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A Cenozoic Diatom Genus *Cavitatus* WILLIAMS; an Emended Description and Two New Biostratigraphically Useful Species, *C. lanceolatus* and *C. rectus* from Japan

By

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Abstract An emended description of a fossil diatom genus *Cavitatus* is presented, because the original description (WILLIAMS, 1989) is based on observation of poorly preserved specimens and lacks such important morphologic features of this genus as its heterovalvate nature, and the presence of areolae and rimoportulae. It is suggested that *Cavitatus* is most close to the genus *Thalassionema*. *Cavitatus* is based on *Synedra jouseana* SHESHUKOVA (1962), and has been monospecific so far. Our study shows that the genus comprises at least six species; *C. jouseanus* (SHESHUKOVA) WILLIAMS, *C. linearis* (SHESHUKOVA) AKIBA et YANAGISAWA stat. et comb. nov., *C. miocenicus* (SCHRADER) AKIBA et YANAGISAWA comb. nov., *C. exiguus* YANAGISAWA et AKIBA sp. nov., *C. lanceolatus* AKIBA et HIRAMATSU sp. nov. and *C. rectus* AKIBA et HIRAMATSU sp. nov. The last two new species have significant biostratigraphic utilities in the Cenozoic of Japan, because the former is restricted to a short interval in the middle Miocene *Denticulopsis lauta* Zone (NPD4A) and the latter is limited to the upper Oligocene through lower Miocene, an interval below the first occurrence of *Thalassiosira fraga*.

Introduction

The aim of this paper is to present morphologic characteristics and stratigraphic occurrences of the genus *Cavitatus* for its better use in the Cenozoic diatom biostratigraphy and also for the better understanding of its phylogeny.

The genus *Synedra* has been an enormous admixture of many forms with different valve structures and habitats, likewise such genera as *Coscinodiscus*, *Fragilaria*, *Melosira*, *Navicula* and *Nitzschia* etc. Recently, however, ROUND (1979), WILLIAMS (1986), WILLIAMS & ROUND (1986) and ROUND *et al.* (1990) have refined the genus and subdivided it into many distinct genera. They examined various recent "*Synedra*" species by detailed scanning electron micrography. A fossil species, *Synedra jouseana* SHESHUKOVA was studied by WILLIAMS (1989) who erected the new genus *Cavitatus* based on the species. He noted unique morphologies of the genus such as a central burrowed sternum, marginal transapical cavities and the absence of rimoportulae (WILLIAMS, 1989). Most of the features, however, are found here to be due to very poor preservation of the specimens he observed. An emended description of the genus including its heterovalvate nature and the presence of areolae and rimoportulae, therefore, is presented here based on our observation of the genus using better preserved specimens.

As *Cavitatus jouseanus* (SHESHUKOVA) WILLIAMS is an extinct marine taxon and one of the main and cosmopolitan constituents of the Oligo-Miocene open marine diatom flora, it has been very familiar to Neogene diatom biostratigraphers for the past three decades (SHESHUKOVA-PORETZKAYA, 1962, 1967; KOIZUMI, 1973; BARRON, 1985b; FENNER, 1985; AKIBA, 1986; HARWOOD, 1986 and others). Although WILLIAMS (1989) transferred only this species into *Cavitatus*, there are three other taxa closely related to the species: *S. jouseana* f. *linearis* SHESHUKOVA (1962), *S. miocenica* SCHRADER (1976) and *S. jouseana* var. 1 (BARRON, 1980; ITO, 1986; YANAGISAWA *et al.*, 1989). In addition, our diatom biostratigraphic study of several Cenozoic sections of Japan recognized two new taxa characterized by distinct valve outlines. Comparative study of the six taxa suggests that all of them are distinct species, and then the genus *Cavitatus* presently comprises following six species; *C. jouseanus* (SHESHUKOVA) WILLIAMS, *C. lanceolatus* AKIBA et HIRAMATSU sp. nov. (=*S. jouseana* var. 1), *C. linearis* (SHESHUKOVA) AKIBA et YANAGISAWA stat. et comb. nov., *C. exiguus* YANAGISAWA et AKIBA sp. nov., *C. miocenicus* (SCHRADER) AKIBA et YANAGISAWA comb. nov. and *C. rectus* AKIBA et HIRAMATSU sp. nov. The stratigraphic occurrence of *C. lanceolatus* sp. nov. and *C. rectus* sp. nov. is restricted to very limited horizons in the Cenozoic of Japan. They are therefore biostratigraphically highly useful.

Material and Methods

Figure 1 shows the locations of selected Cenozoic sequences in Japan which are examined or referred to in this paper. Samples or sections used either to typify new species or to examine their stratigraphic occurrences are described below in detail.

1. Type locality of *C. rectus* sp. nov. is designated in the Tokiwa Formation of the Atsunai Group in the vicinity of Ikuchise, Atsunai area, eastern Hokkaido (Fig. 2). A series of 16 samples (JDS-11563-11571 and 11616-11623) from the Okubonosawa Section was studied to demonstrate the biostratigraphic occurrence of the new species (Fig. 2). The Atsunai Group, which is very diatomaceous and exposed widely in this region, has long been studied, but there have been various opinions on the stratigraphic subdivision and age assignment (AKIBA *et al.*, 1982a; AKIBA & ICHINOSEKI, 1983; TADA & IIJIMA, 1986; AKIBA & YANAGISAWA, in prep.). This paper follows formation names by TADA & IIJIMA (1986) and age assignments by AKIBA & YANAGISAWA (in prep).

2. DSDP, Leg 57, Hole 438A, off northeastern Honshu, was first studied by BARRON (1980) in great detail and includes almost continuous early Miocene through Pleistocene diatom zones. This is one of the best reference sections in this region and therefore has been repeatedly studied by many authors (AKIBA *et al.*, 1982b; MARUYAMA, 1984; AKIBA, 1986; ORESHKINA & RADIONOVA, 1987; YANAGISAWA & AKIBA, 1990).

3. The type locality of *C. lanceolatus* sp. nov. is located in the Otsuka For-

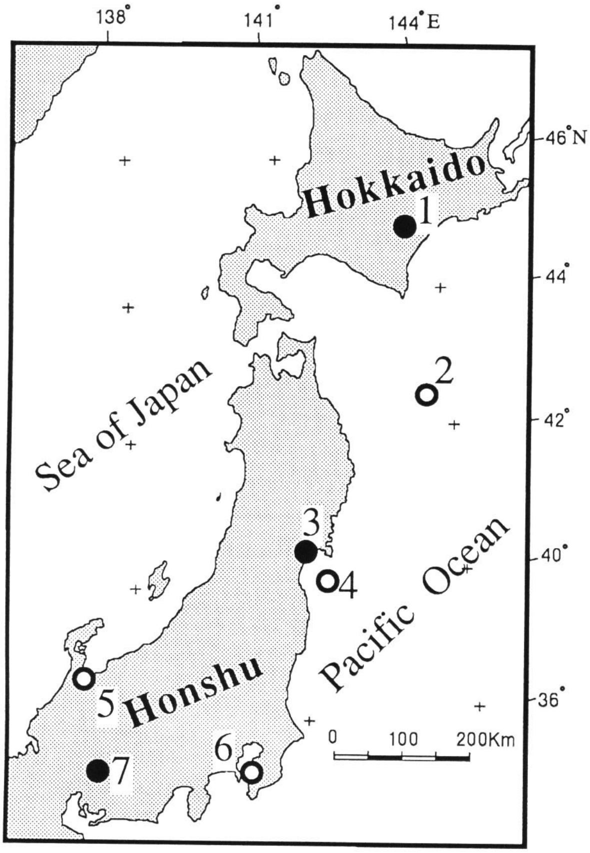


Fig. 1. Locality of selected Cenozoic sequences in Japan treated in this paper. Black circles indicate type localities of new taxa of *Cavitatus*. 1, The Tokiwa Formation and the Okubonosawa Section: Holotype locality of *Cavitatus rectus* sp. nov. 2, DSDP, Leg 57, Site 438A. 3, The Otsuka Formation, Matsushima area, Miyagi Prefecture: Holotype locality of *Cavitatus lanceolatus* sp. nov. 4, An offshore well, MITI-Souma-oki. 5, Neogene sequences in Kanazawa area, Ishikawa Prefecture and Yatsuo area, Toyama Prefecture. 6. The Okuyama Formation of the Sakuma Group, Boso Peninsula, Chiba Prefecture. 7, The Oidawara Formation, Mizunami area, Gifu Prefecture: Holotype locality of *Cavitatus exiguus* sp. nov.

mation of the Matsushimawan Group distributed in the Matsushima area, Miyagi Prefecture, northeast Honshu (Fig. 3). The diatom biostratigraphy of the Neogene sequences in this area was reported by Akiba *et al.* (1982b), which shows that the holotype sample belongs to the middle Miocene *Denticulopsis lauta* Zone (NPD4A).

4. MITI Souma-oki, an offshore well, off Souma, Fukushima Prefecture, northeast Honshu (37°51′07.688″N, 141°34′45.473″E) with a total depth of 3,500 m was drilled by the Ministry of International Trade and Industry (MITI) in 1990, in order to obtain basic information on hydrocarbon accumulation in this area. Eight diatom

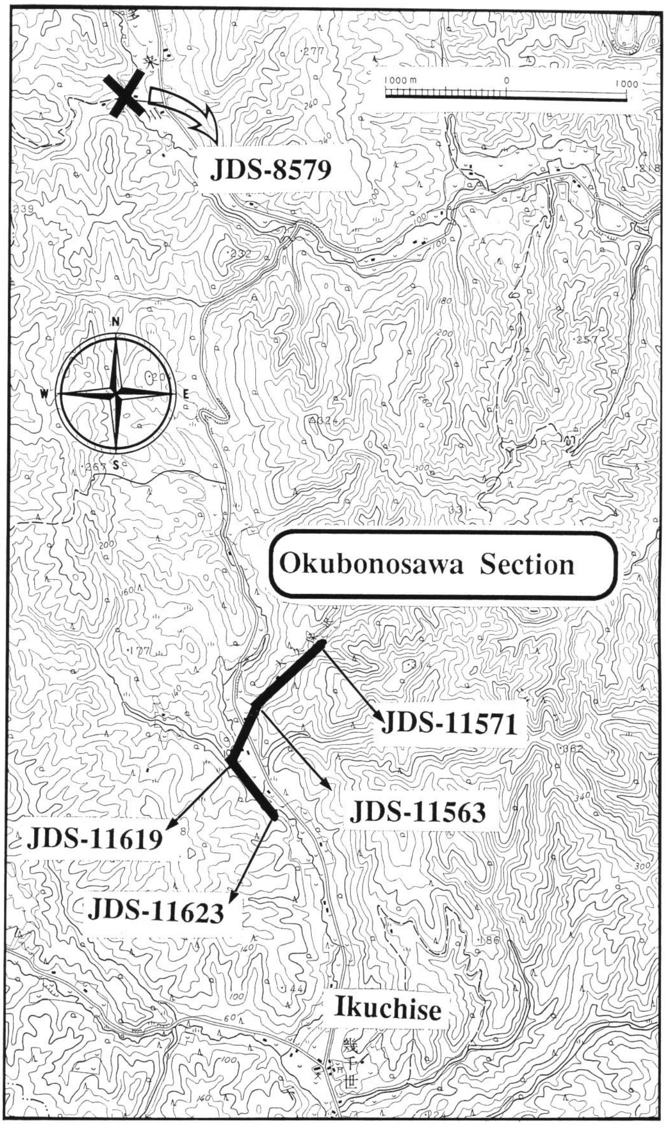


Fig. 2. Locality of the holotype material of *Cavitatus rectus* sp. nov. (JDS-8579) and the samples from the Okubonosawa Section (Topographic map, "Tokomuro", 1: 50,000 in scale, Geographical Survey Institute).

zones of early Miocene through Pleistocene age with several major hiatuses were recognized in the upper part of the well (J.N.O.C., 1991; AKIBA *et al.*, 1992). *Cavitatus lanceolatus* sp. nov. occurs very abundantly in the middle part of the *Denticulopsis lauta* Zone (NPD4A) recognized in the well, and a sample from the zone was used for the SEM observation of the species.

