Article

Tetracyclus radius (Bacillariophyta) a new fossil species from Miocene freshwater sediments in the Japan Sea

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Abstract

A new fossil diatom species, *Tetracyclus radius* sp. nov, is described from freshwater sediments under the Yamato Bank in the Japan Sea. Its valve outline is circular with radiating costae and has a single rimoportula. There is no distinct sternum but a hyaline central area is present. The freshwater sediments are deposited before the Early Pliocene by diatom biostratigraphy of the overlying marine sediments.

Introduction

The diatom genus *Tetracyclus* Ralfs is mainly composed of extinct, freshwater species, most having characteristic valve shapes. The valve outline can be circular (Williams & Li 1990), elliptical/rhomboidal (Williams 1996), elongate (Williams 1996) or with certain parts constricted (Williams 1989, 2007, 2009). All known species, however, have uniseriate striae that may be somewhat disorganized but are transversely arranged on a flat valve face; they are not interrupted by the internal costae. The more or less elongate valves are symmetrical about the apical axis and the sternum is of an irregular structure, defined by terminating striae.

At present *Tetracyclus* has over 30 species (Williams 1996). A number of fossil species have been described from East Asia: *T. japonicus* (Petit 1890: 2) Tempère & Peragallo (1909: 185) and *T. polygibbum* (Pantocsek 1892: pl. 2, fig 19) Jousé (1952: 242) from Japanese sediments (Williams 1996); *T. ovaliformis* Li (1984: 234), *T. shanduensis* Li (1984: 235), *T. subclypeus* Li & Williams (in Williams & Li 1990: 336); and *T. subdivisium* Williams & Li (1990: 337) from Late Miocene deposits in Inner Mongolia (Williams & Li 1990). This paper documents a new fossil species of *Tetracyclus* from freshwater sediments at the earliest Middle Miocene. The specimens were found in the central part of the Japan Sea (Burckle & Akiba 1978). In this area, freshwater lakes were known to be formed during the Early to earliest Middle Miocene (about 20 to 15 Ma), accompanied by the birth and expansion of the Proto-Japan Sea (Otofuji *et al*. 1985; Torii *et al*. 1985; Jolivet & Tamaki 1992; Tamaki *et al*. 1992).

Material and methods

A deep-sea core, RC12-394, was recovered from the northeast flank of the Yamato Bank at lat. 40º 19' N, long. 136º 13.5' E in 2338 m of water depth (Burckle & Akiba 1978). The core was composed of 376 cm-thick freshwater sediments under 225 cm-thick marine sediments. Raw material taken from 490 cm core depth was

examined for this study. The freshwater sediments had no marine diatoms but many species from the non-marine genera *Aulacoseira* Thwaites (1848: 167) and *Actinocyclus* Ehrenberg (1837: 61).

Based on geographical, geological and biostratigraphical evidence, Burckle & Akiba (1978) proposed that the freshwater sediments were formed when the Japan Sea was a fresh-water lake. Yamato Bank is irregularly raised in the Japan Sea and its basement granitic rocks originate from continental crust (Ludwig *et al.* 1975). It differs from the basaltic basement in Nihon and Yamato Basins around the bank. Diatom biostratigraphy (Burckle & Akiba 1978) suggests the bottom of the marine sediment in RC12-394 core corresponds to the early Pliocene. The freshwater section would have been deposited earlier than the marine sediment, probably in the Late Miocene, considering little erosion and deposition between freshwater and marine strata.

The raw material was boiled in 15 % hydrogen peroxide (H_2O_2) for 30 minutes and decanted 3 times with distilled water. For light microscopy (LM), suspended material was dried on 18 × 18 cover slips (Matsunami, No. 1), mounted on glass slides (Matsunami, S-1112) with styrax resin (Sigma Storax) and heated at 80 ℃ for 2 weeks to fix the resin. For scanning electron microscopy (SEM), the suspension was filtered with a Millipore type HA filter. The filter was dried and mounted on JEOL tin stubs. LM and SEM were performed using a Nikon ECLIPSE 80i and a JEOL JSM-5310 (National Museum of Nature and Science), respectively. Terminology follows Ross *et al.* (1979) and Round *et al.* (1990).

