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Original Paper

Unraveling centric diatoms from the Caatinga: Coscinodiscophyceae and Mediophyceae in northwestern Ceará, Brazil

Maria Gabrielle Rodrigues Maciel [1,3,5], *Kaoli Pereira Cavalcante* [2] & *Thelma Alvim Veiga Ludwig* [1,4]

Abstract

The Caatinga is the largest tropical dry forest region in South America and harbors an impressive biological diversity. However, efforts in the studies of many groups of organisms, especially aquatic ones, are very small compared to other Brazilian regions. The state of Ceará stands out due to the major concentration of surface water in the semi-arid region, and the diatom flora is virtually unknown. We performed a pioneering and extensive taxonomic study on the centric diatoms from the Caatinga, documenting the morphological variation of the species found, expanding their geographic distribution, and reviewing taxonomic and nomenclatural aspects when relevant. The study was based on planktonic and periphytic samples collected in four hydrographic basins located in the northwestern region of Ceará, northeastern Brazil. Fifteen infrageneric diatom taxa were identified, described, and illustrated using light and scanning electron microscopy. *Discostella stelligera* was first recorded for northeastern Brazil and *D. woltereckii* is a new record to the country. Diminutive centric diatoms are well represented in the samples and their taxonomy is discussed. *Terpsinoë musica* occurred in a population with high phenotypic plasticity and we discussed the related taxonomic implications.
Key words: Bacillariophyta, intermittent water bodies, semiarid, taxonomy.

Resumo

A Caatinga é a maior região de floresta tropicalmente seca da América do Sul e abriga uma diversidade biológica impressionante. Porém, os esforços no estudo de diversos grupos de organismos, principalmente aquáticos, são muito escassos se comparados a outras regiões brasileiras. O estado do Ceará destaca-se pela grande concentração de águas superficiais no semiárido e a flora de diatomáceas é praticamente desconhecida. Realizamos um estudo taxonômico pioneiro e extenso sobre as diatomáceas cêntricas da Caatinga, documentando a variação morfológica das espécies encontradas, ampliando sua distribuição geográfica e revisando aspectos taxonômicos e nomenclaturais quando relevantes. O estudo baseou-se em amostras planctônicas e perifíticas coletadas em quatro bacias hidrográficas localizadas na região noroeste do Ceará, nordeste do Brasil. Quinze táxons de diatomáceas infra-genéricos foram identificados, descritos e ilustrados usando microscopia óptica e eletrônica de varredura. *Discostella stelligera* foi registrada pela primeira vez para o nordeste do Brasil e *D. woltereckii* é um novo registro para o país. Diatomáceas cêntricas diminutas estão bem representadas nas amostras e sua taxonomia é discutida. *Terpsinoë musica* ocorreu em uma população com alta plasticidade fenotípica e se discutiram as implicações taxonômicas relacionadas.
Palavras-chave: Bacillariophyta, corpos d'água intermitentes, semiárido, taxonomia.

See supplementary material at <https://doi.org/10.6084/m9.figshare.21339363.v1>

[1] Universidade Federal do Paraná, Setor de Ciências Biológicas, Depto. Botânica, Centro Politécnico, Curitiba, PR, Brasil.
[2] Universidade Estadual Vale do Acaraú, Centro de Ciências Agrárias e Biológicas, Campus Betânia, Sobral, CE, Brasil. ORCID: <https://orcid.org/0000-0001-7843-4114>.
[3] ORCID: <https://orcid.org/0000-0002-8594-2990>.
[4] ORCID: <https://orcid.org/0000-0003-0576-3499>.
[5] Author for correspondence: gabrielle.r.maciel@gmail.com

Introduction

The Caatinga is an important Brazilian ecological region, recognized as the largest seasonally dry tropical forest in South America (Silva *et al.* 2017). It is predominant in the semi-arid region of northeastern Brazil, but is interspersed with remnants of humid and sub-humid areas due to elevation and ocean proximity (Bastos & Cordeiro 2012). Studies have demonstrated the vast biodiversity of the Caatinga (Leal *et al.* 2005; Albuquerque *et al.* 2012). The fauna and flora are well adapted to water shortages (Santos *et al.* 2011; Silva *et al.* 2017), but significantly affected by extensive processes of environmental change and deterioration caused by unsustainable use of its resources (Leal *et al.* 2003).

The state of Ceará includes a major concentration of surface water in the Caatinga region (Andrade *et al.* 2017). A large part of the state has a tropical, semi-arid climate, with high annual average temperatures, high rates of evaporation, and scarce and irregular rainfall that is restricted to a short period of the year (IPECE 2016). Consequently, most water bodies are seasonally intermittent and many were made permanent by dam construction (IPECE 2016). Concerning factors are pollution from industry, lack of basic sanitation, siltation resulting from riparian deforestation, and the numerous dams built for water retention (Moro *et al.* 2015). Freshwater sources are threatened by anthropogenic pressures and biodiversity is declining (Virta *et al.* 2019).

Diatoms are ordinary and abundant components in freshwater systems. They play important ecological roles in aquatic environments as primary producers at the base of the trophic web, which can occur in different nutrient regimes, pH, salinity, and temperature (Julius & Theriot 2010). The rapid response time to environmental changes, make diatoms reliable aquatic bioindicators often employed to assess water quality (Kelly *et al.*1998; Lobo *et al.* 2010, 2015; Álvarez-Blanco *et al.* 2013; Lai *et al.* 2014; Stevenson 2014; Dalu & Froneman 2016).

In Brazil, diatom research is mostly concentrated in the South and Southeast, due to the greater representation of specialized research centers in these regions (Menezes *et al.* 2015). Focusing on inventories describing the diversity of diatoms in poorly studied regions of the country is crucial. The earliest studies on diatoms in northeastern Brazil were carried out by Patrick (1940a, b), who recorded 30 taxa in Ceará. More recently, only a few studies involving microalgae have been conducted in the southern Ceará, and diatoms have generally been identified to class or genus level, rarely to species level (Aquino *et al.* 2011; Vieira *et al.* 2013; Amorim *et al.* 2015; Costa *et al.* 2015). There are approximately 50 taxa of centric diatoms registered in freshwaters from Brazil (Eskinazi-Leça *et al.* 2015; Ludwig & Tremarin 2017) but there are few records of the centric diatom in the Caatinga region (*e.g.*, Patrick *et al.* 1940a, b; Tremarin *et al.* 2013), highlighting actual regional biodiversity gap and the great need taxonomic studies in that area.

This study aims to expand the knowledge of diatom biodiversity in the state of Ceará reducing gaps in our understanding of the geographic distribution of centric diatoms in the semi-arid region of Brazil. We performed a taxonomic study including samples from four hydrographic basins in northwest Ceará. Herein, we focus on population analysis of the species, detailed descriptions, taxonomic comments, and illustrations using light and electron microscopy.

Material and Methods

Ceará state is divided into seven mesoregions. The study area is located in the northwest of the state (Fig. 1) and covers 34,560 km² with a population of 326,847 inhabitants distributed across 47 cities (IPECE 2008), 12 of which were included in this study (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.21339363.v1>). Four hydrographic basins make up this mesoregion: Acaraú River, Coreaú River, Coastal rivers, and Parnaíba River (Nascimento 2011).

Sampling was conducted during 2016, 2018, and 2019 in different freshwater environments in the river basins (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.21339363.v1>). Twenty-three samples were collected: 17 epiphytic, 3 epilithic, 1 epipsamic, and 2 phytoplanktonic. Plankton was obtained with a plankton net (20 µm mesh) and periphyton, which are attached to natural substrates, were collected manually. We measured conductivity and pH, when possible (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.21339363.v1>), using conductivity meter CG1400 and pH-meter PG1400, respectively (Gehaka, Ltda).

Samples were preserved in 4% formaldehyde and cleaned according to Simonsen (1974), with modifications described by Moreira-Filho & Valente-Moreira (1981). Permanent slides were mounted with Naphrax® resin (refractive index = 1.74). Diatoms were analyzed and illustrated using an Olympus BX40 light microscope (Olympus, Tokyo, Japan) equipped with an Olympus DP71 image capture camera. Cleaned sub-samples were deposited in aluminum stubs, coated with gold using a Bal-Tec SCD050 Sputter Coater (Bal-Tec, Balzers, Liechtenstein). Preparations were analyzed in the JEOL JSM 6360-LV (Jeol, Japan) and TESCAN VEGA 3 LMU scanning electron microscopes (Tescan Analytics, Brno, Czech Republic), housed at the Electron Microscopy Center of the Federal University of Paraná (UFPR).

Classification follows Medlin & Kaczmarska (2004) for supra-ordinal taxa and Round *et al.* (1990) for subordinal ones. Striae density and marginal processes of centric diatoms were calculated according to Hasle (1983) and modified by Syvertsen & Hasle (1984). Morphological terminology was based on Round *et al.* (1990), Houk (2003) and Houk *et al.* (2010). Samples and slides were registered and deposited in the herbaria of the Federal University of Paraná (UPCB), Curitiba, Paraná, and the State University of Vale do Acaraú (HUVA), Sobral, Ceará, Brazil (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.21339363.v1>).

The frequency of occurrence was calculated according to Dajoz (2005), as follows: constant (C ≥ 50%), common (C ≥ 30% or ≤ 50%), sporadic (C ≥ 10% or ≤ 30%) and rare (C ≤ 10%) .

Results and Discussion

We present 14 species and one non-typical variety of centric diatoms, distributed among one genera of Coscinodiscophyceae and six genera of Mediophyceae.

Descriptions and comments follow.