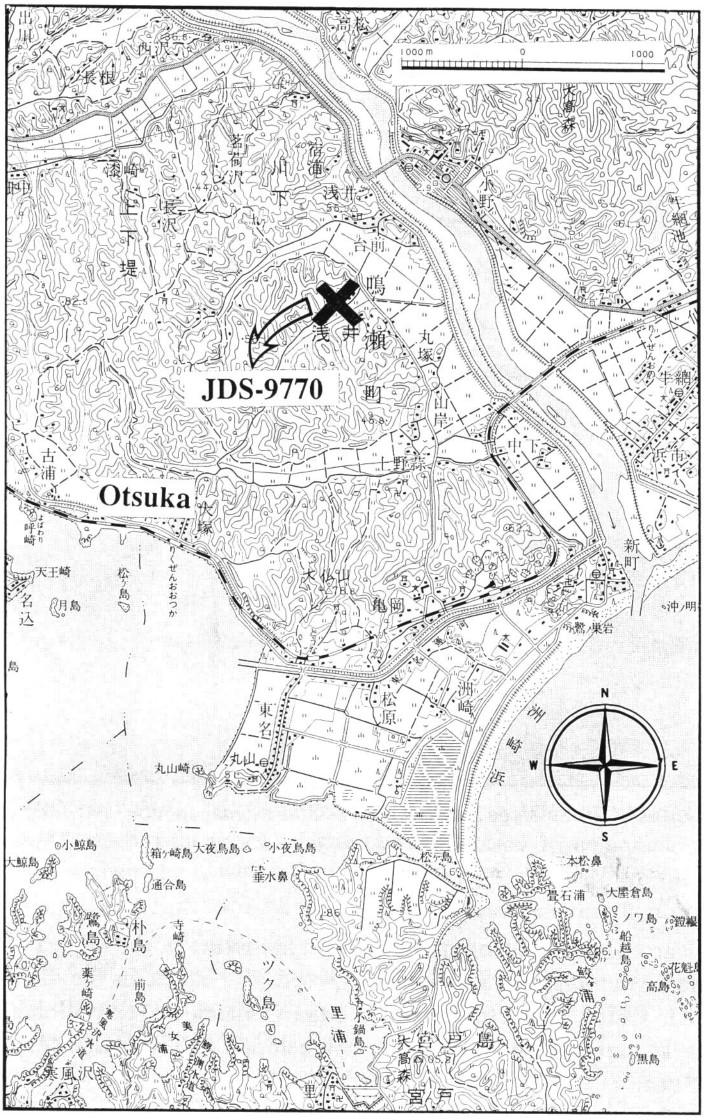


Fig. 3. Locality of the holotype material of *Cavitatus lanceolatus* sp. nov. (Topographic map, "Matsushima", 1: 50,000 in scale, Geographical Survey Institute).

5. The diatom biostratigraphy of several Miocene formations in the vicinity of Kanazawa, Ishikawa Prefecture, and Yatsuo, Toyama Prefecture, central Honshu was studied by Ito (1986), who showed that most of the formations belong to the *Denticulopsis lauta* Zone (NPD4A). *Cavitatus lanceolatus* sp. nov. occurs exclusively in the zone.

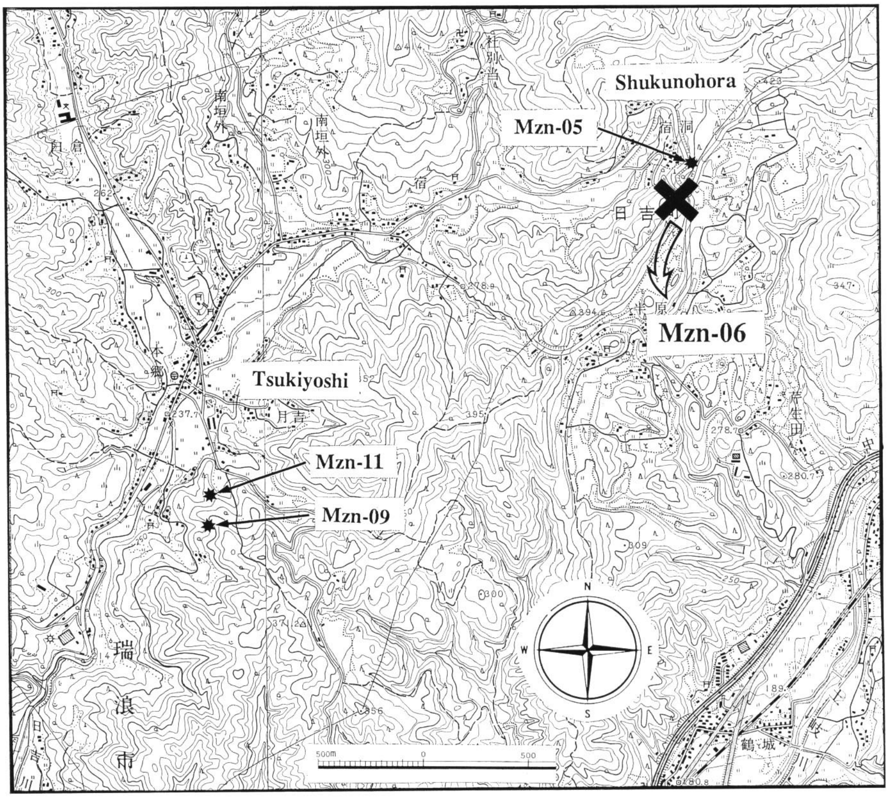


Fig. 4. Localities of the holotype material of *Cavitatus exiguus* sp. nov. (Mzn-06) and samples used for illustration of other *Cavitatus* species. (Topographic maps, "Mizunami" and "Toki", 1: 25,000 in scale, Geographical Survey Institute).

6. A calcareous nodule from the basal conglomerate of the Okuyama Formation of the Sakuma Group (JDS-8789), which exposed at Yokone in the vicinity of Hota, Boso Peninsula, Chiba Prefecture, central Japan, yields an exceptionally well preserved diatom assemblage (AKIBA, 1980). It belongs to the lower Miocene *Thalassiosira fraga* Zone.

7. Type locality of *Cavitatus exiguus* sp. nov. is selected in the Oidawara Formation in Mizunami area, Gifu Prefecture, central Honshu (Fig. 4). The diatoms of the formation were studied by SAWAMURA (1963), MORI (1974) and KOIZUMI (1981), who showed that the formation is assignable to the middle Miocene *Denticulopsis lauta* Zone (NPD4A).

The sample preparation and counting methods for LM study followed AKIBA (1986). Those used for SEM observation are after AKIBA & YANAGISAWA (1986) except for those of *C. lanceolatus* sp. nov., for which uncleaned material was used. SEM micrographs of the species were taken using JOEL T-220A by C. H., and those of *C.*

exiguus sp. nov., *C. linearis* stat. et comb. nov., *C. miocenicus* comb. nov. were taken using JOEL T-330A by Y. Y. The holotype slides of the three new species are deposited in the Micropaleontology Collection, National Science Museum, Tokyo. The locations of the holotype specimens are marked by diamond pencil. Terminology follows ANONYMOUS (1975), ROSS *et al.* (1979) and ROUND *et al.* (1990).

Systematic Description

Division Bacillariophyta

Class Fragilariophyceae ROUND, 1990

Subclass Fragilariophycidae ROUND, 1990

Order Thalassionematales ROUND, 1990

Family Thalassionemeataceae ROUND, 1990

Genus ***Cavitatus*** WILLIAMS, 1989 emend. AKIBA, HIRAMATSU et YANAGISAWA (this paper).
Generic Type: *Cavitatus jouseanus* (SHESHUKOVA) WILLIAMS, 1989, p. 360 as *Cavitatus jouseana* (SHESHUKOVA-PORETZKAYA) WILLIAMS (orthographic error) (=*Synedra jouseana* SHESHUKOVA. SHESHUKOVA-PORETZKAYA, 1962, p. 208, fig. 4).
Emended description: Frustule rectangular with rounded corners, and heterovalvate. Valve isopolar, and linear, linear-elliptical, linear-lanceolate or rectangular with rounded apices. Sternum hyaline with either one apical ridge accompanied by two apical grooves or with two apical ridges and an apical groove between them, or rarely totally structureless. Marginal part of valve face and upper part of mantle with dense transapically elongated areolae. Mantle deep, and almost perpendicular to valve face. Rimoportulae present at each apex. Girdle unknown.
Remarks:– The emended description of this genus is made based on our observation, because the original description is based on poorly preserved specimens of WILLIAMS's (1989) *C. jouseanus*, as he fully admitted it.

Frustules of *Cavitatus* were very seldom encountered, but an observed frustule of *Cavitatus rectus* sp. nov. (Fig. 6–8) shows that it is rectangular with rounded corners with dense transapical areolae at the upper part of valve mantle. This morphologic feature is very similar to that of *Thalassionema*, especially to that of *T. schraderi* AKIBA (AKIBA, 1982). As in *T. schraderi*, no intercalary bands are discernible in *Cavitatus*, although a possibility is not ruled out that very narrow or delicate bands might be present.

All the valves of *Cavitatus* species examined were isopolar, and no heteropolar valve was discernible, contrary to the observation of WILLIAMS (1989). A *Cavitatus* species illustrated by SCHRADER (1976; pl. 1, fig. 16 as *Thalassionema hirosakiensis*) has a strongly heteropolar valve, an almost clavate one. The specimen might be an aberrant form, or a distinct taxon. *Cavitatus* is isopolar in its basic morphology, but might be heteropolar in species level, as in the case of the genus *Rouxia*. The valve shape is basically linear in all the species, but with wide range of variation including almost rectangular, broadly lanceolate, linear-lanceolate to linear-elliptical forms. The variety of valve outline is not considered to be infraspecific variations, but to be unique to each species, because no intermediate forms were found, and also because their geologic ranges are different from each other.