New species description

Division Bacillariophyta
Class Fragilariophyceae Round in Round et al. 1990
Order Fragilariales Silva 1962
Family Fragilariaceae Greville 1833
Genus *Tetracyclus* Ralfs 1843
Tetracyclus radius* Saito-Kato, Hayashi & Tanimura, *sp. nov. (Figs 1—20).

Type:—JAPAN. Deep-sea sediments at the earliest Middle Miocene, 490 cm in depth of the RC12-394 core, recovered from the Yamato Bank, Japan Sea (holotype MPC-04211).

Vegetative cells: Valves circular, 10–30 μm in diameter, striae density c. 25–30 in 10 μm at margin on valve face; c. 30 areolae in 10 μm, arranged radially. Valve face flattened, mantle vertical. Valve face with central hyaline area, lacking sternum; valve face and margin with internally developed radial transapical ribs and striae. Some ribs extending towards central area, some part way onto valve face, others present only at mantle. Striae composed of parallel rows of areolae. Single rimoportula, simple slit externally, located within stria, with paired lips, internally. Cingulum composed of more than 5 open copulae, band orientation at 90º to rimoportula. Each copula with ligula and paired areolae divided by septum; areolae in parallel rows. No evidence of further band differentiation.

Initial cells: Hemispherical with thin valve margin, 25–30 μm in diameter. Central area with irregularly arranged areolae and hyaline structures. Marginal area composed of internally developed radial costae and striae. Striae composed of parallel areolae rows, single rimoportula located within stria, structure as in vegetative valve.