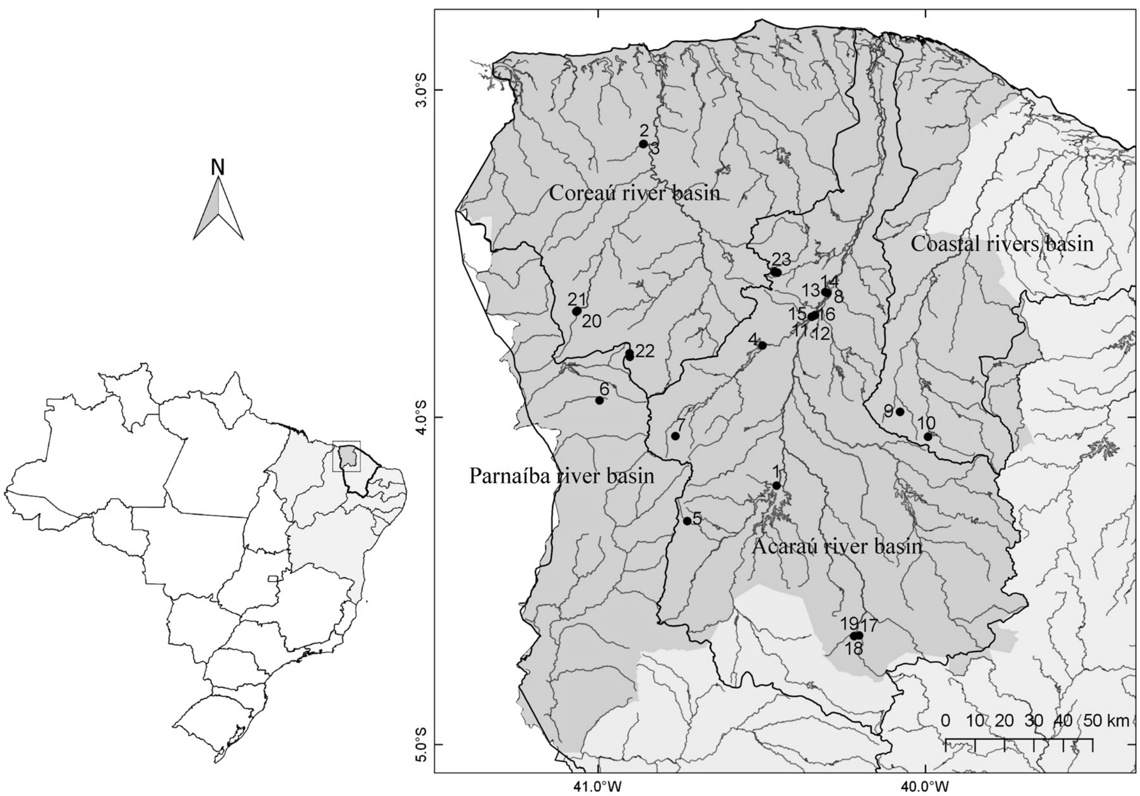

Figure 1 – Map of study area: hydrographic basins of northwestern region (in grey) of the state of Ceará, Brazil. Sampling locations (black circles) were numbered from 1 to 23. Information about the sampling points is shown in Table S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.21339363.v1>.

Bacillariophyta Karsten
Coscinodiscophytina Medlin *et* Kaczmarska
Coscinodiscophyceae Round *et* R.M. Crawford
Aulacoseirales Crawford
Aulacoseiraceae Thwaites
Aulacoseira Thwaites

Aulacoseira ambigua (Grunow) Simonsen, Bacill. 2:56. 1979. Fig. 2a-b

Frustules cylindrical; valve face flat with short rows of rounded areolae restricted to the margin (Fig. 2a); mantle ornamented with striae arranged obliquely in relation to the pervalvar axis in a dextrorse pattern; areolae rounded, delicate. Diameter 5.7–6.4 µm; mantle height 9.9 µm; 17 striae in 10 µm and 17 areolae in 10 µm.

Examined material: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Catunda, Celso weir (UPCB: 78411, HUVA: 24535).

Species found in epilithic and epiphytic samples. Literature consulted: Buczkó *et al.* (2010); Tremarin *et al.* (2013).

Aulacoseira granulata var. ***granulata*** (Ehrenberg) Simonsen, Bacill. 2:58. 1979. Fig. 2c-f

Frustules cylindrical, united in straight filaments; terminal valves with one or two long spines; mantle ornamented with striae arranged parallel to the pervalvar axis; areolae rounded to rectangular; coarse, v-shaped sulcus not very pronounced. Diameter 5.7–7.7 µm; mantle height 11.6–21.3 µm; 8–12 striae in 10 µm and 8–10 areolae in 10 µm.

Examined material: Varjota, Araras weir (UPCB: 78392, HUVA: 24516). Sobral, Jaibaras weir (UPCB: 78395, HUVA: 24519). Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Sobral, Acaraú River (UPCB: 78407, HUVA: 24531). Meruoca, Sítio Cachoeira (UPCB: 78418, HUVA: 24542).

The species was found in epilithic, epiphytic and phytoplanktonic samples. Literature consulted: Krammer (1991); Houk (2003); Cavalcante *et al.* (2013).

Aulacoseira granulata var. ***angustissima*** (O. Müller) Simonsen, Bacill., 2:58. 1979. Fig. 2g-l

Frustules cylindrical, united in predominantly straight filaments by small connecting spines, terminal valves with a long spine; mantle ornamented by obliquely striae (dextrorse pattern) in the connecting valves and parallel in the separation valves; areolae rounded; sulcus not pronounced. Diameter 3–4 µm; mantle height 10.6–13.3 µm; 16–17 striae in 10 µm and 18–20 areolae in 10 µm.

Examined material: Varjota, Araras weir (UPCB: 78392, HUVA: 24516). Sobral, Jaibaras weir (UPCB: 78395, HUVA: 24519). Sobral, Acaraú River (UPCB: 78404, 78407, HUVA: 24528, 24531). Catunda, Carmina weir and Celso weir (UPCB: 78409, 78410, HUVA: 24533, 24534).

Aulacoseira granulata var. *angustissima* was found mainly in epiphytic samples. Literature consulted: Krammer (1991); Houk (2003); Cavalcante *et al.* (2013).

Aulacoseira italica (Ehrenberg) Simonsen, Bacill. 2:60. 1979. Fig. 2m-q

Frustules cylindrical, united in straight filaments by conspicuous conneting spines; valve face flat with inconspicuous areolae (Fig. 2m); mantle ornamented with striae parallel to the pervalvar axis; areolae rounded, delicate. Diameter 8.5–10.6 µm; mantle height 12.6–17.4 µm; 22–24 striae in 10 µm and 18–22 areolae in 10 µm.

Examined material: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Catunda, Celso weir (UPCB: 78411, HUVA: 24535).

Species found in epiphytic and epilithic samples. Literature consulted: Crawford *et al.* (2003); Houk (2003).

Bacillariophytina Medlin *et* Kaczmarska
Mediophyceae (Jousé *et* Proshkina-Lavrenko) Medlin *et* Kaczmarska
Stephanodiscales Nikolaev *et* Harwood
Stephanodiscaceae Makarova
Cyclotella (Kützing) Brébisson

Cyclotella atomus Hustedt, Arch. Hydrobiol. 15:143, pl. 9, figs 1-4. 1937. Fig. 3a-j

Valves circular, ornamented by marginal radiate striae separated by costae; marginal fultoportula ring, with fultoportulae distributed every 3 or 4 striae; one rimoportula located between two marginal fultoportulae; one subcentral fultoportula. Diameter 5–6.5 µm; pervalvar axis 3 µm; 8–14 striae in 10 µm and 3.3–3.8 marginal fultoportulae in 10 µm.

Examined material: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Massapê, temporary pond near to Acaraú River (UPCB: 78399, HUVA: 24523). Sobral, Acaraú River (UPCB: 78403, 78407, 78408, HUVA: 24527, 24531, 24532).

In SEM: valve surface is slightly undulated in the central area (Fig. 3h) and striae irregularly distributed from marginal valve face to mantle with delicate round poroids; marginal fultoportula ring located at the valve face/mantle junction, occurring at an interval of every three or four costae (Fig.

3i,j). Externally, fultoportulae and rimoportula openings are simple pores. Internally, striae are not alveolate (Fig. 3j); the subcentral fultoportula have three satellite pores and marginal fultoportulae have two satellite pores in radial position; one sessile marginal rimoportula with a slightly oblique labiate opening (Fig. 3j).

Populations of *Cyclotella atomus* in northwest Ceará follow the morphometric variation described in the literature (diameter 3.5–8.5 μm), but the striae density showed lower values (12–20 in 10 μm; Tanaka 2007; Houk *et al.* 2010). However, Cavalcante *et al.* (2013) have also registered lower striae density (9–16 in 10 μm) in specimens from Northeastern Brazil. *Cyclotella cryptica* Reimann, Lewin *et* Guillard mainly differs from *C. atomus* due to the marginal fultoportulae located at an interval of every one or two costae (Houk *et al.* 2010).