Contrary to the diversified valve outlines, the basic structure of the valves of *Cavitatus* is very consistent through the six examined species. It is characterized by a more or less wide sternum with distinct apical ridges and grooves ("furrows" by WILLIAMS, 1989) and conspicuous dense transapical marginal areolae.

The apical ridge is generally represented by a conspicuous bright line in LM images, which is recognizable by careful and subtle up and down movements of focuses, or objectives. There are evidently two types of valve; one has a sternum with one apical ridge with two apical grooves (Fig. 6–2, 3, 5, 17), and the other has a sternum with two apical ridges and one apical groove (Fig. 6–1a, b, 4, 6a, b, 13, 14, Fig. 9–8, 9). The apical ridges are sometimes too faint to recognize (*e.g.* Fig. 6–11), or in cases they may be totally missing (Fig. 9–10, 11).

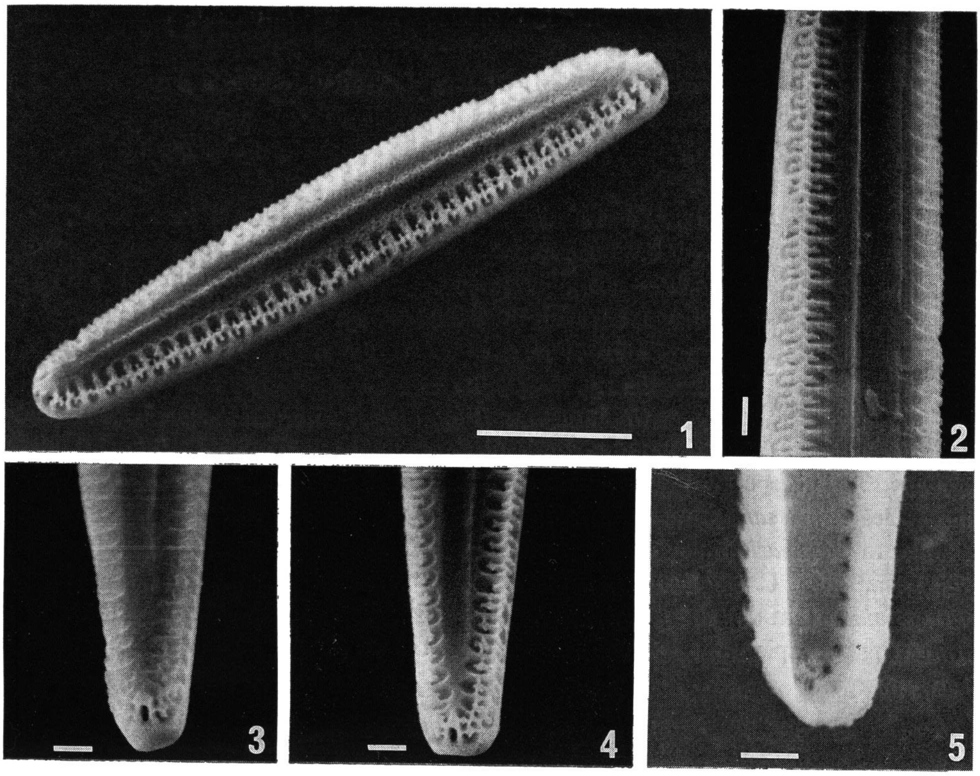
The areolae surround the entire valve face and are perpendicular to the valve margin. They vary in length from elongated areolae penetrating deeply to apical axis in *C. lanceolatus* (Fig. 6–4) or *C. linearis* (Fig. 6–17) to short ones restricted to the valve margin in *C. jouseanus* (Fig. 6–19) or *C. miocenicus* (Fig. 9–10). The transapical areolae are very densely arranged. As in the case of *Thalassionema schraderi* (AKIBA, 1982), the valve mantles are sometimes removed totally or partially from the valve face in poorly preserved specimens (Fig. 6–5, 11, 15, 16), probably due to the structural weakness of valve edge.

Cavitatus exiguus YANAGISAWA et AKIBA sp. nov.

(Fig. 5–1—11)

Description: Valve narrowly linear, or linear elliptical with rounded apices, very small, 16–45 μm long, 3–5 μm wide. Sternum relatively broad and hyaline with two apical lines, formed by two ridges or grooves. Areolae form a single row along each side, 16–18.5 in 10 μm. A rimoportula at each apex, with slit-like elongated outer opening and lip-shaped inner opening oblique to longitudinal axis.
Type locality: Sample Mzn 06 collected by F. YOSHIDA from the Oidawara For-

Fig. 5. *Cavitatus exiguus* YANAGISAWA et AKIBA, sp. nov. Scale bars equal 5 μm for 1, 1 μm for 2–5 and 10 μm for 6a-11, the Oidawara Formation, Mizunami area, Gifu Prefecture, the *Denticulopsis lauta* Zone (NPD 4A). 1–5, Scanning electron micrographs (sample Mzn 06); 6–11, Light microscopic photographs. 1, Oblique outer view of valve. 2, Outer view of valve face and mantle. 3, 4, Outer views of valve apex. Note silt-like outer opening of rimoportula. 5, Inner view of valve apex. Note a lip-shaped rimoportula oblique to the longitudinal axis. 6a-b, Holotype. 6–7, Sample Mzn 06; 4, Sample Mzn 11; 5, Sample Mzn 06; 6, Sample Mzn 05.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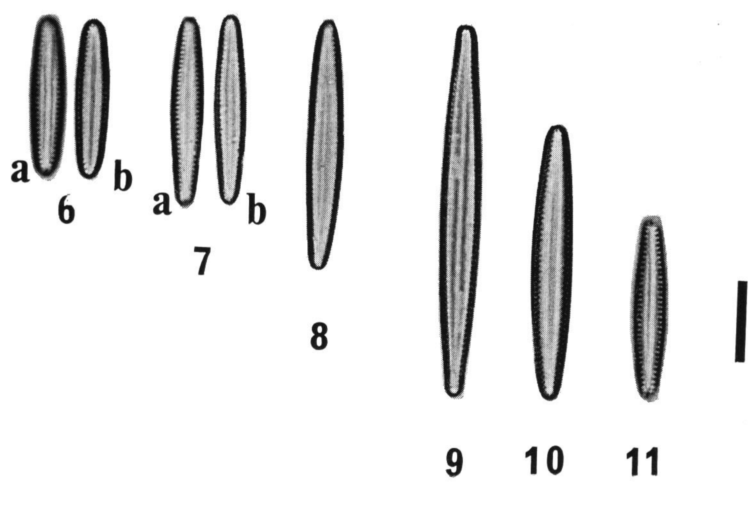
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mation, 35°24′31.22″N, 137°16′17.8″E, Shukunohora, Hiyoshi-machi, Mizunami City, Gifu Prefecture (Fig. 4).

Holotype: Fig. 5–6a–b, Slide no. MPC04955 deposited in the Micropaleontology Collection, National Science Museum, Tokyo.

Geologic Age: Early middle Miocene (lower part of the *Denticulopsis lauta* Zone, NPD4A).

SEM observation: The sternum is relatively broad and hyaline without perforation. There are two longitudinal lines formed by either two ridges (Fig. 5–1), or two grooves (Fig. 5–2). The marginal areolae, finely punctate 16–18.5 in 10 μm, open into depressions or small cavities on the valve edge and the upper half of the mantle (Fig. 5–1–2). They have small internal openings and are surmounted externally by triradiate struts which may carry irregular side branches (Fig. 5–2, 4).

At each apex, there is a rimoportula with a lip-shaped internal opening oblique to longitudinal axis (Fig. 5–5) and a short slit-like external opening (Fig. 5–3, 4).

Remarks: This species is characterized by very small size and linear valve outline. It resembles *C. jouseanus*, but differs in its smaller size and linear valve outline. It is also similar to *C. linearis* in having linear valve outline, but is distinct from the latter by its very small size. *C. exiguus* appears similar in shape and structure to *Thalassionema nitzschioides* (GRUN.) H. et M. PERAGALLO, but it is distinguished from the latter taxon in having two apical lines on the valve face and more finely punctated areolae on the valve margin.

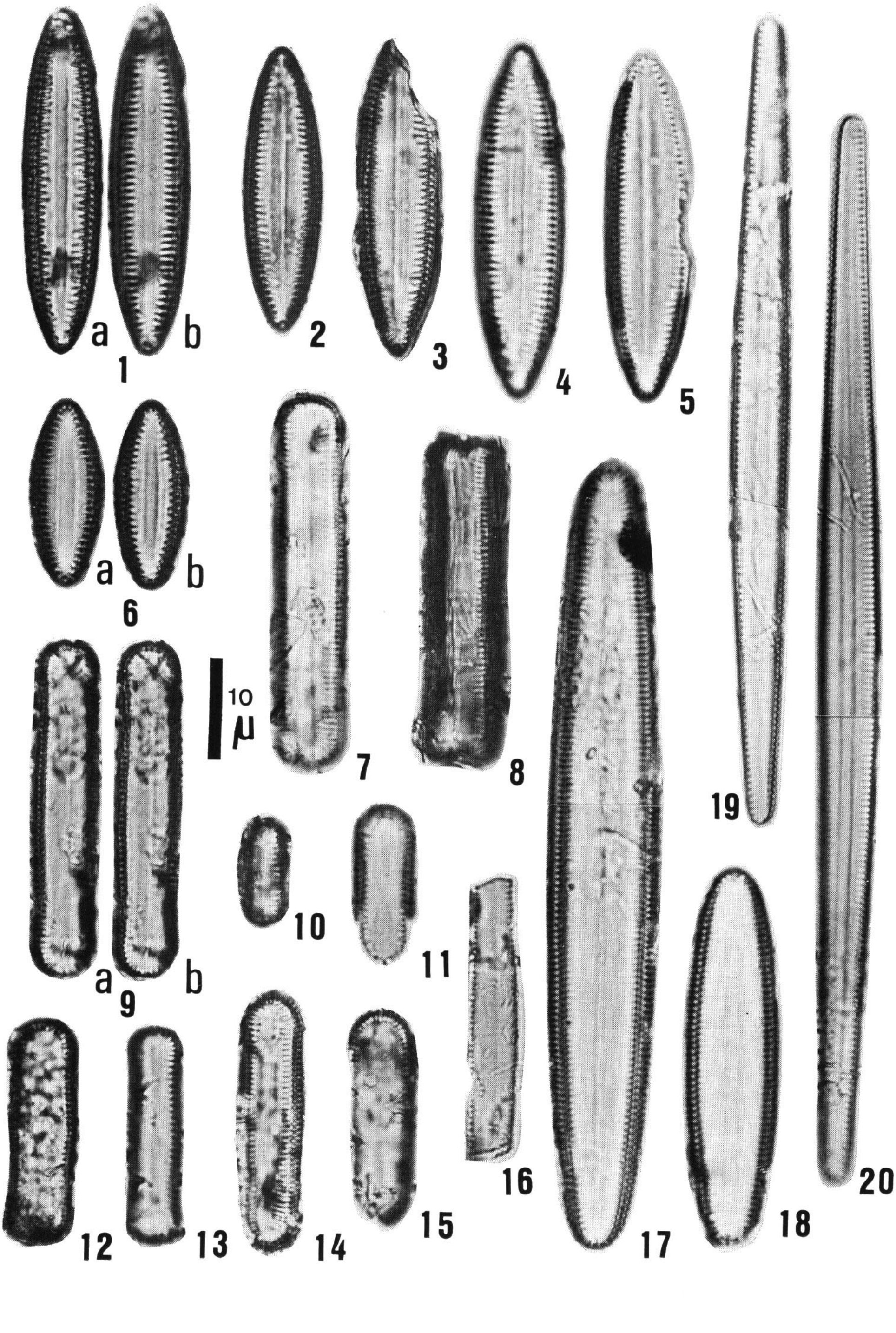
Cavitatus jouseanus (SHESHUKOVA) WILLIAMS, 1989

(Fig. 6–19—20)

WILLIAMS, 1989, p. 260.