Observations

The vegetative valves are circular, 10–30 μm in diameter (Figs 1–3). The valve face is flattened and the mantle vertical, situated almost at right-angles to the valve face (Figs 8, 9). The valve face has an irregularly spaced central hyaline area, lacking any obvious sternum (Figs 1–3, 8, 11, 12, 17–19). On the valve face and margin, along with uniseriate striae, there are well developed radial transapical ribs (Figs 11, 12, 17–19).
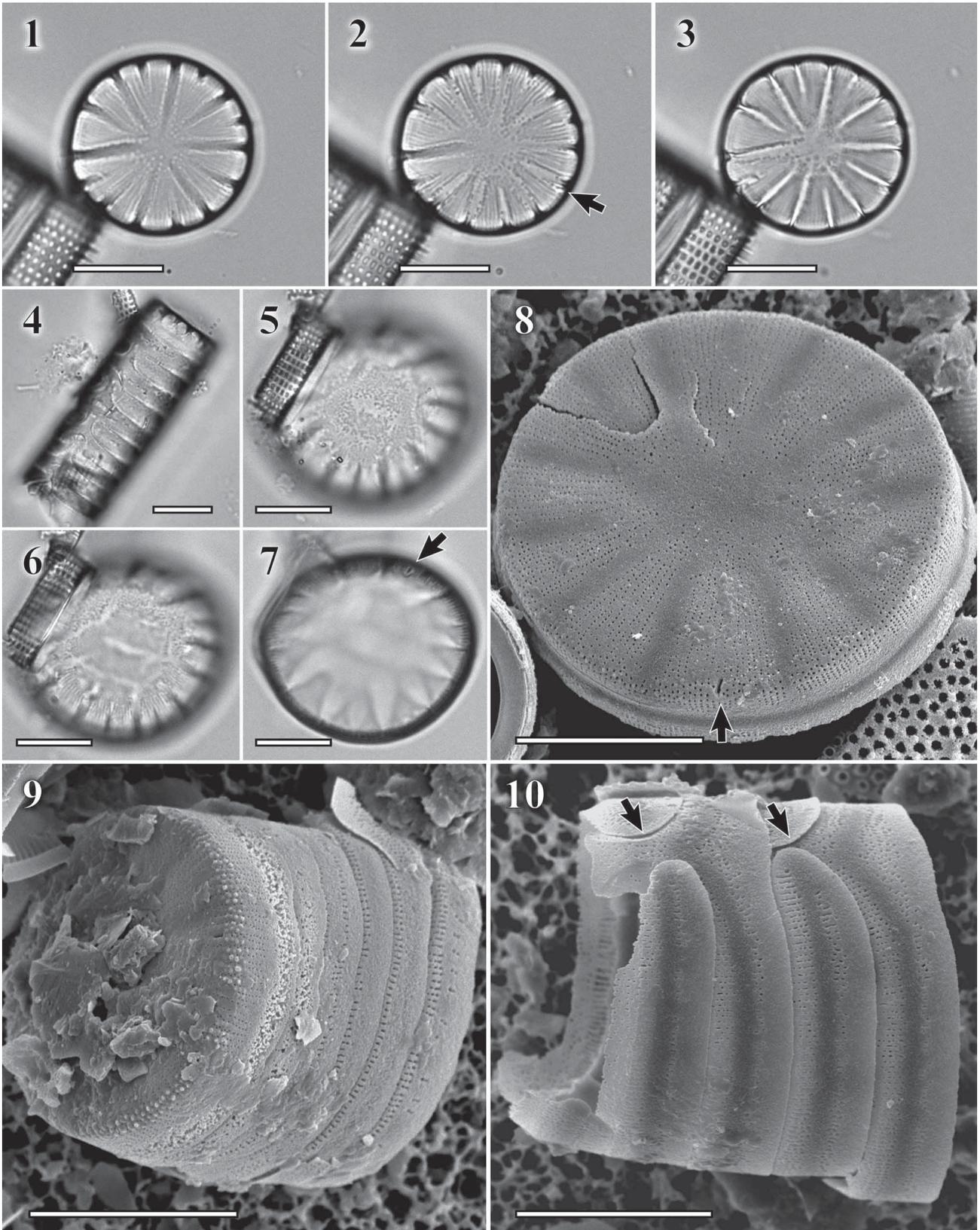
FIGURES 1–10: *Tetracyclus radius*. Figs 1–3: LM images of holotype specimen at different focal depths. Arrow indicates position of rimoportula in Fig. 2. Figs 4–7: LM images of further specimens from