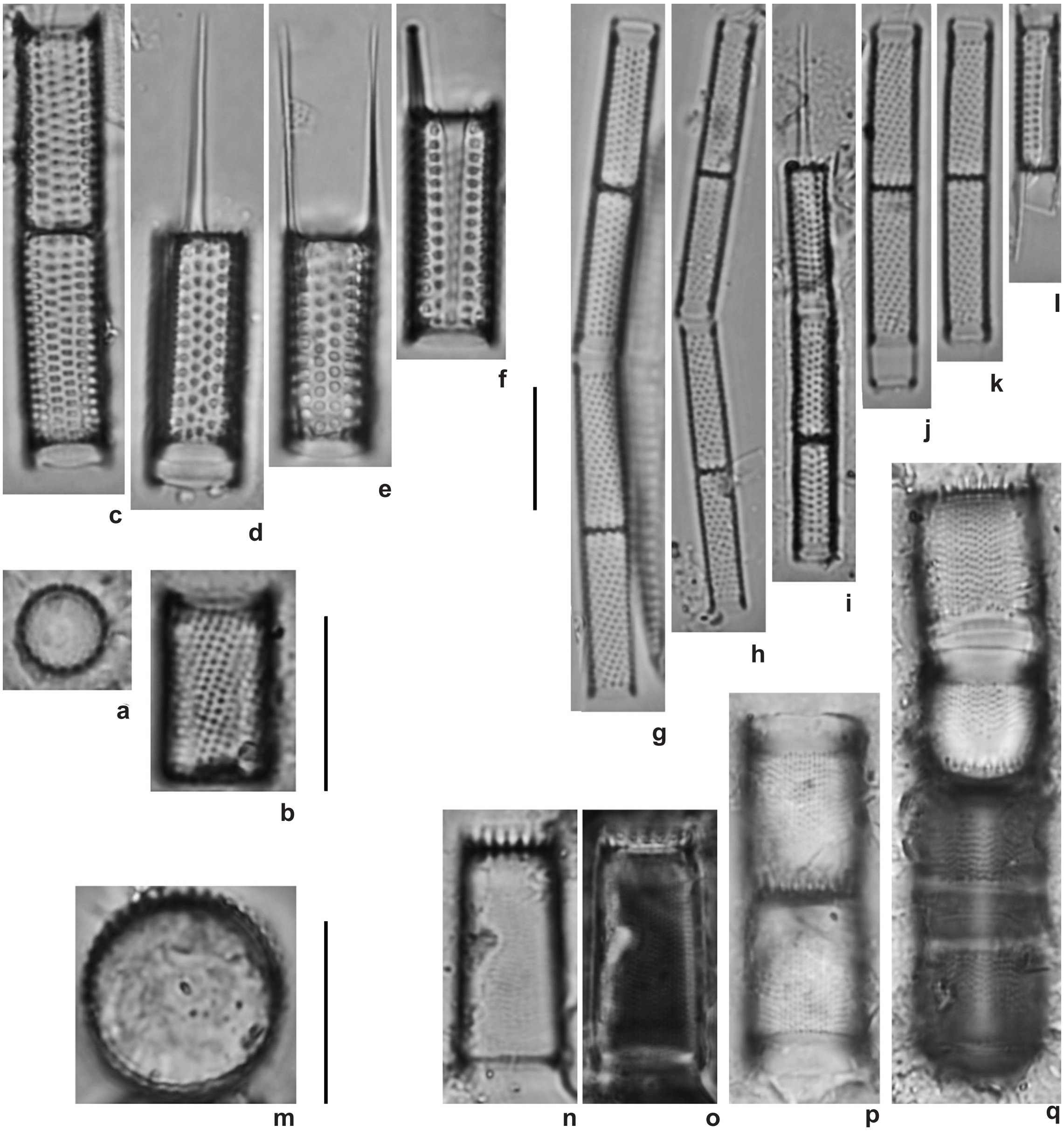

Figure 2 – a-q. *Aulacoseira* species – a-b. *Aulacoseira ambigua*, in valve and girdle views, respectively; c-f. *Aulacoseira granulata* var. *granulata*; g-l. *Aulacoseira granulata* var. *angustissima*; m-q. *Aulacoseira italica* – m. valvar view; n-q. girdle view. Scale bar: 10 μm.

The species occurred in epiphytic, epilithic and phytoplanktonic samples. Literature consulted: Tanaka (2007); Cavalcante *et al.* (2013); Houk *et al.* (2010).

Cyclotella cryptica Reimann, Lewin *et* Guillard. Phycol. 3:82, figs. 4-11. 1963. Fig. 4a-k

Valves circular, ornamented by marginal radiate striae separated by costae; marginal fultoportulae ring, fultoportulae distributed in an interval of every one or two costae and always associated to the costa; one sessile rimoportula located between two marginal fultoportulae; one subcentral fultoportula. Diameter 6–12 µm; pervalvar axis 5.9 µm; 6–8 striae in 10 µm and 2–4.5 marginal fultoportulae in 10 µm. **Examined material**: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Massapê, temporary pond near the Acaraú River (UPCB: 78399, HUVA: 24523). Sobral, Acaraú River (UPCB: 78403, 78406, 78407, 78408, HUVA: 24527, 24530, 24531, 24532). Taperuaba, lake in Pedra da Andorinha (UPCB: 78402, HUVA: 24526). Catunda, Carmina weirs (UPCB: 78409, HUVA: 24533) and Celso weirs (UPCB: 78410, HUVA: 24534). Varjota, Araras weir (UPCB: 78392, HUVA: 24516).

In SEM: internally, semi-open alveolate striae (Fig. 4i-k); subcentral and marginal fultoportulae with three satellite pores around a long tube (Fig. 4i-j); one marginal rimoportula with small labiate opening that is oriented obliquely lies on the costa (Fig. 4j).

Cyclotella cryptica and *C. meneghiniana* Kützing are similar in valve diameter and number of marginal processes, but *C. meneghiniana* differs mainly due to the internally closed alveoli, which makes the separation between the central and marginal areas quite evident (Houk *et al.* 2010). Moreover, it has already been observed that *C. cryptica* may resemble *C. meneghiniana* when found in low salinity (1.4) environments and show typical morphological characteristics of *C. cryptica* when salinity is > 4.3 (Schultz 1971).

The species occurred in epiphytic, epilithic, and phytoplanktonic samples. Literature consulted: Cavalcante *et al*. (2013); Houk *et al*. (2010).

Cyclotella marina (Tanimura, Nagumo *et* M. Kato) Aké-Castillo, Okolodkov. *et* Ector, in Aké-Castillo *et al.* Nova Hedwigia Beih. 141: 267, figs 2-9. 2012. Fig. 5a-h

Valves circular, delicate ornamentation, difficult to observe in MO; three to four marginal fultoportulae distant from each other; one rimoportula between two marginal fultoportulae; alveolate striae inconspicuous. Diameter 2.6–4.5 µm; 2–4 marginal fultoportulae in 10 µm.

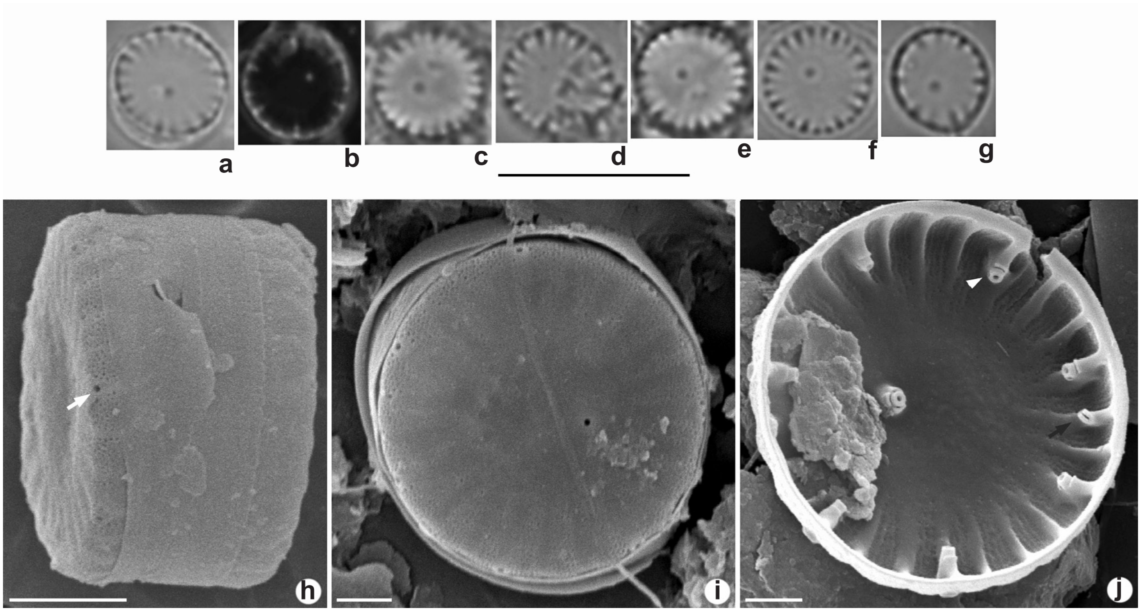

Figure 3 – a-j. *Cyclotella atomus* – a-g. valves in LM; h-j. frustules and valves in SEM – h. frustule in girdle view showing marginal fultoportula external opening (arrow); i. external valve face view; j. internal view of the valve, marginal fultoportulae with two satellite pores (arrowhead), subcentral fultoportula with three satellite pores and marginal rimoportula with obliquely labiate opening (dark arrow). Scale bars: a-g = 10 µm; h = 2 µm; i-j = 1 µm.

Examined material: Sobral, Acaraú River (UPCB: 78403, 78405, 78408, HUVA: 24527, 24529, 24532).

In SEM: internal valve surface flat; striae radiate, delicate, extending toward the central region; alveoli absent and marginal fultoportulae surrounded by two satellite pores, arranged at the face/mantle junction and one pedunculated marginal rimoportula (Fig. 5h).

Cyclotella marina differs from *C. atomus* due to less developed alveolate striae and the absence of central fultoportula (Tanimura *et al.* 2004). Also, the literature states the preference of *C. marina* for coastal, high-nutrient marine environments (Aké-Castillo *et al.* 2012; Hevia-Orube *et al.* 2015). However, the species has been registered in freshwater environments, which implies that it has a wide distribution (Cavalcante *et al*. 2013; Genkal & Yarmoshenko 2013; Genkal & Okhapkin 2013; Genkal & Bilous 2015). *Cyclotella marina* was registered in Brazil by Cavalcante *et al.* (2013) in riverine waters of Bahia state, Northeastern Brazil. According to Tanimura *et al*. (2004) and Chung *et al.* (2010), it is a metaphytic species occurring in both plankton and epiphyton. The present study is the second record of *C. marina* in freshwater systems in Brazil.

The species was registered exclusively in Acaraú River, influenced by domestic sewage, in epiphytic, epipsamic, and phytoplanktonic samples. Literature consulted: Aké-Castillo *et al.* (2012); Cavalcante *et al.* (2013).

Cyclotella meduanae Germain, Flore des Diatomées. p. 36, pl. 8, fig. 28, pl. 154, figs. 4, 4a. 1981.Fig. 5i

In SEM: internal view, circular valve ornamented by marginal radiate striae with delicate areolae, separated by costae; striae are not alveolate; subcentral fultoportulae absent; marginal fultoportulae ring surrounded by three satellite pores, located at the face/valve mantle junction, at every two or three striae; one marginal rimoportula located between two fultoportulae on the costae, obliquely oriented. Diameter 5.9 µm; 9.5 striae in 10 µm and 4.3 marginal fultoportulae in 10 µm.

Examined material: Sobral, Acaraú River (UPCB: 78408, HUVA: 24532). Catunda, Carmina weir (UPCB: 78409, HUVA: 24533).