Synonymy: *Synedra jouseana* SHESHUKOVA. SHESHUKOVA-PORETZKAYA, 1962, p. 208, fig. 4; 1967, p. 245, pl. 42, figs. 4a-b, pl. 43, figs. 12a-b; KANAYA, 1971, p. 556, pl. 40.5, fig. 15; SCHRADER, 1973, p. 710, pl. 23, figs. 21–23, 25, 38; 1974, fig. 5.3; 1976, pl. 1, figs. 11, not 12–13; KOIZUMI, 1973, p. 833, pl. 6, fig. 17; MORI, 1974, pl. 100, fig. 7; MCCOLLUM, 1975, pl. 13, fig. 5; GOMBOS,

Fig. 6. 1–6b, *Cavitatus lanceolatus* AKIBA et HIRAMATSU sp. nov. All specimens from holotype sample, JDS-9770, the Otsuka Formation, Miyagi Prefecture. 1a–b, 4, 6a–b, Valves of two ridge-type. 2–3, Valves of one ridge-type. 1a–b, Holotype specimen. 3, Part of apex is broken. 5, Part of mantle is missing (upper right part of the valve). 7–15, *Cavitatus rectus* AKIBA et HIRAMATSU sp. nov. All from the holotype sample, JDS-8579, the Tokiwa Formation, eastern Hokkaido, and all specimens are in valve views except for 8 which is slightly oblique girdle view. 7, 9, Valves of one ridge-type. 10–15, Valves of two ridge-type, though some ridges are very faint to recognize. 9a–b, Holotype. 11, 14, 15, Part of mantle is missing. 16, *Cavitatus* cf. *jouseanus* (SHESHUKOVA) WILLIAMS. Broken specimen. 17–18, *Cavitatus linearis* (SHESHUKOVA) AKIBA et YANAGISAWA stat. et comb. nov., all specimens from sample JDS-8789, the Okuyama Conglomerate of the Sakuma Group, Boso Peninsula, Chiba Prefecture. 17, One ridge-type valve. 18, Two ridge-type valve. 19–20, *Cavitatus jouseanus* (SHESHUKOVA) WILLIAMS, all specimens from sample JDS-8789, the Okuyama Formation of the Sakuma Group, Boso Peninsula, Chiba Prefecture. 19–20, Two ridge-type valves.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1976, p. 598, pl. 12, fig. 7; BARRON, 1975, p. 156, pl. 13, fig. 4; 1980, pl. 2, figs. 13–14; 1983, pl. 5, figs. 9–10; 1985a, pl. 8, fig. 17; 1985b, p. 790, fig. 13.10; BALDAUF & BARRON, 1982, pl. 7, fig. 13; ABBOTT & ERNISSEE, 1983, pl. 13, fig. 3; MARUYAMA, 1984, pl. 11, fig. 8; AKIBA, 1986, pl. 21, fig. 9; ITO, 1986, pl. 2, fig. 8; KIM & BARRON, 1986, pl. 5, fig. 15; YANAGISAWA *et al.*, 1989, pl. 5, fig. 46; HARWOOD & MARUYAMA, 1992, p. 706, pl. 11, figs. 8–9; *Synedra jouseana* v. A, GOMBOS, 1976, p. 598, pl. 12, fig. 6; *Synedra jouseana* v. B, GOMBOS, 1976, p. 598, pl. 12, fig. 5.

Geologic Age: Oligocene through late Miocene.
Remarks: This species is characterized by linear-lanceolate valves. This species has been reported from various localities in the world, and reportedly ranges from Oligocene through late Miocene. The species identification and its geologic ranges should be reexamined, because this study suggested previous authors might have mixed this species with related taxa described in this paper or other ones. For example, *C. jouseanus* as illustrated by WILLIAMS (1989) appears to differ somewhat from those as illustrated by us, and we suggest it may be a distinct taxon and need further study.

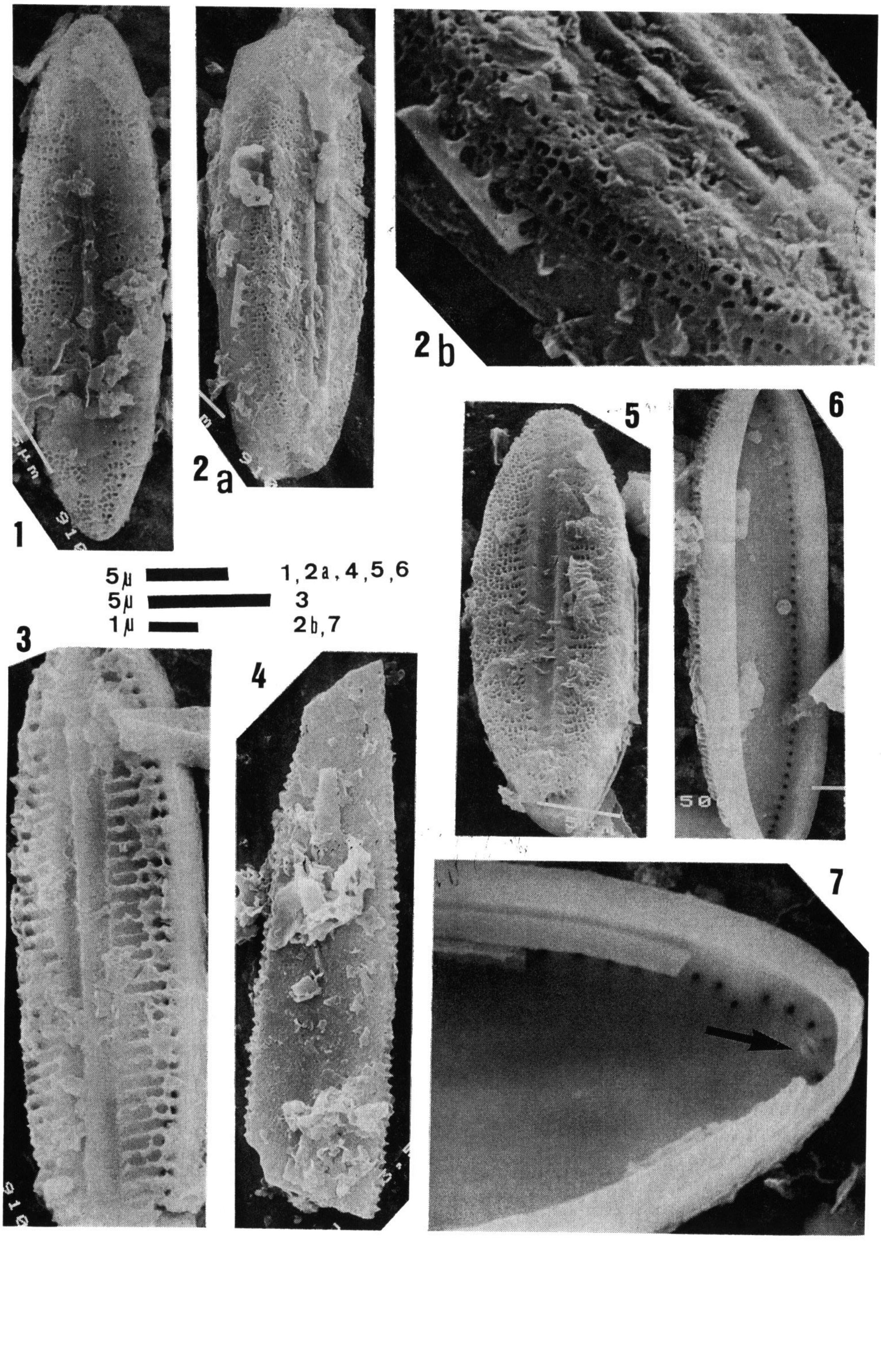
Cavitatus lanceolatus AKIBA et HIRAMATSU sp. nov.

(Fig. 6–1a—6b, Fig. 7–1—7)

Synonymy: *Synedra jouseana* var. 1, BARRON, 1980, p. 672, pl. 1, fig. 33; YANAGISAWA *et al.*, 1989, pl. 5, fig. 45; *Synedra jouseana* SHESHUKOVA-PORETZKAYA. AKIBA *et al.*, 1982b, pl. 3, figs. 83–84; *Synedra jouseana* SHESHUKOVA-PORETZKAYA var. 1, ITO, 1986, pl. 2, figs. 4–7; *Synedra jouseana* f. *linearis* SHESHUKOVA. SHESHUKOVA-PORETZKAYA & GLESER, 1962, pl. 4, fig. 8b, not 8a, not pl. 5, fig. 5.

Description: Valve almost flat, and linear to linear-lanceolate with cuneate apices, 19–60 μm, mostly 22–38 μm long, 8–11 μm wide. Sternum wide and hyaline with two apical lines, formed by either two apical ridges or grooves. Valve margin with conspiculously elongated areolae, which are transapically arranged except for at each apex where they are radial, 13–16 punctae in 10 μm.
Type Locality: Sample No. JDS-9770 (Orig. no. OT-7 collected by Y. YANAGISAWA in 1980), 38°23′37″N, 141°8′52″E, from the Otsuka Formation, Matsushima area, Miyagi Prefecture, Northeast Honshu (Fig. 3).
Holotype: Fig. 6–1a–b, Slide no. MPC 04956 (Orig. no.; JDS-9770b) deposited in the Micropaleontology Collection, National Science Museum, Tokyo.