the same horizon as holotype. Fig. 4 is the frustule in girdle view, Figs 5–7: Initial cell at different focal depths. Fig. 7: Valve with rimoportula arrowed. Figs 8–10: SEM images of specimens from the same horizon as holotype. Fig. 8: Valve with external opening of rimoportula (arrow). Fig. 9: Valve and part of the girdle, with 5 bands. Fig. 10: Partial cingulum showing opening and ligula (arrows). All scale bars = 10 μm.
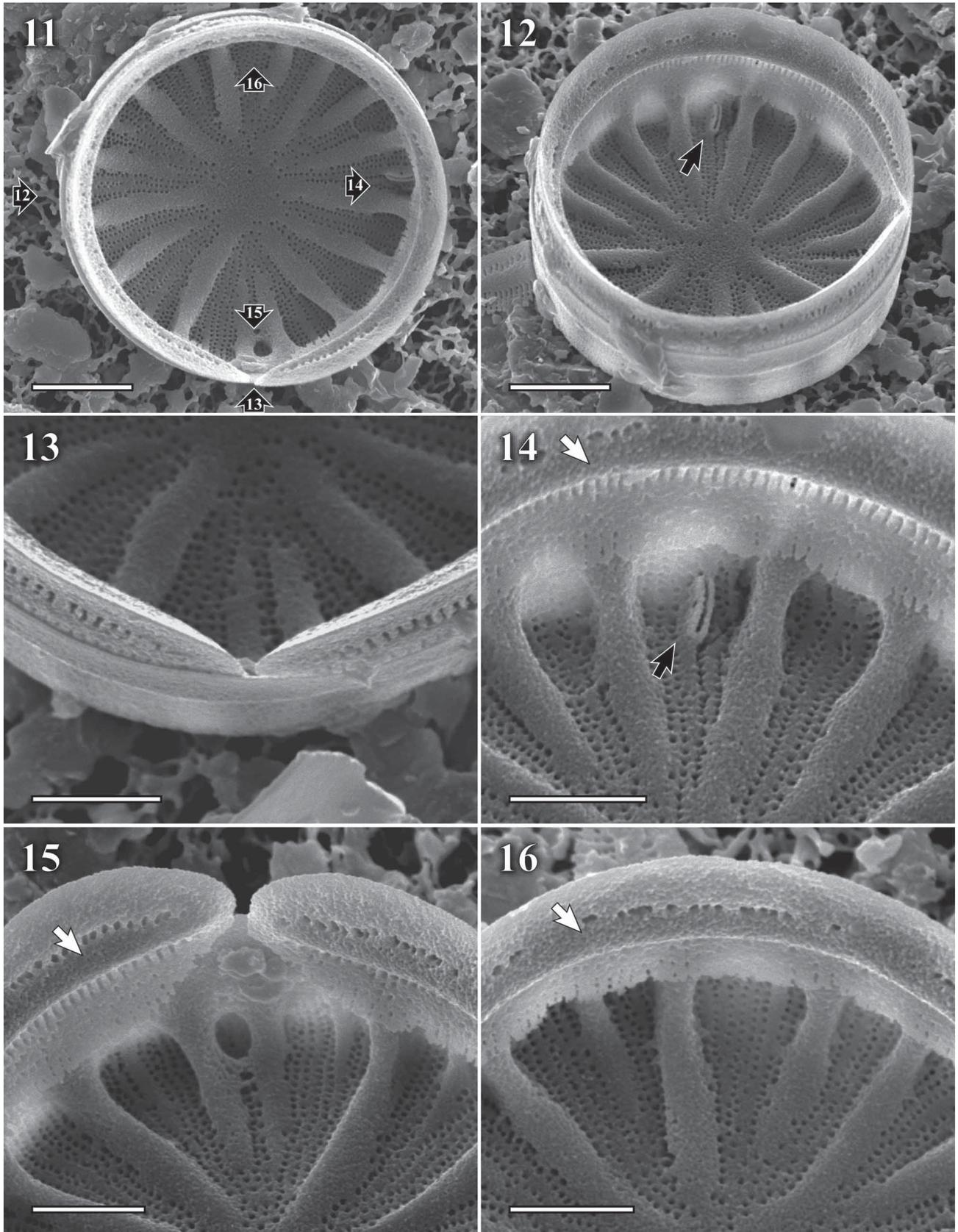
FIGURES 11–16: *Tetracyclus radius*. SEM images of specimen from the same horizon as holotype. Fig. 11: Internal view of valve. Figs 12–16: Various higher magnification images of the valve in Figure 11 (numbers on Figure 11 