The only specimen found during SEM preparations is consistent with descriptions by Houk *et al.* (2010) and Cavalcante *et al.* (2013). *Cyclotella katiana* Sala *et* Ramírez, which was proposed in Colombia (Sala & Ramírez 2008), was recently considered synonymous with *C. meduanae* based on

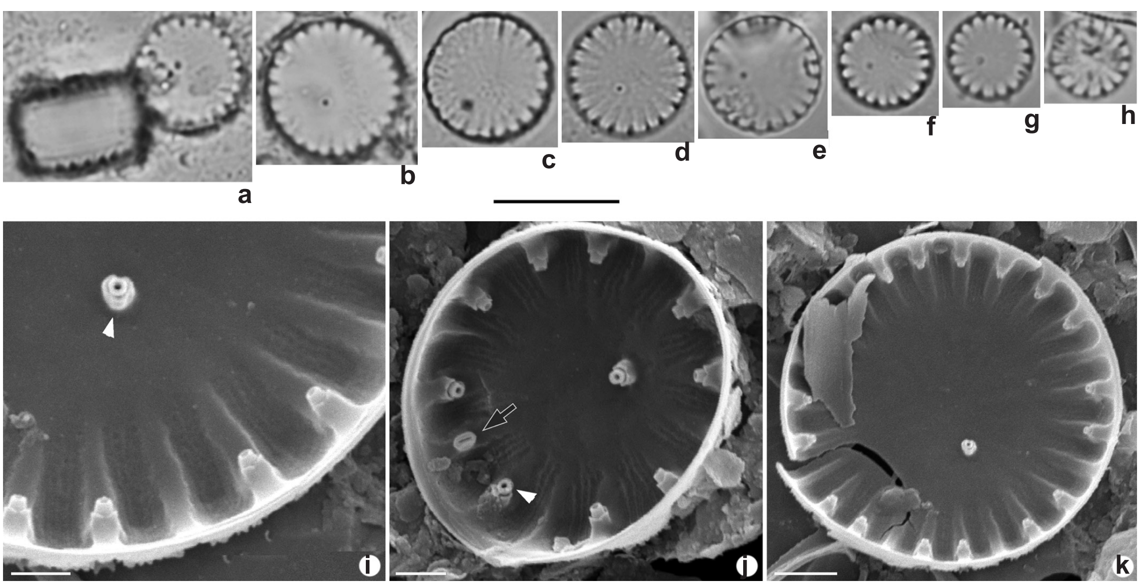

Figure 4 – a-k. *Cyclotella cryptica* – a-h. valves in LM; i-k. valves in SEM – i. internal valve view, detail of the subcentral fultoportula with three satellite pores (arrowhead); j. marginal fultoportula with three satellite pores (arrowhead), and detail of the sessile marginal rimoportula (dark arrow), and detail of the semi-open alveoli and ring of marginal fultoportulae; k. valve overview showing details of subcentral fultoportula and marginal rimoportula and fultoportula ring. Scale bars: a-h = 10 µm; k = 2 µm; i-j = 1 µm.

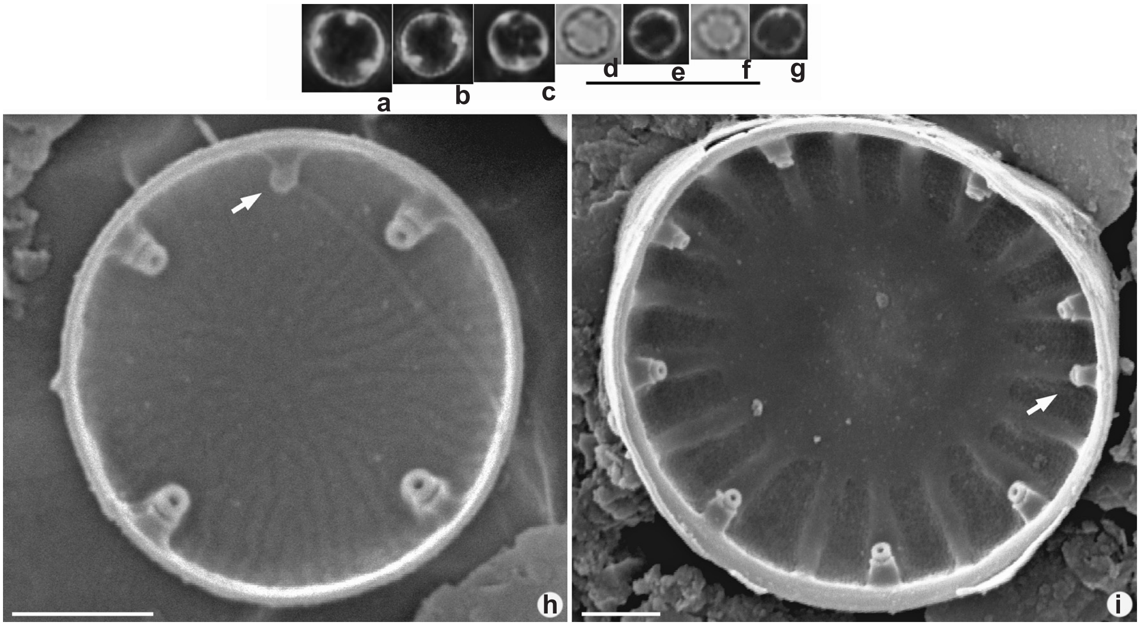

Figure 5 – a-i. *Cyclotella* species – a-g. *Cyclotella marina* – valve view in LM; h. internal view of the valve in SEM, detail of the sessile marginal rimoportula (arrow). i. *Cyclotella meduanae* – internal valve view in SEM, detail of the marginal rimoportula between a costa and a marginal fultoportula (arrow). Scale bars: a-g = 10 µm; h-i = 1 µm.

their overlapping diacritical characteristics (Genkal 2014). *Cyclotella meduanae* resembles *C. cryptica* but differs mainly in relation to the absence of the subcentral fultoportula in *C. meduanae* (Houk *et al.* 2010).

The species occurred only in plankton in epiphyton. Literature consulted: Tanaka (2007); Houk *et al.* (2010); Cavalcante *et al.* (2013).

Cyclotella meneghiniana Kützing, Die Kies. Bacill. oder Diat., p. 50, pl. 30, fig. 68. 1844. Fig. 6a-k

Valves circular, with evident separation between central and marginal areas, central area with tangential undulation; marginal striae alveolate; marginal fultoportula ring, with one fultoportula in each stria, sometimes absent; one rimoportula inserted between two marginal fultoportulae; one to two subcentral fultoportula. Diameter 7.9–18.4 µm; 7–8 striae in 10 µm and 4.9 marginal fultoportulae in 10 µm.

Examined material: Varjota, Araras weir (UPCB: 78392, HUVA: 24516). Granja, Gangorra weir (UPCB: 78393, 78394, HUVA: 24517, 24518). Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Massapê, temporary pond near the Acaraú River (UPCB: 78399, HUVA: 24523). Taperuaba, lake in Pedra da Andorinha and Olho d'água do Pajé (UPCB: 78402, 78400, HUVA: 24526, 24524). Sobral, Acaraú River (UPCB: 78403, 78404, 78406, 78407, 78408, HUVA: 24527, 24528, 24530, 24531, 24532). Catunda, Carmina and Celso weirs (UPCB: 78409, 78410, HUVA: 24533, 24534). Viçosa do Ceará, Quatiguaba River (UPCB: 78413, HUVA 24537).

In SEM: the external valve surface is slightly undulated in the central region, ornamented by granules; subcentral fultoportulae; marginal single or double spines positioned in line with each costa (Fig. 6i). Internal view with closed alveoli, marginal and subcentral short tube fultoportulae surrounded by three satellite pores (Fig. 6j-k); one pedunculated marginal rimoportula between two marginal fultoportulae, with obliquely oriented labiate opening (Fig. 6k).

The species occurred in epiphytic, epilithic, and phytoplanktonic samples. Literature consulted: Houk *et al.* (2010); Cavalcante *et al.* (2013).

Discostella Houk *et* Klee

Discostella stelligera (Cleve *et* Grunow) Houk *et* Klee, Diat. Res. 19(2): 208. 2004. Fig. 7a-i

Valves circular, with convex central area, ornamented by short striae irregularly arranged in form of a rosette; marginal area occupies less than half of the valve surface; marginal alveolate

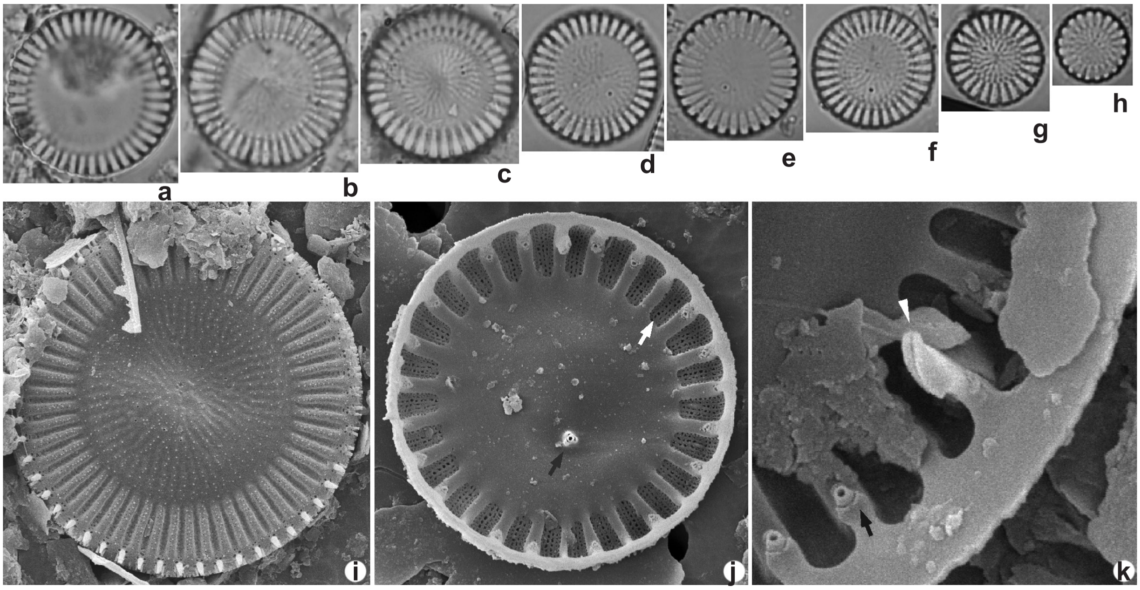

Figure 6 – a-k. *Cyclotella meneghiniana* (valve view in LM and SEM) – a-h. external view of valve surface in LM; i. external view of valve surface in SEM, detail of the valve surface, of the marginal spines; j. internal view, alveolate striae, closed alveolous (white arrow), subcentral fultoportula with three satellite pores (dark arrow); k. pedunculated marginal rimoportula (arrowhead) obliquely oriented, marginal fultoportula (dark arrow). Scale bars: a-h = 10 µm; i, j = 5 µm; k = 2 µm.

striae, radial and regular in length; marginal ring of fultoportulae inconspicuous in LM. Diameter 5.9–12 µm and 7.5–11.5 striae in 10 µm.

Examined material: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Granja, Gangorra weir (UPCB: 78393, HUVA: 24517). Sobral, Acaraú River (UPCB: 78403, 78409, HUVA: 24527, 24533).

In SEM: internal view with marginal fultoportulae located in line with striae and between costae, in the valve face/mantle junction, surrounded by two satellite pores; one small marginal rimoportula present between marginal fultoportulae (Fig. 7i). The internal opening of the alveolate striae is shortened when it coincides with fultoportula or rimoportula. A hyaline area separates the marginal from the central striations.