Fig. 7. Scanning electron micrographs of *Cavitatus lanceolatus* AKIBA et HIRAMATSU sp. nov. Magnifications of figures are in various scales shown in the middle of the figure. All from sample, JDS-17013 (an offshore well, MITI-Souma-Oki, 653 m in depth), the *Denticulopsis lauta* Zone (NPD4A). 1, Outer valve view of one ridge-type valve. 2a–b, Oblique outer valve view of two ridge-type valve. 3, Partially dissolved one ridge-type valve, in which the top (edge) of the ridge is very acute. Note transapical rows of "cavities", which are inner spaces of areoale. Dark small hole near the end of each "cavity" is an inner opening of the areolae. 4, Internal view of valve face without mantle, broken at a row of internal openings of areolae. 5, Outer valve view of two ridge-type valve. 6, Oblique internal view of valve. Note the row of inner openings at the edge between valve face and mantle. 7, Internal view of valve. Arrow indicates rimoportula.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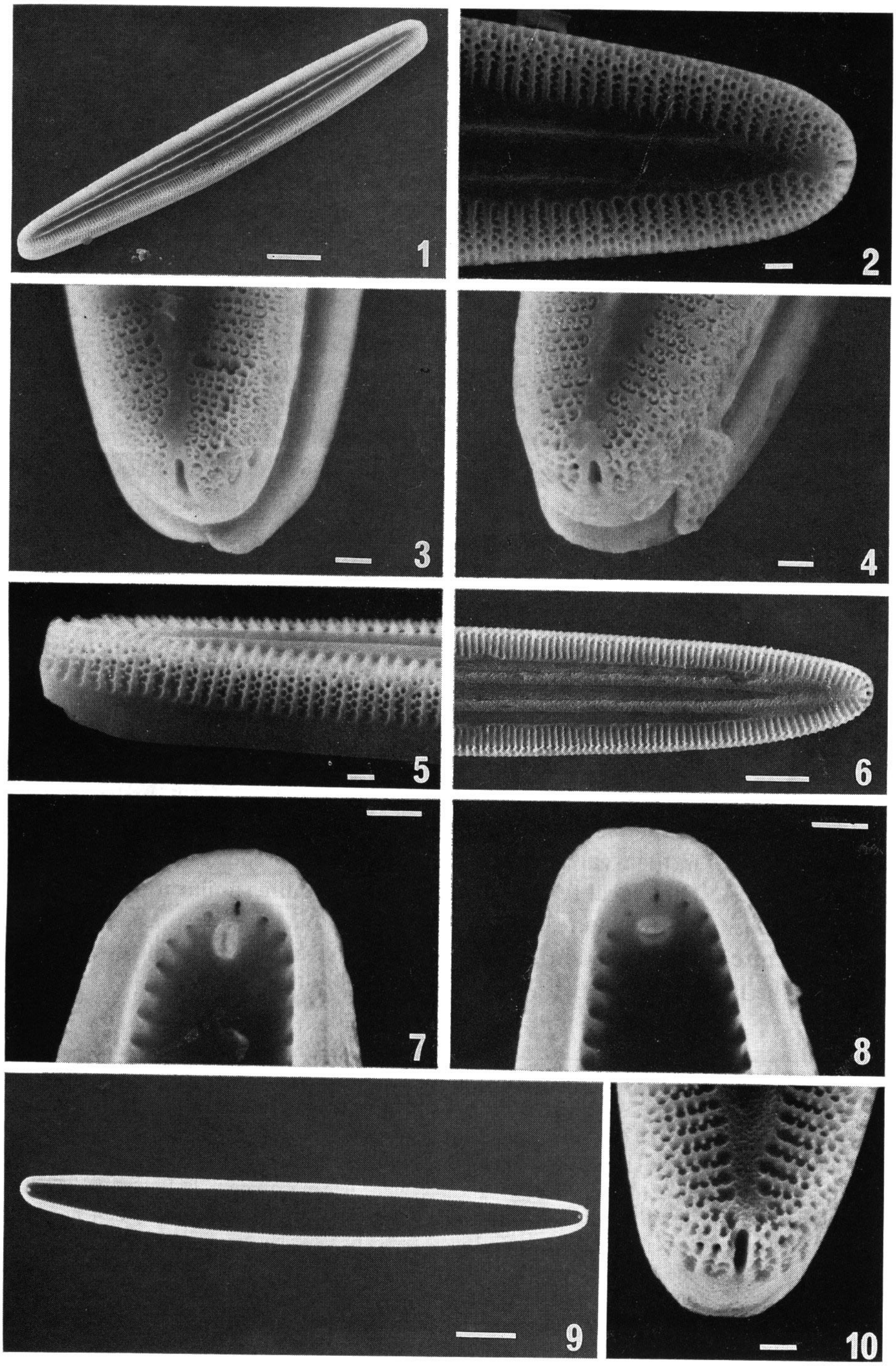
Isotype: Fig. 6–6a–b, Slide no. JDS-9770 (a) deposited in the Diatom Collection of the JAPEX Research Center, Chiba.
Geologic Age: Early middle Miocene (middle part of the *Denticulopsis lauta* Zone).
SEM observation: The valve of this species is lanceolate with tapered apices (Fig. 7–1). The sternum is narrow and hyaline with two longitudinal apical lines. The two lines are formed by two apical ridges with an apical groove between them in some valves (Fig. 7–2, 5), whereas they are formed by one apical ridge with two apical grooves at its both sides in other valves (Fig. 7–1, 3). The top of the ridges are gently rounded (Fig. 7–1, 2, 5), but in poorly preserved specimens they are acute without an upper siliceous layer (Fig. 7–3). In poorly preserved specimens, there is a series of transapical ridges extending to the upper half of the mantle, where the pairs of the ridges form an open "canal" or "cavity" (Fig. 7–3). In well preserved valves (Fig. 7–1, 2, 5), however, each "cavity" is covered with a thin siliceous layer perforated by transapical rows of a more or less irregularly shaped and apically elongated puncta (Fig. 6–1, 2b, 5). Part of the rows are occuluded probably by clay materials, since the material was not cleaned at all, but it is supposed that the puncta may be basically and originally arranged in quincunx patterns (Fig. 7–5). Near the edge of the valve, there is a small opening in each "cavity" which penetrates into the valve interior (Fig. 7–3). The valve interior is smooth and structureless except for the row of marginal openings on each side (Fig. 7–6). The marginal openings are very closely arranged, and consequently they may be interconnected each other in poorly preserved specimens, and an isolated valve without its valve mantle is often observed (Fig. 7–4). At each apex, there is a rimoportula with lip-shaped internal extension, which is diagonal to the longitudinal axis (Fig. 7–7). The external opening of the rimoportula is a small slit, although our SEM micrographs failed to illustrate it clearly in this species.
Remarks: This species has been frequently referred to as *Synedra jouseana* var. 1 (BARRON, 1980; ITO, 1986; YANAGISAWA *et al.*, 1989), but no formal taxonomic treatment has been made. This new species is close to *C. linearis*, but is easily differentiated from the latter by the lanceolate valve with more or less cuneate apices and very conspicuous transapical puncta.

Fig. 8. Scanning electron micrographs of *Cavitatus linearis* (SHESHUKOVA) AKIBA et YANAGISAWA stat. et comb. nov. Scanning electron micrographs. Scale bars equal 10 μm for 1, 9; 5 μm for 6, and 1 μm for 2–5, 7, 8, 10, respectively. Sample Mzn 06, the Oidawara Formation, Mizunami area, Gifu Prefecture, the *Denticulopsis lauta* Zone (NPD 4A). 1, Oblique outer view of two-ridge type valve. 2, Enlargement of 1 showing an apex. 3, Outer view of valve apex. Note slit-like outer opening of rimoportula. 4, Other valve apex of the same valve figured in 3. 5, Side view of valve. 6, Outer view of partly dissolved valve. 7, Inner view of an apex of valve shown in 9. Note a rimoportula with lip-shaped inner opening parallel to longitudinal axis and a small pore above the rimoportula. 8, Inner view of the other apex of the valve shown in 9. Note transapical direction of rimoportula. 9, Inner view of valve. 10, Outer view of valve apex.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Cavitatus linearis (SHESHUKOVA) AKIBA et YANAGISAWA stat. et comb. nov.

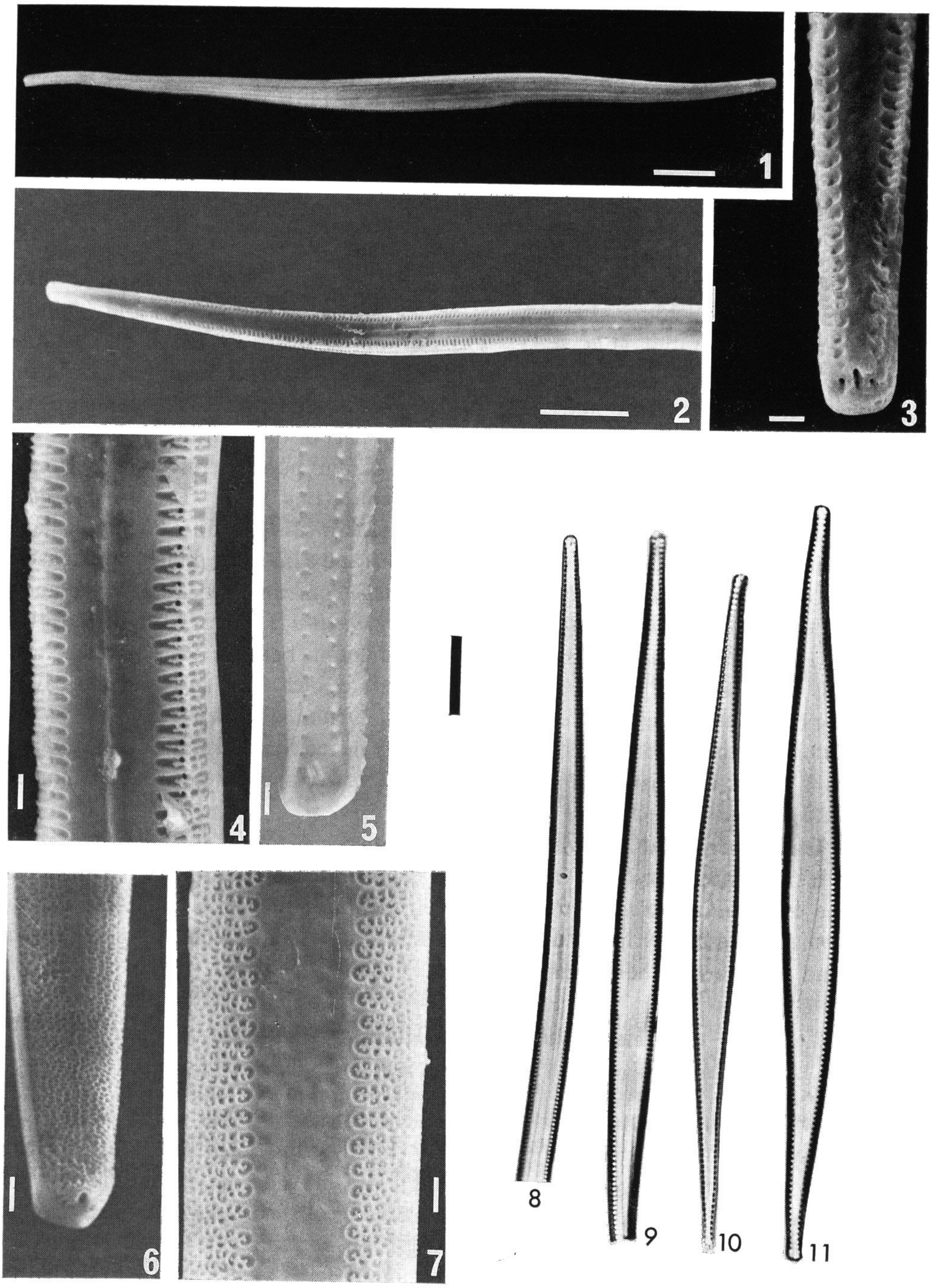
(Fig. 6–17—18; Fig. 8–1—10)

