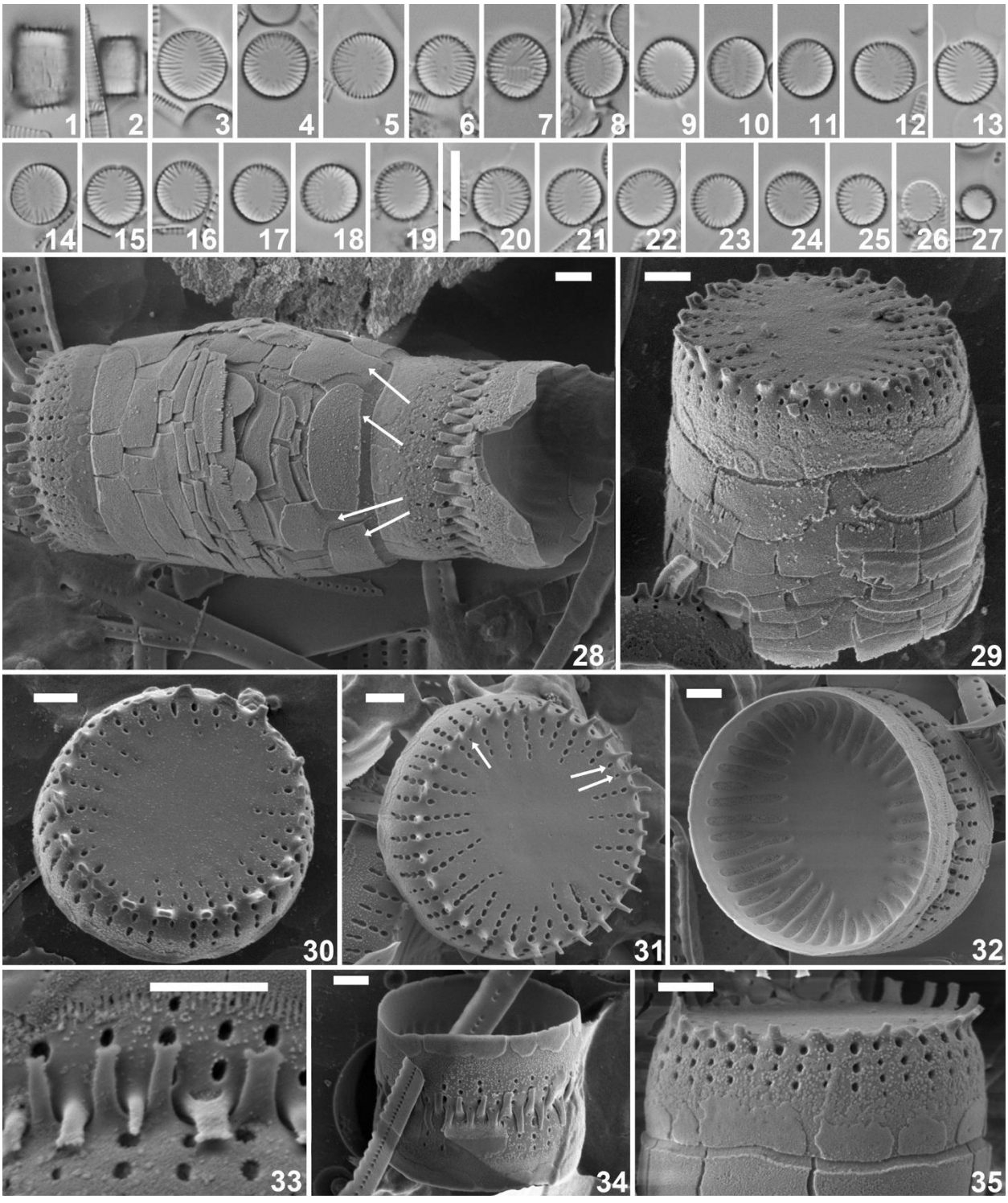
Figure captions

Figures 1–35. *Nanofrustulum fogedii* Van de Vijver; Pottiez, Beauger & C.E.Wetzel sp. nov. LM and SEM taken from the holotype sample (BR-4855, Spitsbergen, Bockfjord Area, Jotunspring 1, Norway, sample Foged 462). 1–2. LM pictures of two frustules in girdle view. 3–27. LM pictures of valves in valve face view in decreasing length. 28–29 SEM external view of complete frustules in girdle view showing the girdle structure with the quasifract copulae (white arrows indicating the scale-like valvocopula), the large mantle with the mantle plaques and the linking spines. 30–31. SEM external view of two valves showing the large lanceolate sternum, the spine structure, and the striae with 1–6 areolae. The white arrows indicate short striae composed of only 1 areola. 32. SEM internal view of a complete valve showing the finely branched closing plates. 33. SEM external detail of the linking spines with serrated tips. 34. SEM external view of two valves in girdle view connected to each other with linking spines. Note the very large mantle plaques. 35. SEM external view of a valve in girdle view showing the structure of the valve mantle with short striae, granules and mantle plaques. Scale bars: 10 μm (1–27); 1 μm (28–35).