Species found mainly in epiphytic samples. Literature consulted: Houk (2004); Houk *et al.* (2010); Tuji & Williams (2006); Guerrero & Echenique (2006).

Discostella woltereckii (Hustedt) Houk *et* Klee, Diat. Res. 19(2): 223. 2004. Fig. 7j-o

Valves circular, flat to a moderately convex central area, with two ornamentation patterns: elongated marginal striae, of irregular length, which extends to the valve center (Fig. 7j-m), or irregular marginal striae occupying more than one half of the valve, separated from the central region, which presents short radiated rosette-shaped striation, (Fig. 7n-o); marginal ring of fultoportulae inconspicuous in LM. Diameter 4.8–5 µm; 8.5 striae in 10 µm.

Examined material: Varjota, Araras weir (UPCB: 78392, HUVA: 24516).

Discostella woltereckii var. minor Öberg, Risberg *et* Stabell differs from the typical species due to the smaller valve diameter (1.9–4 µm) and the dichotomously arranged valve face (Öberg *et al.* 2009). *Discostella guslyakovyi* Genkal, Bondarenko *et* Popovskaya also differs in diameter (2.8–5.7 µm), valve contour, and non-tubular marginal fultoportulae (Genkal *et al.* 2007).

Similarities are notable between *D. pseudostelligera* (Hustedt) Houk *et* Klee and *D. woltereckii.* Both have irregular marginal striations, long tubular marginal fultoportulae, and may present a central area ornamented by short striae arranged in a rosette shape (Houk *et al.* 2010). However, according to Guerrero & Echenique (2006), *D. pseudostelligera* exhibits a broad hyaline ring occupying about half of the valve diameter, located between the central and the marginal area,

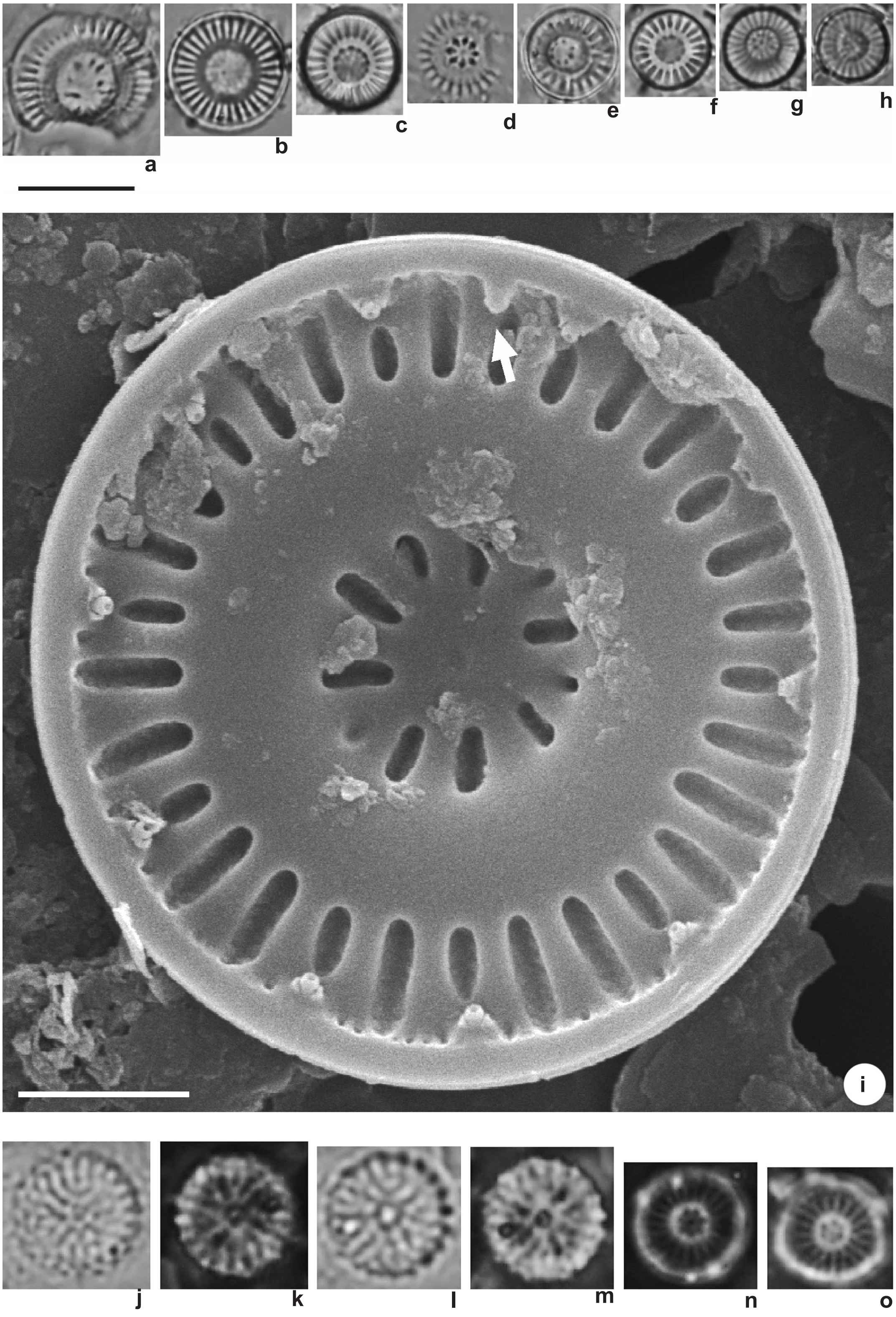

Figure 7 – a-o. *Discostella* species – a-i. *Discostella stelligera* – a-h. valves in LM; i valve in internal view, SEM; j-o. *Discostella wortereckii* – valves in LM. Scale bars: a-h, j-o = 10 µm; i = 2 µm.

while in *D. woltereckii* the central area is very small, sometimes reduced to an isolated stria.

The population in Ceará is similar to that presented by Houk *et al.* (2010) fig.19, pl.354, Hustedt (1942) fig.25, pl.324 for *D. woltereckii* type material, and also Huber-Pestalozzi (1942, fig. 488A, pl. CXVIII). When analyzing the type material of both taxa, Houk *et al.* (2010) stated that, although the morphology can sometimes overlap, making identification inaccurate, the separation of the taxa can be related to ecological differences; *D. pseudostelligera* is mainly a species of temperate regions, while *D. woltereckii* occurs preferentially in tropical zones. Morphological and ecological features led us to assume that the population in Ceará corresponds better with the characterization of *D. woltereckii.*

The studied population was recorded in epiphytic samples. Literature consulted: Houk *et al.* (2010); Guerrero & Echenique (2006).

Thalassiosirales Glezer *et* Makarova
Thalassiosiraceae M. Lebour
Conticribra Stachura-Suchoples *et* D.M. Williams
Conticribra weissflogii (Grunow) Stachura-Suchoples *et* Williams, Eur. J. Phycol. 44(4): 482. 2009. Fig. 8a-m

Valves circular with a flat surface; striae delicate, irregularly oriented; marginal fultoportulae ring located in the face/mantle junction, with conspicuous external tubes; one pronounced rimoportula interrupting the ring of marginal fultoportulae. Diameter 19.8–32 µm; marginal fultoportulae 5.5–7.6 in 10 µm; central fultoportulae 5–6 in 10 µm.

Examined material: Graça, Belizário waterfall (UPCB: 78398, HUVA: 24522). Sobral, Acaraú River (UPCB: 78403, 78406, 78408, HUVA: 24527, 24530, 24532).

In SEM: external valve surface ornamented with granules (Fig. 8h-j) and areolate striae with an irregular continuous radial pattern. Marginal ring of fultoportulae with long external tubes, central fultoportulae with moderately elongated tubes (Fig. 8i-j). Rimoportula with an elongated external tube, slightly longer than those of fultoportulae (Fig 8i). For internal view, marginal and central fultoportulae are present as small tubes with four satellite pores (Fig. 8k-m). Rimoportula with a large labial opening, short pedunculated, arranged radially (Fig. 8l).

The species occurred in epilithic, epiphytic, and phytoplanktonic samples. Literature consulted: Stachura-Suchoples & Williams DM (2009); Cavalcante *et al.* (2013).

Eupodiscales Bessey
Eupodiscaceae Ralfs
Pleurosira (Meneghini) Trevisan
Pleurosira laevis (Ehrenberg) Compère var. ***laevis***, Bacill., 5: 177-178, fig. 1-17, 20, 39. 1982. Fig. 9a-d; 10a-f

Subcircular to elliptical valves; valve face flat, ornamented by radial striae with delicate round areolae; two large ocelli located at the valve margin, opposite to each other, ornamented by delicate poroids; two rimoportulae located near the center of the valve. Larger diameter 38.1–45.5 µm; smaller diameter 30.9–47.2 µm; 10–14 areolae in 10 µm.

Examined material: Ipu, Bica do Ipu (UPCB: 78396, HUVA: 24520). Sobral, Acaraú River (UPCB: 78403, HUVA: 24527). Viçosa do Ceará, Quatiguaba River (UPCB: 78412, 78413, HUVA: 24536, 24537).

In SEM: valve surface is ornamented by irregular starry spines mostly concentrated in the central region and close to the ocelli (Fig. 10i-k); rimoportulae with an external opening as a simple slit (Fig. 10h) and internally as a sessile labiate opening (Fig. 10g).

Pleurosira laevis var. *paludosa* (Tempère *et* Peragallo *ex* Forti) Compère, differs from the typical variety as it shows rimoportulae closer to the central area (Compère 1982). *Pleurosira socotrensis* (Kitton) Compère differs due to its elliptical valves and irregularly arranged striae in the central region of the valve (Compère 1982; Ludwig *et al.* 2004; Karthick & Kociolek 2011).

Population recorded mainly in epilithic and epiphytic samples. Literature consulted: Compère (1982); Joh (2010); Cavalcante *et al*. (2013).

Orthoseirales Crawford
Orthoseiraceae Crawford
Orthoseira Thwaites
Orthoseira roeseana (Rabenhorst) Pfitzer, Bot. Abh. 1(2): 134. 1871. Fig. 11a-h

Cylindrical frustule in girdle view, united by inconspicuous spines; mantle ornamented by striae parallel to the pervalvar axis, little pronounced constriction (stricter region in the mantle) (Fig. 11a-c); valve surface slightly wavy, with scattered punctuations, striae radial, conspicuously areolate; central area with three carinoportulae (Fig. 11e). Diameter 8.7–26.4 µm; mantle height 25.7–35.6; 15–17 striae in 10 µm; 18–19 areolae in 10 µm.