Basionym: *Synedra jouseana* f. *linealis* SHESHUKOVA. SHESHUKOVA-PORETZKAYA, 1962, p. 209, fig. 3.
Synonymy: *Synedra jouseana* f. *linearis* SHESHUKOVA. SHESHUKOVA-PORETZKAYA & GLESER, 1962, pl. 4, fig. 8a, not 8b, pl. 5, fig. 5; SHESHUKOVA-PORETZKAYA, 1967, p. 246, pl. 42, fig. 5, pl. 43, fig. 13; BARRON, 1983, pl. 5, fig. 12; 1985b, p. 790, fig. 13.9; AKIBA, 1986, pl. 21, fig. 8; KIM & BARRON, 1986, pl. 5, fig. 16; YANAGISAWA *et al.*, 1989, pl. 5, fig. 47; *Synedra jouseana linearis* SHESHUKOVA-PORETZKAYA. POWERS, 1988, pl. 10, fig. 8; RADIONOVA, 1991, pl. 23, figs. 4–6; *Thalassionema hirosakiensis* (KANAYA) SCHRADER. SCHRADER, 1976, pl. 1, figs. 14–16; SCHRADER & FENNER, 1976, pl. 5, figs. 3–4, 6–7.

Geologic Age: Late Oligocene to early middle Miocene.
SEM observation: The valve of the species is linear with bluntly rounded apices (Fig. 8–1). The sternum is relatively narrow and hyaline with two longitudinal ridges running from one apex to the other. The areolae appear in one row on each side. The areolae has a small internal opening at the valve edge (Fig. 8–7, 8), while externally it broadens transapically to the valve face and valve mantle and forms an elongated cavity (inner space) covered with a reticulate velum. The velum is perforated by two rows of small puncta, with each punctum covered with a very small strut (Fig. 8–3, 4). In poorly preserved specimens where the velums are completely lost, the inner cavities are easily visible (Fig. 8–6). They are elongated transapically, but slightly curved near each apex. Internally, each valve apex carries a lip-shaped extension of rimoportula which is parallel to the longitudinal axis at one apex (Fig. 8–7), and perpendicular to the longitudinal axis at the other apex (Fig. 8–8).
Remarks: WILLIAMS (1989) reserved specific validity of this taxon, citing SHESHUKOVA-PORETZKAYA's (1962) comment that there is an intermediate form between her *S. jouseana* and *S. jouseana* f. *linearis*, but our observations suggest that the two taxa have sufficient differences in their valve shapes to be separated in species level.

The overall morphological feature of this species is quite similar to that of *Thalassionema hirosakiensis* (KANAYA) SCHRADER or *T. schraderi* AKIBA except for their different structures in sterna, and therefore previous authors in cases misidentified this species with the latter ones, as the above synonym list shows.

Fig. 9. *Cavitatus miocenicus* (SCHRADER) AKIBA et YANAGISAWA comb. nov. Scale bars equal 10 μm for 1, 2; 1 μm for 3–7 and 10 μm for 8–11, the Oidawara Formation, Mizunami area, Gifu Prefecture, the *Denticulopsis lauta* Zone. 1–7, Scanning electron micrographs (sample Mzn 06), 8–11, Light microscopic photographs. 1, Outer view of a valve with slightly lanceolate outline. 2, Outer view of a valve with linear outline. 3, Enlargement of 2 showing a valve apex. Note a slit-like opening of rimoportula. 4, Enlargement of 2 showing valve face and mantle. 5, Inner view of a valve apex. Note a lip-shaped rimoportula oblique to apical axis. 6, Outer view of an apex of valve without ridges on valve face. 7, Valve face without ridges on vlave face. 8, Typical form with linear valve outline, Mzn 09. 9, Slightly lanceolate form, Mzn 11. 10–11, Slightly lanceolate form without apical lines, 10, Mzn 06; 11, Mzn 05.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Cavitatus miocenicus (SCHRADER) AKIBA et YANAGISAWA comb. nov.

(Fig. 9–1—11)

Basionym: *Synedra miocenica* SCHRADER, 1976, p. 636, pl. 1, figs. 1, 1a-b.
Synonymy: *Synedra miocenica* SCHRADER. BARRON, 1983, pl. 5, fig. 11; KIM & BARRON, 1986, pl. 5, figs. 13–14; ? RADIONOVA, 1991, p. 96, pl. 23, figs. 8–9; *Synedra jouseana* SHESHUKOVA-PORETZKAYA. SCHRADER, 1976, pl. 1, figs. 12–13, not 11; *Thalassionema obtusum* (GRUNOW) ANDERWS, POWERS, 1988, pl. 10, figs. 9–10.

Geologic Age: Late Oligocene to early late Miocene.
SEM observation: The valve of this species is very long and narrow with linear valve outline (Fig. 9–2), but some specimens are broadened at the middle part and exhibit a slightly lanceolate outline (Fig. 9–1). The sternum is relatively broad and hyaline with two apical lines. The two lines are formed by two longitudinal grooves in the specimens examined in this study (Fig. 9–4). The marginal areolae open into depressions or cavities in the valve edge and the upper part of the mantle (Fig. 9–4). The depressions might be covered with velums, but in our poorly preserved specimens there are only triradiate struts over the depressions (Fig. 9–4). The areolae have internal small pores which penetrate into the valve interior (Fig. 9–5). Each pole has a rimoportula with an outer slit-like opening (Fig. 9–3) and a lip-shaped internal extension oblique to the longitudinal axis (Fig. 9–5). We have sometimes encountered a lanceolate form without apical lines in the axial area (Fig. 9–10–11). This form has a rather rounded and arched cross section so that the distinction between the valve face and mantle is not clear (Fig. 9–7). It has complicated areolae with an elongated cavity extending to the axial area covered with a reticulate velum (Fig. 9–6–7).
Remarks: This species has rarely been mentioned in the literature after its establishment in 1976, but it is distinguished from other *Cavitatus* species by broadly rounded or rostrate apices.

We have observed a form very similar to this species that is characterized much shorter, broader and lanceolate valves, which is illustrated by SCHRADER (1976) under the name of *Synedra jouseana*. We have been identified the lanceolate form also as *S. miocenica* for years, because it has also characteristic rostrate apices like *S. miocenica* s. str., and we followed the identification here.

Cavitatus rectus AKIBA et HIRAMATSU sp. nov.

(Fig. 6–7—15)

Description: Frustule rectangular with rounded corners. Valve linear-oblong, almost rectangular, and in some specimens very slightly constricted near apices, which are very broadly rounded, 11–40 μm long, and 4.5–7 μm wide. Sternum narrow and hyaline with two apical lines, which are more or less inconspicuous. Marginal areolae elongated, fine and perpendicular to valve margin, 16–18 puncta in 10 μm.
Type Locality: Sample No. JDS-8579 (Orig. no. Af-79313) collected by F. AKIBA in 1979, 42°56′37″N, 143°35′42″E, from the Tokiwa Formation, eastern Hokkaido (Fig.

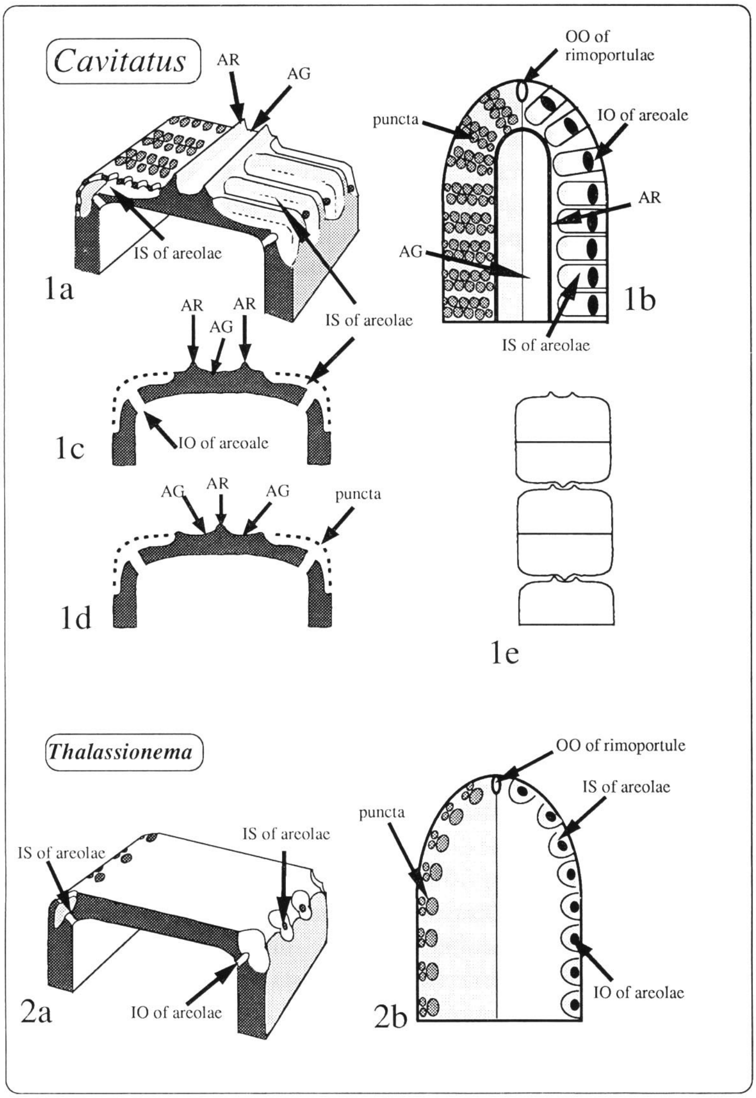

Fig. 10. Schematic valve structures of *Cavitatus* and *Thalassionema*. AG, Apical groove. AR, Apical ridge. IS, Inner space of areolae. IO, Internal opening of areolae. OO, Outer opening of areolae. 1a–e, *Cavitatus*. 1a, Oblique outer view of part of valve, the left half is of a complete valve and the right half is of incomplete valve (without cribrum). 1b, Valve view, again the left half is of a complete valve and right half is of incomplete valve (without cribrum). 1c, Cross section of two ridge-type valve. 1d, Cross section of one ridge-type valve. 1e, Suggested colony formation (two and half frustules), a combination of one ridge-type valve and two ridge-type valve. 2a–b, *Thalassionema*. 2a, Oblique outer view of part of valve, the left half is of a complete valve and the right half is of incomplete valve (without cribrum). 2b, Valve view, again the left half is of a complete valve and right half is of incomplete valve (without cribrum).