indicate area in Figs 12–16). Rimoportula on valve face/mantle junction (Figs 12 & 14, indicated by black arrows); open valvocopula with striae and septa (Figs 13–16, white arrows indicate the septum). Scale bars: Figs 11 & 12: 5 µm; Figs 13–16: 3 µm.
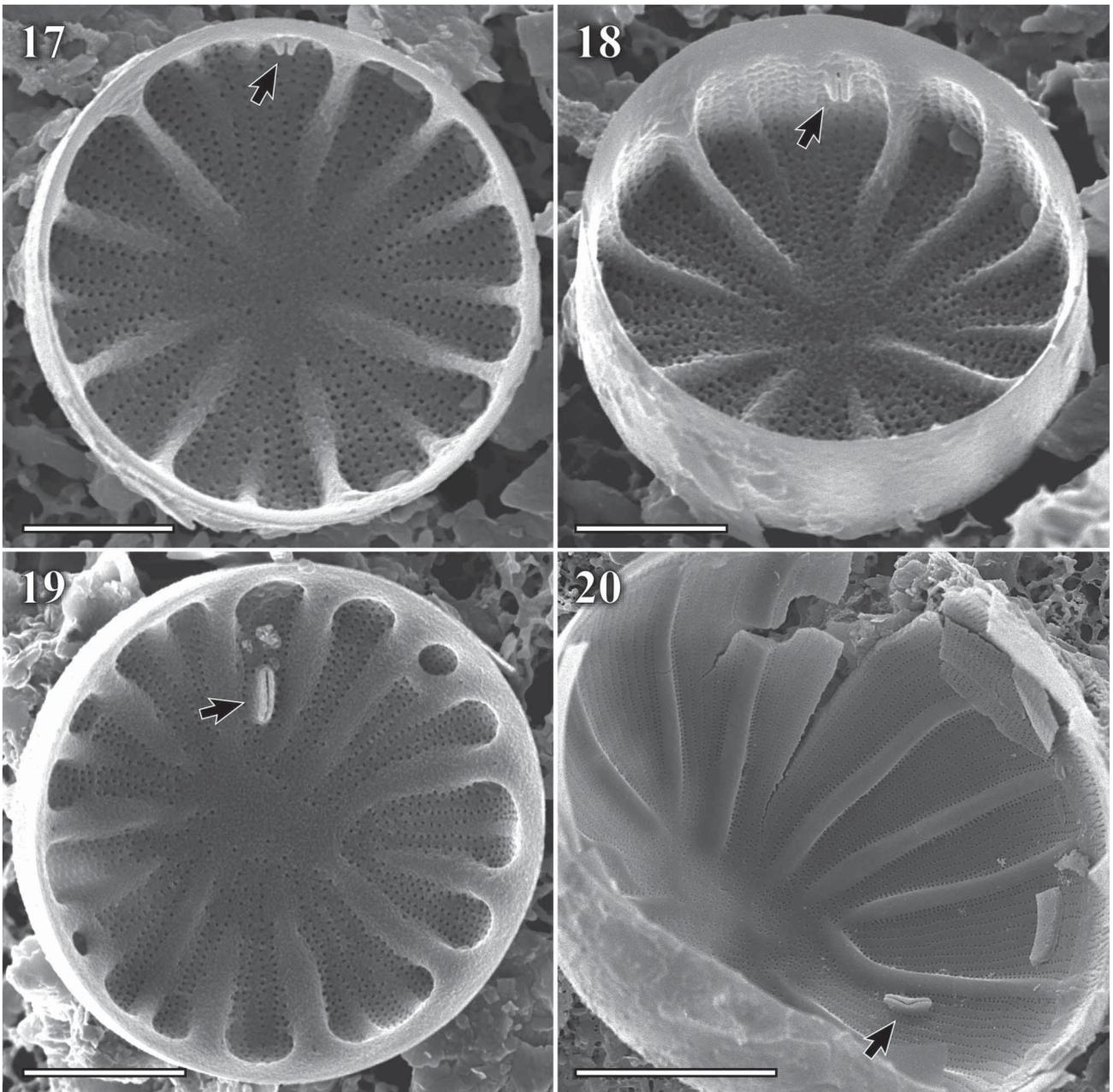
FIGURES 17–20: *Tetracyclus radius*. SEM images of specimens from same horizon as holotype specimen. Figs 17 & 18: Internal and oblique view of same valve; note rimoportula on mantle (arrows). Fig. 19: Valve with rimoportula on valve face near the central area (arrow). Fig. 20: Initial valve. Note sessile labium of rimoportula (arrow). Scale bars: Figs 17 & 18: 3 μm; Fig. 19: 5 μm; Fig. 20: 10 μm.