Examined material: Ipu, Bica do Ipu (UPCB: 78396, HUVA: 24520). Ibiapina, Bica do Pajé (UPCB: 78397,

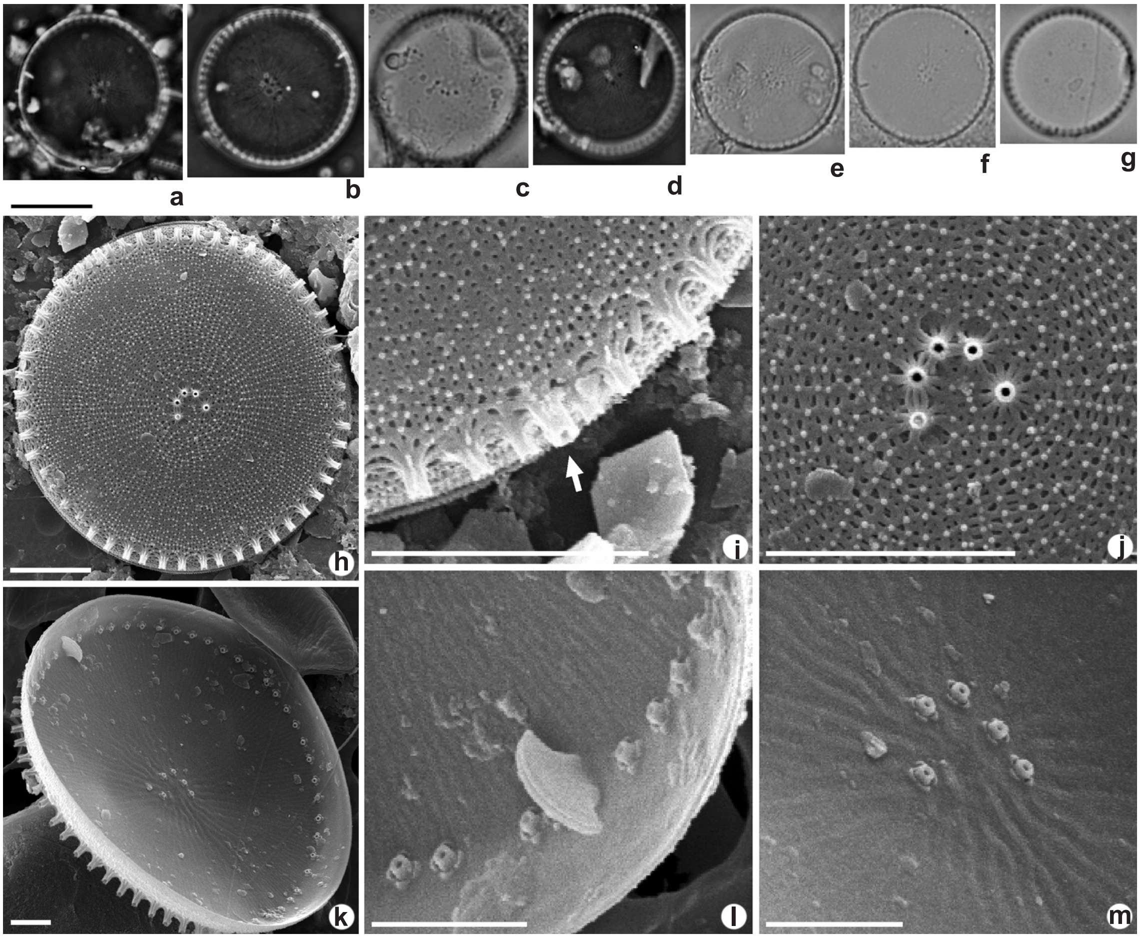

Figure 8 – a-m. *Conticribra weissflogii* (valve view in LM and SEM) – a-g. valve view in LM, flat surface and delicate stretch marks; h-j. external view of valve surface in SEM – h. external valve surface ornamented with granules, marginal ring of fultoportulae with long external tubes; i. details of marginal fultoportulae and rimoportulae openings (arrow); j. central fultoportulae openings; k-m. internal valve view in SEM – k. internal surface of the valve without pronounced ornamentation, internal view of the ring of marginal fultoportulae interrupted by a rimoportula; l. details of large sessile rimoportula; m. central fultoportulae with for satellite pores surrounding a short tube. Scale bars: a-g = 10 µm; h-j = 5 µm; k-m = 2 µm.

HUVA: 24521). Ubajara, Sítio São Luis (UPCB: 78414, HUVA: 24538).

In SEM: carinoportulae occluded internally (Fig. 11g) and externally, presence of spines (Fig. 11h).

In Brazilian studies, specimens of *Orthoseira roesena* are presented by Landucci & Ludwig (2005, fig. 1), Brassac *et al.* (1999, fig. 29), and Ferrari & Ludwig (2007, figs 7 and 8), while *Orthoseira dendroteres* (Ehrenberg) Genkal *et* Kulikovskiy is presented by Nardelli *et al.* (2014, fig. 13). When comparing the illustrations and descriptions of these studies, they likely correspond to the same taxon. The delimitation between *O. dendroteres* and *O. roeseana* becomes difficult due to the vast morphological variation of both taxa (Houk 1993, 2003; Spaulding & Kociolek 1998). The populations in this study exhibited considerable morphological variation in terms of valve diameter, overlapping with the characteristics of both species. Therefore, we opted to adhere to the broad taxonomic concept of *O. roeseana* found in Houk (2003). Gargas *et al.* (2018) comment on the need for more studies to resolve the taxonomy and the typification of *O. dendroteres* and *O. roeseana.*

Populations found in periphyton in epilithic of humid subaerial samples. Literature consulted: Houk (1993, 2003).

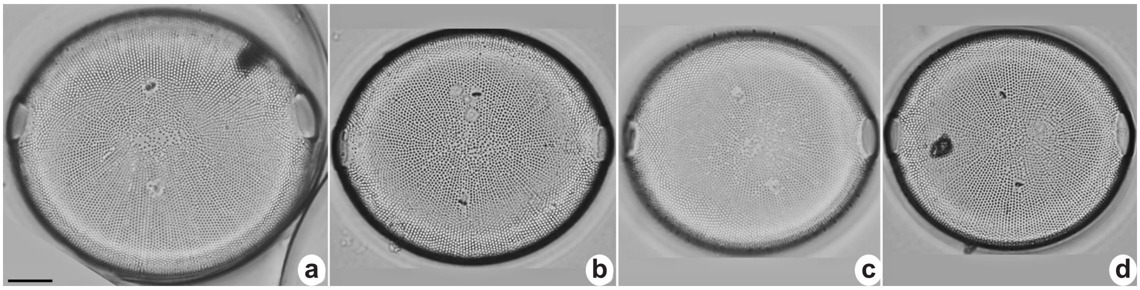

Figure 9 – a-d. *Pleurosira laevis* var. *laevis* – valve view in LM. Scale bars: a-d = 10 µm.

Terpsinoaceae Ralfs in Pritchard
Terpsinoë Ehrenberg
Terpsinoë musica Ehrenberg, Abh. Akad. Wiss. Berl., p. 425, pl. 3, fig. IV.1, pl. 3, fig. VII. 30. 1841 (1843). Figs. 12a-q; 13a-h

Frustules rectangular in girdle view with transapical bars resembling musical notes and short pseudoseptum near the edge of valve mantle; bipolar, elongated valves, generally with three marginal undulations of nearly equal size, but smaller valves showed one (Fig. 12i-m) to three marginal undulations (Fig. 12a-g); valve ends rostrate to subcapitate with pseudocelli; transapical costae between each undulation and near to the valve ends (less developed); coarse areolae irregularly arranged on the surface of the valve; one or three (Fig. 12a) subcentral rimoportula located in the central undulation. Length 61.7–137.9 µm; width 32.8–42.2 µm; pervalvar axis 74.5–107.9 µm and 8–10 areolae in 10 µm.

Examined material: Ipu, Bica do Ipu (UPCB: 78396, HUVA: 24520).

In SEM: internal view shows a small rimoportula in form of a crack (Fig. 13c) or a closed lip (Fig. 13d), and the rimoportula external view shows a slit shape (Fig. 13e).

The wide morphological variation of *T. musica* populations was previously recorded in the literature (Schmidt 1812–1899; Luttenton *et al.* 1986; Jiménez *et al.* 2017; Metzeltin *et al.* 2005; Metzeltin & Lange-Bertalot 2007). However, documentation of specimens with only one central undulation is rare. Wu (2013) described valves with one undulation in *T. musica* specimens, stating that the number of undulations decreases in smaller valves. Metzeltin & Lange-Bertalot (2007) illustrated "*Terpsinöe* (? nov.) spec." with frustules containing a single undulation (pl. 296:5–12), demonstrating uncertainties in identification. In our material, all valves were found in the same population (see Examined material), including intermediate forms between one and two marginal undulations. Our observations suggest that these forms correspond to the same taxon. Variability in morphology and symmetry may be the result of cell reduction or initial cell formation (Cox 2014), as in the interrupted projections of the bipolar diatom *Hydrosera* (Cox 2013). Functional aspects, such as nutrient availability and adaptation to the environment, also provoke significant morphological variability in populations (Jiménez *et al*. 2017).

Small specimens with a single central undulation from the study population are similar to *Terpsinoë petitiana* (Leuduger-Fortmorel) Hendey found in marine samples from West Africa (Leuduger-Fortmorel 1898) and the Galapagos (Hendey 1972). The possibility remains that *T. musica* and *T. petitiana* are conspecifics, not only because of their phenotypic plasticity, but also because *T. musica* presents a wide ecological distribution, occurring in fresh and brackish water, as well as marine environments (Round *et al.* 1990). In this study, specimens of *T. musica* were found on bryophytes growing on rocks in a humid subaerial environment, for which we documented valves with one to three central undulations (Fig. 11a-m).