2).
Holotype: Fig. 6–9a–b from Slide no. MPC04975 (Orig. no.; JDS-8579 Type) deposited in the Micropaleontology Collection, National Science Museum, Tokyo.
Isotype: Fig. 6–12 from the same slide as above.
Geologic Age: Late Oligocene to early Miocene.
Remarks: This species is characterized by an almost rectangular valve, which is quite different from those of any other five species in this genus. No SEM observation of this new species was made at present.

Valve Structure of *Cavitatus*

Based on the above observations, the valve structure of *Cavitatus* is schematically presented in Figure 10 with that of its related genus *Thalassionema*.

The most characteristic features of the valve structure seemingly unique to *Cavitatus* are two folds, a sternum with apical ridge (AR) and groove (AG), and transapically elongated areolae.

The sternum is hyaline and has two types; one with one apical ridge surrounded by two apical grooves (one ridge-type valve) (Fig. 10–1d), and the other with two apical ridges and an apical groove between them (two ridge-type valve) (Fig. 10–1c). These two types of sterna are easily differentiated even by LM. The presence of the two types of sterna suggests that the frustule of *Cavitatus* is obviously heterovalvate, and furthermore that the colony formation of *Cavitatus* might be made by face to face contacts between the two types (Fig. 10–1e). Some valves without no discernible apical ridges or grooves on the sternum may suggest that those valves may be the initial valves which are solitary by its nature and need not to develop ridges and grooves for colony formation.

The apical ridges observed by SEM show slightly different aspects between the well preserved specimens and poorly preserved ones as mentioned before, namely the former has rounded edges, whereas the latter has acute ones. This aspects suggest that the ridge may have originally been covered with a thin siliceous layer, likewise the areolae has.

The second unique morphologic feature of *Cavitatus* is transapically elongated areolae. The areolae have external openings through two rows of small puncta arranged basically in quincunx rows, and also have an internal opening (IO), which is a simple hole at the valve edge. WILLIAMS (1989) described transapical "cavities" on the valve face as an unique morphology of this genus, from which the generic name *Cavitatus* was derived, but the feature has been clarified by this study to be due to the poor preservation of the specimens he examined. The "cavity" is, in fact, an inner space (IS) of areolae covered by thin siliceous layer with puncta (cribrum).

An additional important morphologic feature of this genus missed in the original description is the presence of rimoportulae at each apex. The observed rimopotulae has a simple outer slit at the valve edge, which is elongated parallel to the pervalvar axis,and a lip-shaped internal extension. The lip-shaped extension is variable in direction, namely either diagonal, parallel or perpendicular to the pervalvar axis.

The valve structures of *Cavitatus* described above suggest the genus is morphologically most close to an extant genus *Thalassionema* (Fig. 10–2a–b). *C. exiguus* sp. nov. and *C. miocenicus* comb. nov. have the same type of areolae as that of *Thalassionema*, although the remainder of *Cavitatus* have slightly different type of areolae. The only unique morphologic feature left for *Cavitatus*, therefore, seems to be the sternum with ridge and groove.

WILLIAMS (1989) suggested two alternative phyletic relationships of *Cavitatus* to other related genera in the araphid diatoms. First one is its close relationship to *Thalassionema*, *Thalassiothrix* and *Trichotoxon*, and the second is that to *Catacombas* and *Hyalosynedra*. The first one is based on the similar appearance of the areolae and the lack of apical pore fields among the four genera, but he doubted their phyletic relations because *Cavitatus* lacks "outer cribrate coverings" of the areolae and rimortulae. However, our study found the two features persent also in *Cavitatus*, and therefore WILLIAMS's (1989) doubt has lost its reasons. The second one is based on again the postulated similar internal structures of areolae between the three genera, but it is hardly probable since *Cavitatus* lacks pore field which well characterizes the two genera, *Catacombas* and *Hyalosynedra*.

Stratigraphic Occurrence

Stratigraphic occurrences of the six *Cavitatus* species are shown in Figure 11. Dotted line shows uncertainty due to either very rare occurrence or previous taxonomic ambiguity. Our observed and reported range of each species shortly follow below. It is noteworthy that the biostratigraphic utilities of the two new species, *C. lanceolatus* sp. nov. and *C. rectus* sp. nov., are particularly high in the Cenozoic of Japan.

Cavitatus exiguus sp. nov.: This new species occurs rarely in the lower part of the *Denticulopsis lauta* Zone (NPD4A). We have found this species in the Oidawara Formation of Mizunami area and the Otsuka Formation of Matsushima area. However, its precise stratigraphic range has not been examined at present.

Cavitatus jouseanus: The geologic range of this species here circumscribed is not very certain yet due to the circumstances described in the systematic description. Our observations of the Neogene sequences of Japan show that it ranges at least from the early Miocene *Thalassiosira fraga* Zone through the late Miocene *Rouxia californica* Zone.

Reported range of this species is as follows. The first occurrence of this species is recognized in the late Oligocene Honbetsuzawa Formation of the Kawakami Group in eastern Hokkaido, Japan (HAGA, 1992), but its precise age is not known to date. In the Southern Ocean, the first occurrence of *C. jouseanus* exists in the upper part of the b Subzone of the *Rhizosolenia oligocenica* Zone (BALDAUF & BARRON, 1991), or at the base of the *Synedra jouseana* Zone (HARWOOD & MARUYAMA, 1992) and can be estimated at about 33.0 Ma or 32.6 Ma. In the equatorial Pacific, BARRON (1985a) ob-

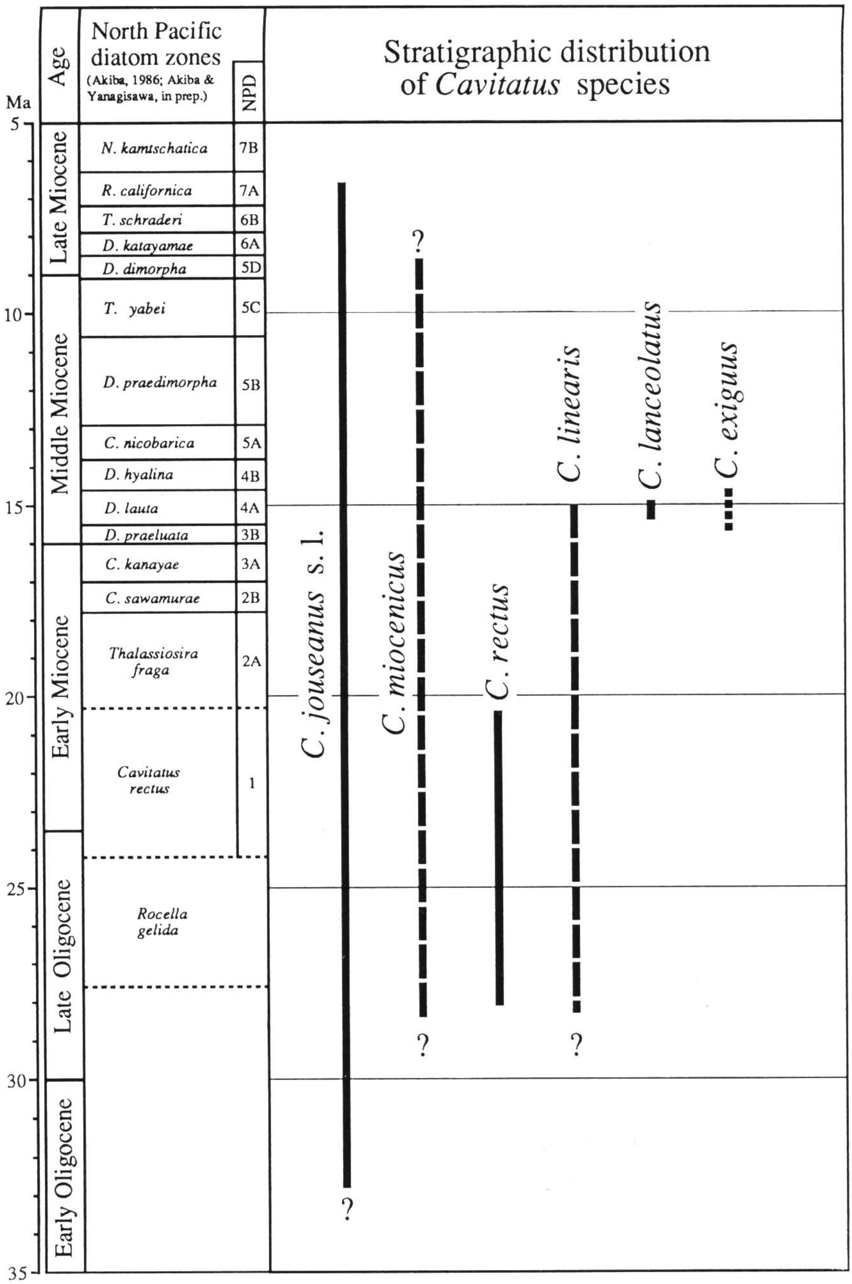

Fig. 11. Stratigraphic ranges of *Cavitatus* species in the middle-to-high latitude North Pacific. Diatom zonal framework is basically after AKIBA (1986), but its early Miocene part is that modified by AKIBA & YANAGISAWA (in prep.).

served that *C. jouseanus* first occurs near the base of the b Subzone of the *Rocella vigilans* Zone at about 28.5 Ma. Kim & Barron (1986) also recorded that its first occurrence approximates the base of the b Subzone of the *R. vigilans* Zone in Baja California. Fenner (1984, 1985) recognized that *C. jouseanus* first occurs in the lower Oligocene *Cestodiscus reticulatus* Zone in the equatorial Atlantic.