Figures 36–71. *Nanofrustulum cataractarum* (Hustedt) C.E.Wetzel et al. LM and SEM taken from the type material (Hustedt sample AS1524, Tjibeureum Wasserfall, Java, Indonesia, Figs 36–52) and the Zagat springs in the Massif Central region, France (Figs 53–71). 36–50. LM pictures of valves in valve face view in decreasing length. 51. SEM external view of two valves in girdle view connected to each other with linking spines. Note the short striae, granules and mantle plaques. 52. SEM external view of a complete valve showing the large sternum and the relatively short striae with up to 3 areolae in decreasing size. Note the slit-

like areolae in the sternum. 53–68. LM pictures of valves in valve face view in decreasing length. 69. SEM external view of a valve in girdle view showing the structure of the valve mantle with short striae, and the mantle plaques. 70. SEM external view of a complete valve showing the large sternum and the relatively short striae with up to 3 areolae in decreasing size. 71. SEM internal view of a complete valve showing the finely branched closing plates. Scale bars: 10 μm (36–50, 53–68); 1 μm (51–52, 69–71).

Figures 72–94. *Nanofrustulum bardii* (Beauger et al.) Van de Vijver; Pottiez, Beauger & C.E.Wetzel comb. nov. LM and SEM taken from the holotype sample (CLF104885 : Bard 2 spring at Boudes, Puy-de-Dôme, France). 72. LM picture of a frustule in girdle view. 73–90. LM pictures of valves in valve face view in decreasing length. 91–92. SEM external view of two complete frustules in girdle view showing the girdle structure with the quasifract copulae, the large mantle with the mantle plaques and the linking spines. 93. SEM external view of a valve in girdle view showing the structure of the valve mantle with the single mantle areola, the serrated spines, and the mantle plaques. 94. SEM internal view of a complete valve showing the finely branched closing plates. Scale bars: 10 μm (72–90); 5 μm (91–94).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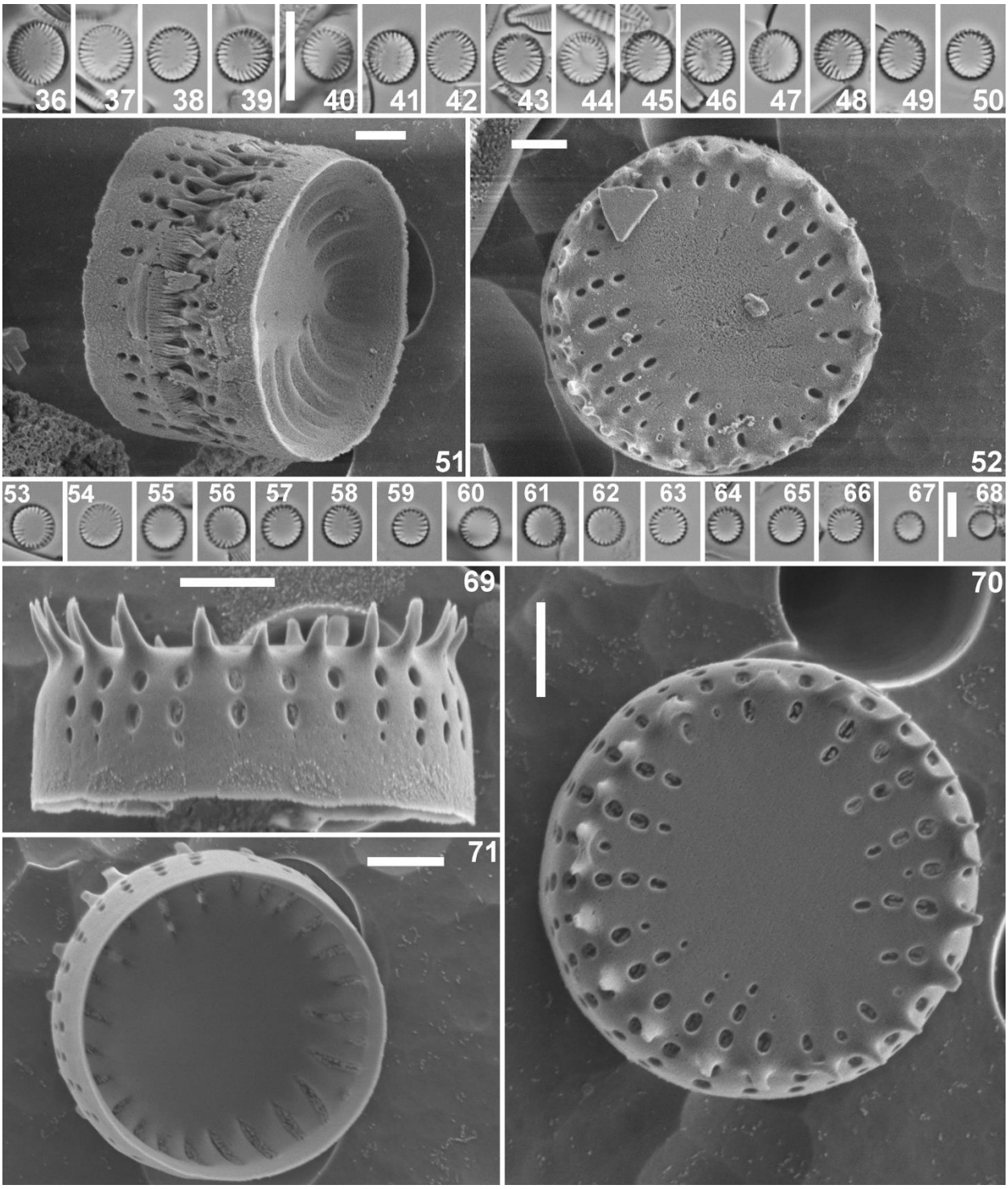
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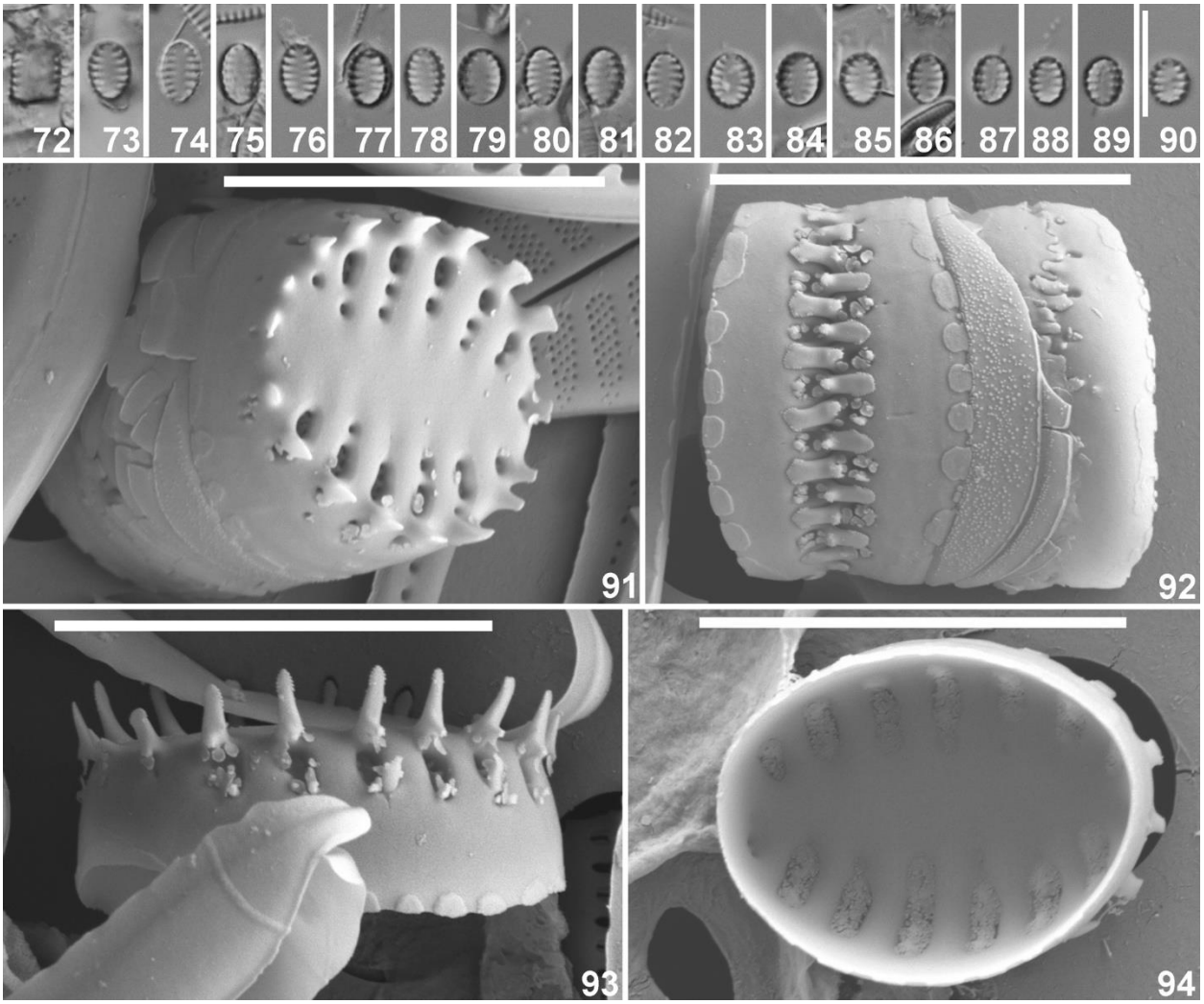
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