Tuji (2018) describes *T. muninensis*, a species very similar to *T. musica*, as endemic to the freshwater of the North Pacific islands. The author differentiates *T. muninensis* as it presents less silicified apices and interrupted pseudosepta, which do not form musical notes, as is characteristic of *T. musica* (Ehrenberg 1843). However, this characteristic seems to vary within the same population. In the samples from Ceará, the pseudosepta present as well silicified (Fig. 12d-e), with a low level of silicification (Fig. 12a-c,f), or are not visible (Fig. 12n-q). In the

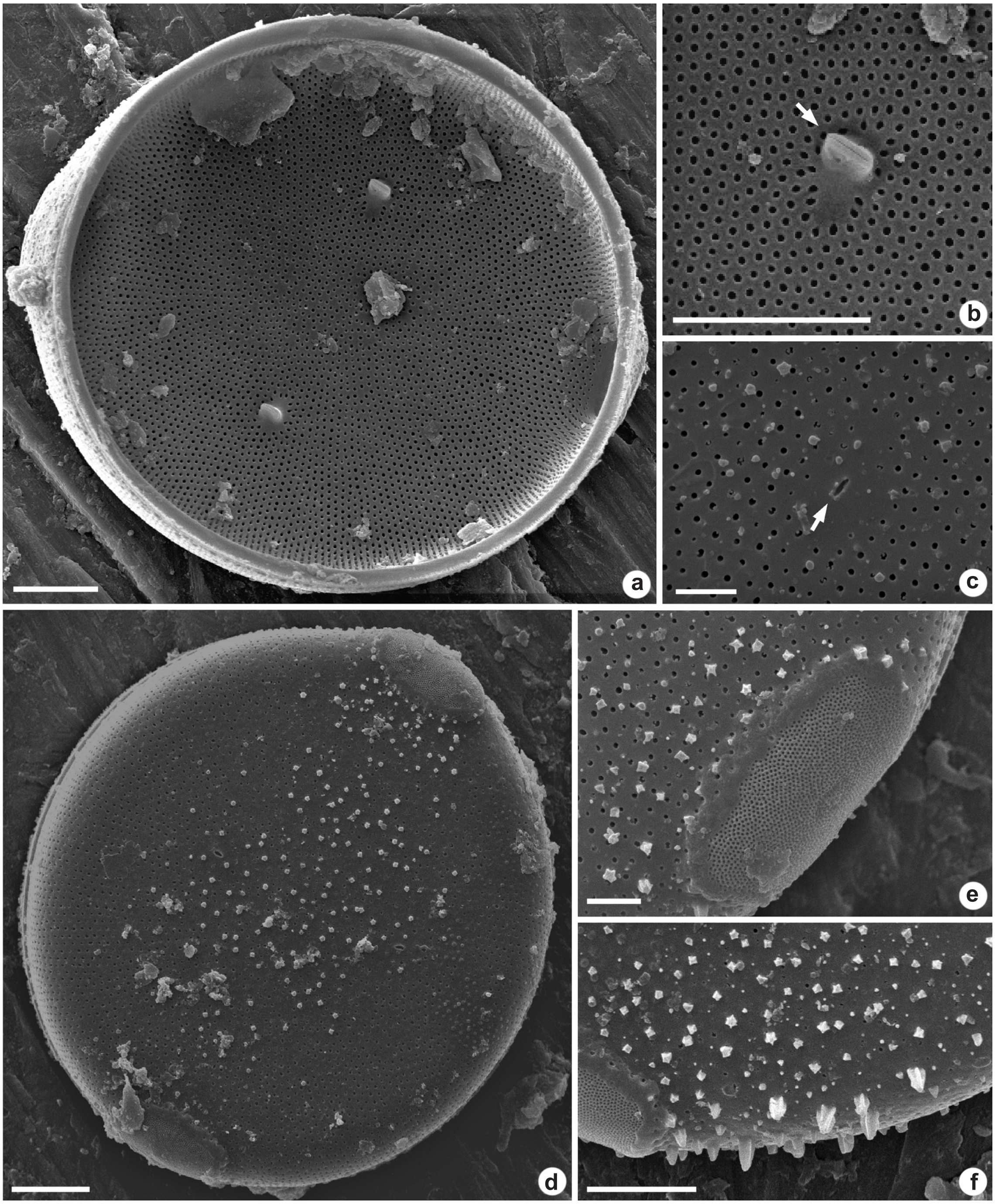

Figure 10 – a-f. *Pleurosira laevis* var. *laevis* (valve view in SEM) – a. internal view of the valve, two rimoportulae located near the center of the valve; b. detail of the rimoportula opening in internal view (arrow); c. external view of the rimoportula opening; d. external valve surface ornamented with small spines irregularly spaced; e. external view of ocellus; f. detail of the spines, SEM. Scale bars: a-b,d = 10 µm; f = 5 µm; c,e = 2 µm.

population described by Jiménez *et al.* (2017), Figs. 8 and 11 show well-developed pseudosepta, which is not seen in Fig. 10. The authors also state that *T. musica* would have a median marginal undulation greater than the others, differing from those of equal size in *T. muninensis*. However, Jiménez *et al.* (2017) illustrate (Fig. 8) *T. musica* with marginal undulation of the same size and apices with well-developed pseudosepta. Tuji (2018) states that differences in the molecular sequence support the existence of two taxa, but also recommends further studies on the morphological and molecular phylogenetic variability of the two species. Also, some more representatives of the genus *Terpsinoë* have sequences deposited at GenBank that should be used by the author for a better comparison and a closer representation of the genus phylogeny.

In light of the above discussion, we believe that the Ceará population fits the concept of *T. musica*, a taxon with significant morphological plasticity.

Population found in periphyton of humid subaerial samples, associated with bryophytes. Literature consulted: Metzeltin *et al.* (2005); Wu (2013); Jiménez *et al.* (2017).

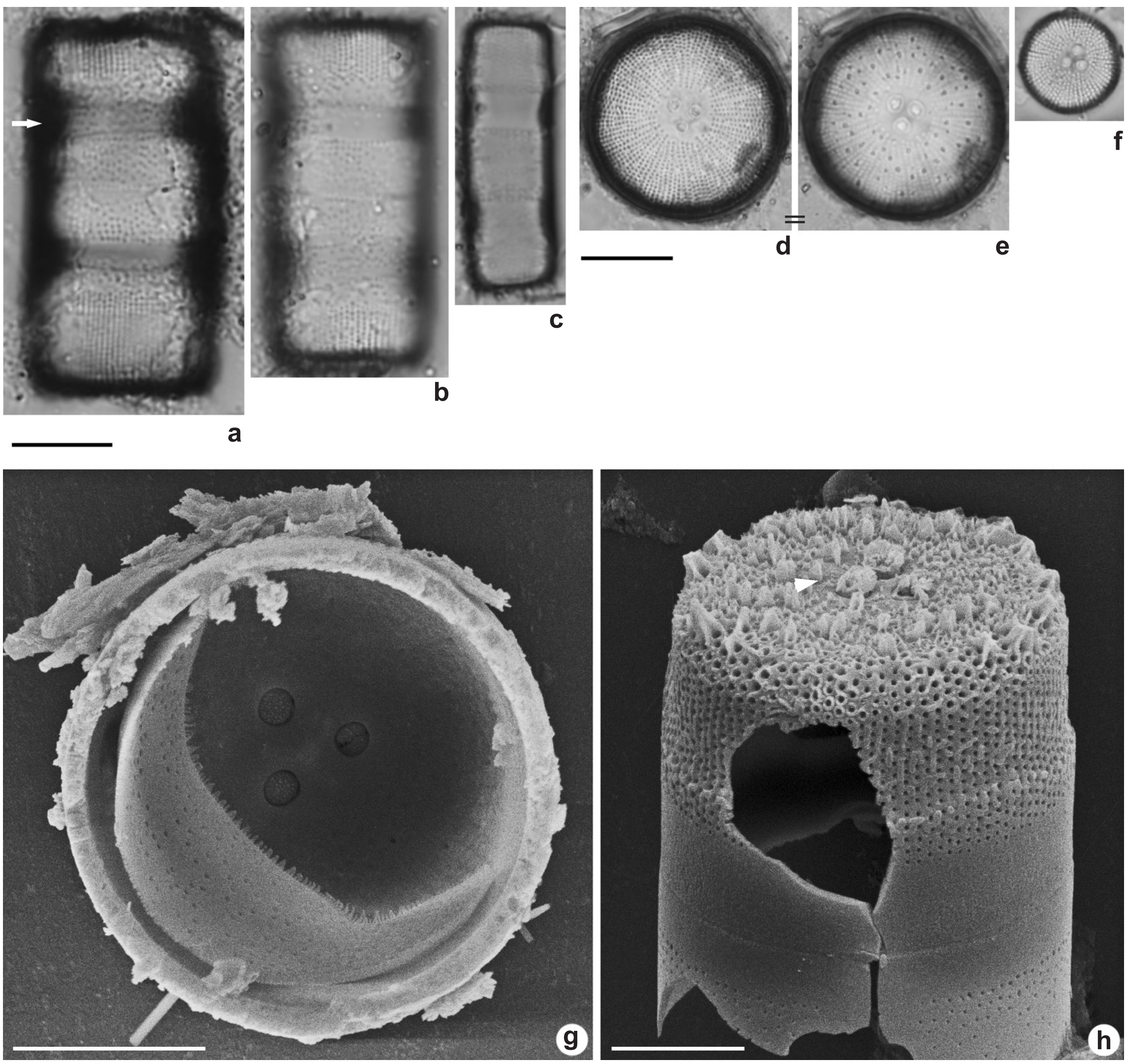

Figure 11 – a-h. *Orthoseira roeseana* – a-f. valves in LM – a-c. girdle views, observe the valve constrictions (arrow); d-f. valve views; g-h. valves in SEM – g. detail of carinoportulae in internal view; h. external view. Scale bars: a-f = 10 µm; g-h = 5 µm.