The last occurrence of *C. jouseanus* is distinctly diachronous. In the middle- to high-latitude North Pacific, the last occurrence of this species is in the uppermost part of the uppermost Miocene *Rouxia californica* Zone (Barron, 1980; Koizumi & Tanimura, 1985; Akiba, 1986) and can be dated about 6.4 Ma. In the tropical Pacific, the last occurrence of *C. jouseanus* falls in the *Craspedodiscus coscinodiscus* Zone and is estimated to be 12.3–12.1 Ma (Barron, 1985a). In the Southern Ocean, the last occurrence is recognized in the *Denticulopsis hustedtii-Nitzschia grossepunctata* Zone (Baldauf & Barron, 1991) or *N. grossepunctata* Zone (Gersonde & Burckle, 1990; Harwood & Maruyama, 1992) and its age can be estimated to be between 14 Ma and 14.7 Ma.

Cavitatus lanceolatus sp. nov.: Ito (1986) was the first who showed the very abundant and limited occurrence of this species in part of the *Denticulopsis lauta* Zone (NPD4A) in several sections in the Hokuriku Province, central Japan, although he did not emphasize its biostratigraphic high utility. After his study, our observations of many other sections including those of the Matsushima area, the type locality of the new species, DSDP Hole 438A and MITI-Souma-oki confirm us that it restrictedly occurs in the middle part of the *Denticulopsis lauta* Zone of Akiba (1986). For example, at MITI Souma-oki where 590 m to 835 m subbottom depths were designated to the *Denticulopsis lauta* Zone, the occurrence of *C. lanceolatus* sp. nov. was observed in a short interval from 638 m to 653 m subbottom depths with its relative abundance of 8–26% of the total diatom flora (J.N.O.C., 1991; Akiba *et al.*, 1992). *C. lanceolatus* sp. nov. is, therefore, a good marker species representing the middle part of the middle Miocene *Denticulopsis lauta* Zone in the middle- to high-latitude North Pacific.

Cavitatus linearis: The first occurrence of this species in the middle- to high-latitude North Pacific is not well known at present. In the tropical Pacific and Baja California, it approximates the base of the b Subzone of the *Rocella vigilans* Zone (ca. 28.5 Ma) (Barron, 1985a; Kim & Barron, 1986). *C. linearis* has its last occurrence in the lower part of the *Cestodiscus peplum* Zone or the uppermost part of the *Denticulopsis nicobarica* Zone in the tropical Pacific (Barron, 1983). Barron (1985b) shows that the last occurrence of *C. linearis* falls in the upper part of the *Thalassiosira fraga* Zone in the middle- to high-latitude North Pacific, but it ranges up to at least in the *Denticulopsis lauta* Zone by our observations.

Cavitatus miocenicus: The first occurrence of this species in the middle- to high-latitude North Pacific is not well known at present. In the triopical Pacific and Baja California, it approximates the base of the b Subzone of the *Rocella vigilans* Zone (ca. 28.5 Ma) (Barron, 1985a; Kim & Barron, 1986). The last occurrence of *C. mio-*

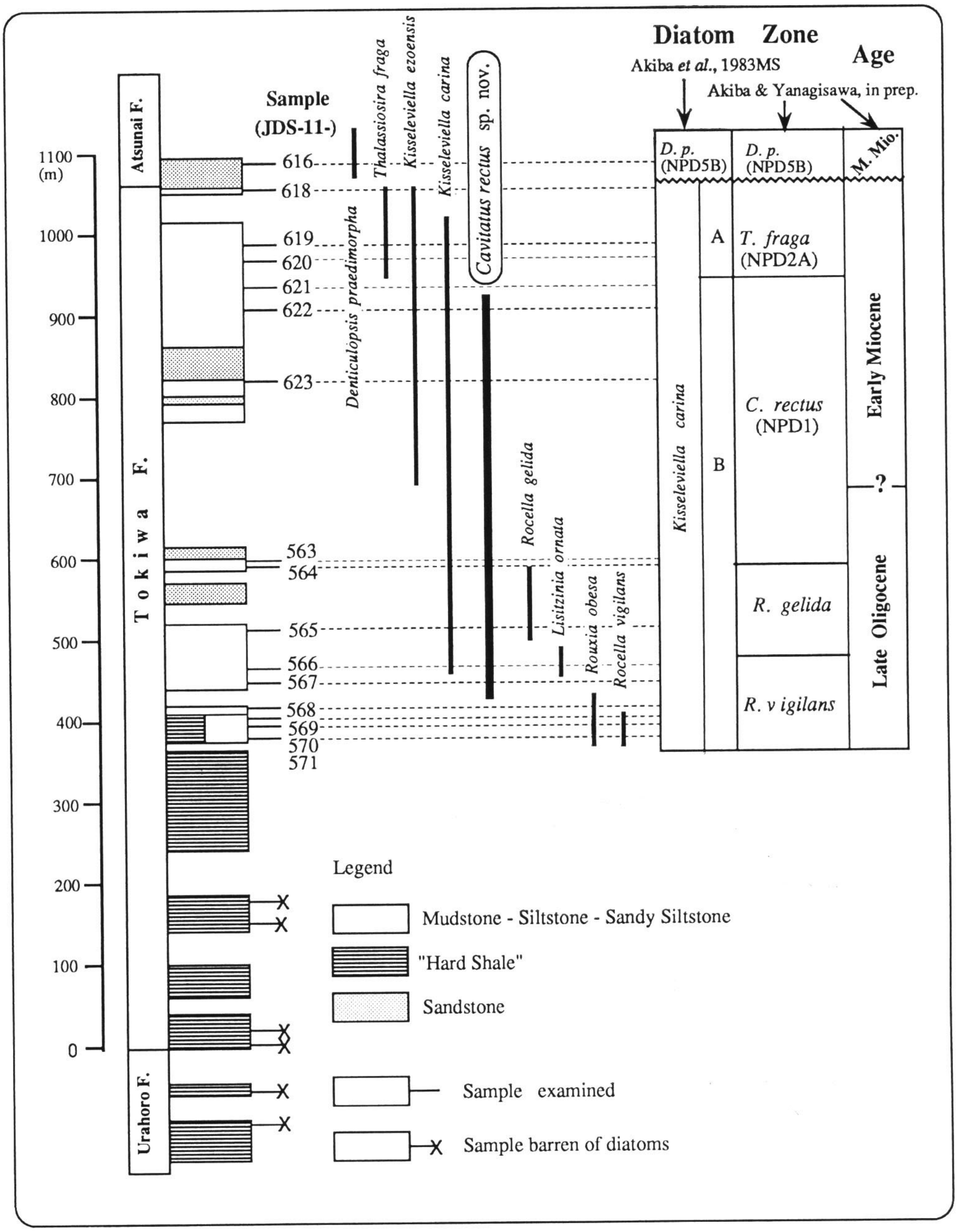

Fig. 12. Stratigraphic occurrence of selected diatoms in the Okubonosawa Section, Atsunai area, eastern Hokkaido.

cenicus is difficult to recognize because of its very rare occurrence, but it may be in the upper Miocene *Denticulopsis katayamae* Zone in the middle- to high- latitude North Pacific (AKIBA, 1986).

Cavitatus rectus sp. nov.: This new species occurs very abundantly in the lower part of the Tokiwa Formation in the Atsunai area and its correlative formations widely distributed in the southeastern part of eastern Hokkaido, an interval below the first occurrence of *Thalassiosira fraga*.

The stratigraphic occurrence of this new species and other selected stratigraphically important diatoms in the Okubonosawa Section, eastern Hokkaido is shown in Figure 12. The diatom biostratigraphy of this section was first studied by AKIBA *et al.* (1983 MS), who recognized the lower Miocene *Kisseleviella carina* Zone of KOIZUMI (1979) in the Tokiwa Formation, which was unconformably overlain by the middle Miocene *Denticulopsis praedimorpha* Zone (NPD5C) in the basal part of the Atsunai Formation. They subdivided the *K. carina* Zone into the upper A Subzone which was characterized by common occurrence of *Thalassiosira fraga* SCHRADER, and the lower B Subzone which characteristically lacked *T. fraga* and yielded *C. rectus* sp. nov. commonly to abundantly. The maximum abundance of *C. rectus* sp. nov. is more than 40% of the total flora in some samples. Later, AKIBA (1986) correlated the A Subzone of the *K. carina* Zone to the lower Miocene *Thalassiosira fraga* Zone of BARRON (1985b), but because he could find no *T. spinosa* SCHRADER in the B Subzone, he postoponed a correlation of the B Subzone of the *K. carina* Zone with the early Miocene *Thalassiosira spinosa* Zone of BARRON (1985b) which underlies the *T. fraga* Zone, and suggested that, at least, some part of the subzone may belong to Oligocene. Our further study of the Okubonosawa Section clarified the occurrence of other biostratigraphically important diatoms in the subzone such as *Rocella gelida* (MANN) BUKRY, *R. vigilans* (SCHMIDT) FENNER, *Lisitzinia ornata* JOUSÉ and *Rouxia obesa* SCHRADER. Based on the data along with other ones recently obtained from other Japanese sections, we newly subdivided the interval into the *Cavitatus rectus* Zone, the *Rocella gelida* Zone and the *R. vigilans* Zone, in descending order. The Oligocene/Miocene boundary may be somewhere in the lower part of the *C. rectus* Zone (AKIBA & YANAGISAWA, in prep.).

Concluding Remarks

This paper clarified several important morphologic features characterizing an extinct Oligo-Miocene diatom genus *Cavitatus* WILLIAMS (1989), which are unknown in the original description. The study also suggested that the genus is most closely related to an extant marine oceanic genus *Thalassionema*. *Cavitatus* has so far been monospecific, but our study shows it comprises at least six species including three new species, and two of which are biostratigraphically highly useful. Further study of this genus from other part of the world might add some additional taxa.

Acknowledgements

We sincerely dedicate this paper to our senior colleague, Dr. Seiichi KOMURA, who had long before recognized *Synedra jouseana* and its related taxa belonging to a distinct genus from *Synedra* s. str., and who discussed with F. A. the necessity of its taxonomic refinements for years. Dr. Nora RADIONOVA pointed out to F. A. the presence of *Cavitatus* WILLIAMS (1989). Samples from the MITI-Souma-oki and the Oidawara Formation were kindly provided by the Japan National Oil Corporation (J.N.O.C.) and Dr. Fumio YOSHIDA, respectively. Dr. Hideaki TAKANO kindly gave us suggestions on orthographic problems. Early draft of this paper was kindly reviewed by Drs. John A. BARRON and Yoshihiro TANIMURA, and Mr. Hiroshi KURITA, and they gave us many useful suggestions to refine it. Technical assistance for the sample preparations of the Okubonosawa Section and MITI-Souma-oki etc. and the SEM observation of *C. lanceolatus* is kindly and nicely made by Mrs. Terumi HIRAMATSU and Mr. Teruo SUZAKI, respectively. Dr. Tadami KATAHIRA of JAPEX and Drs. Tadashi ASAKAWA and Seijuro MAIYA of the JAPEX Research Center of the company have given us constant encouragements during the course of this study and also allow us to publish this paper. We heartily express our sincere thanks to those mentioned above.

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