Some of these ribs extend towards the central area (Figs 11, 12, 17—19), others extend part way onto valve face (Figs 11, 12, 17–19), and others still are present only on the mantle (Fig. 17). The striae are composed of single, parallel rows of areolae, with a density of c. 25–30 in 10 μm at margin on valve face. In total there are c. 30 areolae in 10 μm arranged radially. A single rimoportula is located within stria (Fig. 8), as a simple slit, externally, with paired simple lips, internally (Fig. 14). The cingulum is composed of at least 5 open copulae (Figs 4, 9, 10). The bands are orientated at 90º to the rimoportula (Figs 11, 13). Each copula has a ligula and paired areolae, which are separated by a septum (Figs 15, 16). The copulae areolae are in parallel rows either side of the septum (Fig. 10).

Initial cells were noted as hemispherical with a thin valve margin (Figs 5–7, 20), 25–30 μm in diameter. Like the vegetative valve, the central area has irregularly arranged areolae as well as transapical ribs (Fig. 5–7). The margin, internally, also has transapical ribs as well as striae (Fig. 20). The striae are in parallel rows; there is a single rimoportula located within stria, its structure as in the vegetative valve.

Discussion

Using only LM, it is difficult to distinguish *Tetracyclus radius* from taxa classified in the family Stephanodiscaceae Glezer & Makarova. For example, *T. radius* appears similar to *Cyclotella atomus* Hustedt (1937: 143) as both appear to share a non-areolated central area and the valve margins are composed of a series of radial costae (transaspical ribs) and striae. However, *T. radius* lacks fultoportulae, a defining feature of taxa in Stephanodiscaceae. Additionally, *T. radius* has its rimoportula situated within a stria, whereas in Stephanodiscaceae valves have it fixed to a costa in the mantle (sometimes within the hyaline central area) (e.g. Håkansson 2002). However, a few species in the genus *Discostella* Houk & Klee (2004: 205) do have a rimoportula situated within a stria (e.g. Houk & Klee 2004). In *T. radius* there are some variations in the position of the rimoportula: It can be on the mantle (Figs 17 & 18) or on the valve face near the central area (Fig. 19) (variations in the position of the rimoportula also occur in initial valves; compare Figs 7 and 20), unlike species of *Discostella*.

In *Tetracyclus* itself, most species have elongated valves (either oval, elliptical or rhomboidal) often with the central part expanded or constricted; the striae and transapical ribs are symmetrically relative to the sternum (apical axis) (e.g. Williams 1996, 2009, Williams & Li 1990). In contrast to this group of species, *T. radius* has valves with a perfectly circular outline, and the striae and transapical ribs radially arranged. *T. radius* differs from other species of *Tetracyclus* because the central area does not form an obvious sternum. However, the central area of *T. radius* is often elongated resembling a rudimentary sternum, that is the central area is oriented in line with the open end of the copulae, suggesting that valve silicifcation is like that in other species of *Tetracyclus* (Figs 8, 11, 17, 19). Therefore, the sternum of *T. radius* exists as a simple modified hyaline central area.

Other Miocene fossil species of *Tetracyclus* are *T. subclypeus* and *T. subdivisium* (Williams & Li 1990) both from Inner Mongolia, both resembling *T. radius*. *Tetracyclus subclypeus* has valves with a circular outline, but the striae and transapical ribs are symmetrically arranged with respect to the sternum, as distinct from *T. radius*. *Tetracyclus subdivisium* also has circular to subcircular valves, and smaller specimens have radially arranged transapical ribs, similar to *T. radius*. However, *T. subdivisium* has no more than two transapical ribs, and in larger specimens they are parallel. Therefore, as *T. radius* always has many radially arranged ribs it can be clearly differentiated from *T. subdivisium*.

Li (1982) presented many LM and SEM images of fossil species of *Tetracyclus* from Inner Mongolia, including specimens with valves having a circular outline and radial transapical ribs. These are distinct from *T. radius* as they have an elongated central area which clearly forms a sternum. These specimens were probably misidentified as *T. japonicus* by Li (1982) and may be an as yet described species (see Williams 1989).

References

Burckle, L.H. & Akiba, F. (1978) Implications of late Neogene fresh-water sediment in the Sea of Japan. *Geology* 6: 123–127.

Ehrenberg, C.G. (1837) Nachricht des Hrn Agassiz in Neuchatel über den ebenfalls aus mikroskopichen Kiesel-Organismen gebildeten Polirschiefer von Oran in Afrika vor. *Bericht über die zur Bekanntmachung geeigneten Verhandlungen der Königlich-Preussischen Akademie der Wissenschaften zu Berlin*, 1837: 59–61.

Håkansson, H. (2002) A complication and evaluation of species in the general *Stephanodiscus*, *Cyclostephanos* and

Cyclotella with a new genus in the family Stephanodiscaceae. *Diatom Research* 17: 1–139.

Houk, V. & Klee, R. (2004) The stelligeroid taxa of the genus *Cyclotella* (Kützing) Brébisson (Bacillariophyceae) and their transfer into the new genus *Discostella* gen. nov. *Diatom Research*, 19: 203–228.

Hustedt, F. (1937) Systematische und ökologische Untersuchungen über die Diatomeen-Flora von Java, Bali und Sumatra nach dem Material der Deutschen Limnologischen Sunda-Expedition. *Archiv für Hydrobiologie*, Supplement 15: 131–177.

Jousé, A.P. (1952) K istorii Diatomovoi flory ozera Khanka [About the history of the diatom flora of Lake Khanka]. *Proceedings of the Institute of Geography, Academy of Science USSR (Trudy Instituta Geographii Academia Nauk SSSR)* 51: 226–252.