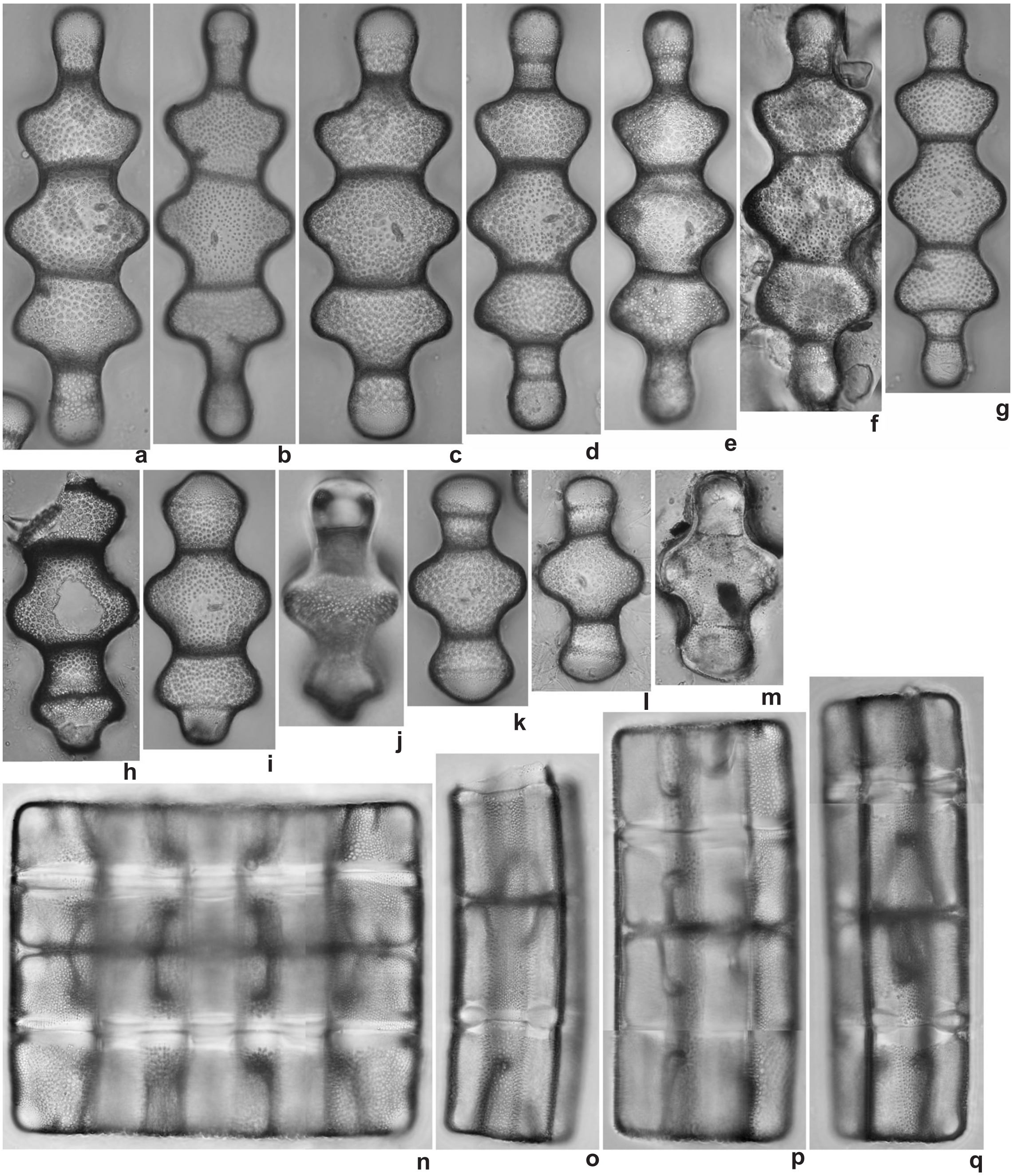

Figure 12 – a-q. *Terpsinoë musica* (valves in LM) – a-m. valve view; n-q. girdle view. Scale bars: 10 µm.

Most taxa were rare (6) or sporadic (7). Only two species were frequent: *Cyclotella meneghiniana*, occurring in 16 of the 24 sampling points, and *Cyclotella cryptica* which occurred in 10 sampling points. Furthermore, only *C. meneghiniana* occurred in all hydrographic basins, showing its wide geographic distribution in the region. In general, *C. meneghiniana* is frequent and abundant in rivers and lakes, under different trophic conditions (Kiss *et al*. 2012), and is particularly common in shallow and nutrient-rich waters (Houk *et al.* 2010). The species has been classified as an eutrophic indicator for highly fertilized waters with high conductivity (Joh 2010).

The taxa that occurred in at least three of the studied hydrographic basins were: *Cyclotella atomus*, *C. cryptica*, and *Discostella stelligera*. Furthermore, it was observed that there was no significant difference in richness among different substrates, but rather in different environments, being higher in rivers and lower in puddles and dams.

Fifteen taxa were identified, with 12 new occurrences for the northwest region of Ceará. *Aulacoseira ambigua* (cited as *Melosira ambigua* (Grunow) O.Müller), *Aulacoseira granulata* var. *granulata* [cited as *Melosira granulata* (Ehrenberg) Ralfs], and *Cyclotella meneghiniana* were previously registered by Patrick (1940a) in the Jaibaras weir, in the municipality of Sobral. *Discostella stelligera* is registered for the first time in Northeastern Brazil, having been previously recorded in the South (Ferrari & Ludwig 2007; Nardelli *et al*. 2014; Silva-Lehmkuhl *et al.* 2019), Southeast (Morandi *et al.* 2006), and Central-west (Da Silva *et al.* 2011) of the country. *Discostella woltereckii* is cited for the first time in Brazil;

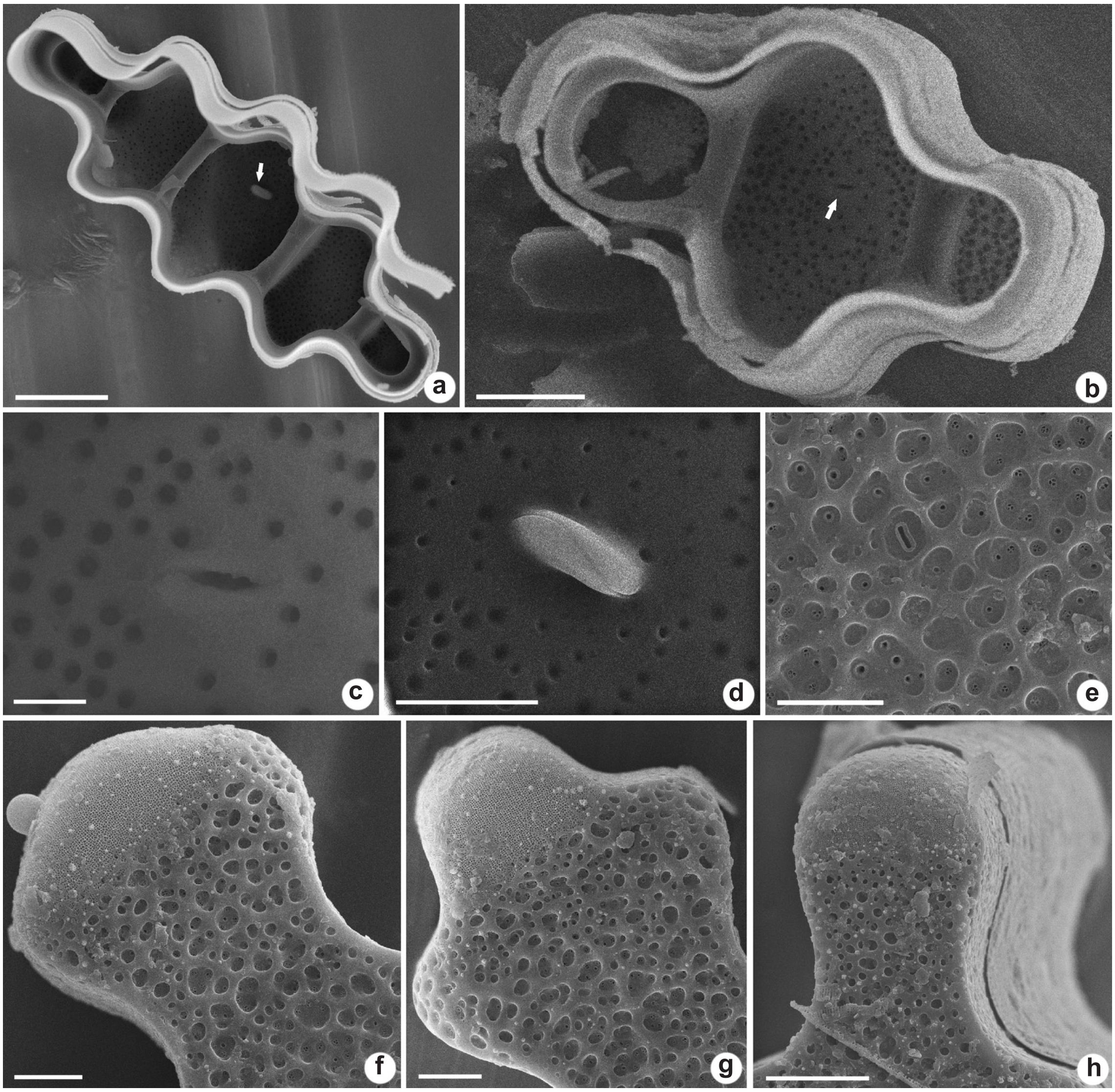

Figure 13 – a-h. *Terpsinoë musica* (valves in SEM) – a-b. internal valve view of the valve, observe the septa; c. internal view of the rimoportula, valve with less undulations; d. internal view of the rimoportula, valve with three undulations; e. external view of the rimoportula; f-g. valve apices of one or bi undulated valves; h. valve apice of triundulated valve. Scale bars: a = 20 µm; b,h = 10 µm; d-g = 5 µm; c. 2 µm.

however, there are previous identifications of *D. pseudostelligera* for which conspecificity must be evaluated (Brassac *et al.* 1999; Morandi *et al.* 2006; Cavalcante *et al.* 2013; Faustino *et al.* 2016). The species complexes *Discostella pseudostelligera*/*D. woltereckii*, *Orthoseira roeseana*/*O. dendroteres* and *Terpsinoë musica*/*T. muninensis* require further attention and additional studies, including analyses of their ecology and lifecycle and assessments using molecular tools, to provide a better delimitation of each.

Cyclotella marina is registered for the second time in a Brazilian freshwater habitat. According to Aké-Castillo *et al.* (2012), this species is generally found in brackish environments with a high-nutrient content. The entry of the species into freshwater can reflect the intermittent conditions of the river systems in northwest Ceará, where evaporation and low-levels of rainfall result in continuous rivers being converted into isolated pools, or dry up completely, during the dry season. High levels of evapotranspiration in the dry seasons lead to ion concentration and an increase in nutrients, especially in streams with no canopy cover (Goméz *et al.* 2017; Olson 2019). In addition, the pollution caused by domestic sewage exacerbates the accumulation of nutrients. The environmental characteristics of the Acaraú River in our study are very similar to those reported in records of *C. marina* by Cavalcante *et al.* (2013) of a shallow urban river in Northeastern Brazil.

Finally, floristic studies are essential to understand the geographic distribution of taxa and to support future ecological studies. This study shows that the diatom diversity in Brazilian semi-arid region is underestimated, contributing to a more consistent understanding of diatom distribution in the country.

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