Jolivet, L. & Tamaki, K. (1992) Neogene kinematics in the Japan Sea region and volcanic activity of the northeast Japan Arc. *In*: Tamaki, K. Suyehiro, K., Allan, J., McWillams, M. *et al.* (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 127/128, Part 2*. College Station, Texas, 1311–1331.

Li, J.Y. (1982) Genus *Tetracyclus* and its stratigraphic significance. *Bulletin of the Institute of Geology, Chinese Academy of Geological Sciences* 5: 149–166.

Li, J.Y. (1984) [Some new species and varieties of the genus *Tetracyclus* Ralfs (Bacillariophyta)]. *Acta Phytotaxonomica Sinica* 22: 231–236.

Ludwig, W.J., Murauchi, S. & Houtz, R.E. (1975) Sediments and structure of the Japan Sea. *Geological Society of America Bulletin* 86: 651–664.

Otofuji, Y., Matsuda, T. & Nohda, S. (1985) Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan–rifting process of the Japan arc. *Earth and Planetary Science Letters* 75: 265–277.

Pantocsek, J. (1892) *Beiträge zur Kenntnis der Fossilen Bacillarien Ungarns.* 3 Teil. Julius Platzko, Nagyy-Tapolcsany. Teil III, Susswasser Bacillarien. Anhang-analysen 15 neuer Depots von bulgarien, Japan, Mahern, Russland und Ungarn. Nagy-Tapolcsány, Buchdrucherei von Julius Platzko. 42 pls.

Petit, P. (1890) Note relative aux diatomées fossiles du Japon de MM. Brun et Tempère. *Journal de Micrographie* 14: 148–151.

Ross, R., Cox, E.J., Karayeva, N.I., Mann, D.G., Paddock, T.B.B., Simonsen, R. & Sims, P.A. (1979) An amended terminology for the siliceous components of the diatom cell. *Nova Hedwigia*, Beihefte 64: 513–533.

Round, F.E. Crawford, R.M. & Mann, D.G. (1990) *The diatoms: biology and morphology of the genera*. Cambridge University Press, Cambridge. 747 pp.

Tamaki, K., Suyehiro, K., Allan, J., Ingle, J.C. & Pisciotto, K. (1992) Tectonic synthesis and implications of Japan Sea ODP drilling. *In*: Tamaki, K., Suyehiro, K., Allan, J., McWillams, M. *et al.* (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 127/128, Part 2*. College Station, Texas, 1333–1348.

Tempère, J. & Peragallo, H. (1909) *Diatomées du Monde Entier*, 2nd edn., fascicule 8–12. Chez J. Tempère, Arcachon, Gironde. pp. 113–208.

Thwaites, G.H.K. (1848) Further observations on the Diatomaceae with descriptions of new genera and species. *Annals and Magazine of Natural History*, 2nd ser., 1: 161–172.

Torii, M., Hayashida, A. & Otofuji, Y. (1985) Rotation of Southwest Japan and the birth of the Japan Sea. *Kagaku* 55: 47–52 (in Japanese).

Williams, D.M. (1989) Observations on the genus *Tetracyclus* Ralfs (Bacillariophyta) II. Morphology and taxonomy of some fossil species previously classified in *Stylobiblium* Ehrenberg. *British Phycological Journal* 24: 317–327.

Williams, D.M. (1996) Fossil species of the diatom genus *Tetracyclus* (Bacillariophyta, 'ellipticus' species group): morphology, interrelationships and the relevance of ontogeny. *Philosophical Transactions of the Royal Society London B* 351: 1759–1782.

Williams, D.M. (2007) Paleogeographic impact of a newly described 'cruciform' sub-group of *Tetracyclus* (Bacillariophyta, Diatomaceae). *Micropaleontology* 53: 421–429.

Williams, D.M. (2009) The identity of *Tetracyclus constrictus* (Bacillariophyceae) and a description of *Tetracyclus bradburyii*, a new Miocene species. *Annales de Paléontologie* 95: 37–51.

Williams, D.M. & Li, J.Y. (1990) Observations on the diatom genus *Tetracyclus* Ralfs (Bacillariophyta). III. Description of two new species from Chinese fossil deposits. *British Phycological Journal* 25: 335–338.