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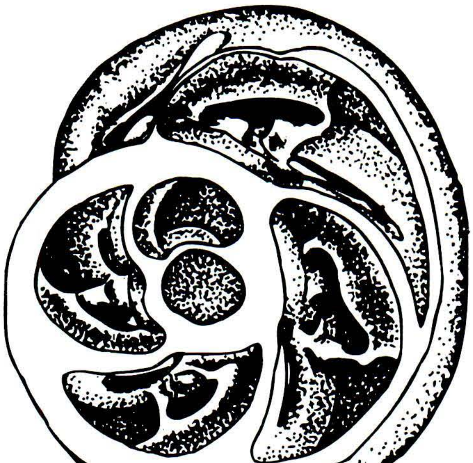

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Contents

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Abstract. Members of the Family Cassidulinidae are common in Tertiary marine sediments. This family is characterized by a biserial chamber arrangement, and is subdivided by using apertural structure, chamber arrangement and crystalline wall structure. Eleven cassidulinid genera are recognized in a recent classification based mainly on these characters. The diversity of these genera and species changed dramatically and developed through the Miocene. I examined Miocene cassidulinids from Japan in order to investigate the timing and paleoenvironmental factors associated with these changes.

I propose that these cassidulinids can be used to define three interval zones. The cassidulinid I Zone occurs in strata deposited between ~17–14 Ma and is characterized by high diversity of globocassidulinid species. The II Zone deposited between ~14–10 Ma is characterized by low diversity. The III Zone from ~10 Ma to 5 Ma is characterized by high diversity among islandiellids and planocassidulinids. Viewed from wall structure, the I Zone is occupied by optically granular taxa, while the III Zone is occupied by optically radial taxa. The taxa from the Sea of Japan borderland in the II Zone are radial, but those from the southern Pacific borderland are dominated by granular. The biogeographic differences in the II Zone may be related to the uplift to the Japanese backbone range and is also related to a global cooling event. Further cooling of the ocean and increased input of organic matter associated with the increase of primary productivity may have led to the evolution of radial taxa. The most common species in the modern Arctic and Subarctic seas have evolved from the cassidulinid III Zone.

Key words: biostratigraphy, cassidulinid, evolution, foraminifera, Miocene, systematics

Introduction

Fifteen years ago, I published about the cassidulinid foraminiferal systematics from the Pleistocene of Japan (Nomura, 1983a, b). At that time, Loeblich and Tappan's suprageneric classification stressed the importance of optical wall structure and internal structure as represented by the toothplate (Loeblich and Tappan, 1964a, b, 1974, 1984). Based on such systematic criteria, cassidulinid foraminifera with enrolled biserial chamber arrangements were divided into two different Families Cassidulinidae and Islandiellidae, and they were recognized as different phylogeny. The distinction of the two families was mainly based on characters such as: 1) presence or absence of the toothplate and, 2) optically radial or granular textures of test walls. However, I have recognized that the foraminiferal toothplate was not useful to describe the apertural structure in the sense of presence or absence. As reviewed by Revets (1993), there are many varied features in the original toothplate (Hofker, 1951a, b). I found foraminifera without the internal free part of the toothplate in the Islandiellidae. Furthermore, I found that the foraminiferal walls have variations which include both radial and granular textures. Many complexities have appeared in the use of wall structure and toothplate for suprageneric classification, despite stressing the importance of wall structure for high hierarchical level (e.g., Loeblich and Tappan, 1974; Hansen, 1979). In fact, there has been much confusion in an identification at both the generic and specific levels. In the case of the Cassidulinidae, several generic names as *Islandiella*, *Globocassidulina* and *Cassidulina* have been used for globular tests, without a check of the wall structure. Such generic identification has made it difficult to understand not only the biogeographic distribution of species, but also their phylogenetic relationships. During examination of these characters in the Cassidulinidae and Islandiellidae, I have redefined the morphological aspects including the toothplate and wall structure (Nomura, 1983a, b).

Loeblich and Tappan (1987) reproposed the suprageneric classification and they recognized the foraminifera assigned to the Order Foraminiferida. They further revised it to the Class Foraminiferea (Loeblich and Tappan, 1992). Thus the Superfamily Cassidulinacea in the Order Buliminida has been recognized as follows:

Family Cassidulinidae d'Orbigny, 1839
Subfamily Cassidulininae d'Orbigny, 1839
Subfamily Ehrenbergininae Cushman, 1927b
Subfamily Orthoplectinae Loeblich and Tappan, 1984
Family Cassidulinitidae Saidova, 1981

In this Paper, Genus *Rutherfordoides,* which has been recognized in the Superfamily Fursenkoinacea, Family Fursenkoinidae, is included in the Subfamily Cassidulininae.

Loeblich and Tappan's revised classification scheme is somewhat similar to those of Saidova (1975), while Saidova (1975) distinguished cassidulinids from buliminids at the order level of hierarchical classification.

This paper is the continuation of my first paper (Nomura, 1983a, b). The description of cassidulinid species follows the same style in order to reconstruct the phylogeny of cassidulinid species. As I first stressed, the ontogenetic changes of apertural structure (including the toothplate structure) in Miocene cassidulinids show a wide variety of apertural features, some of which evolved into the Pliocene and Pleistocene cassidulinids. Their structures fall within several discriminated types in Pleistocene and Recent cassidulinids, as forming the same phylogeny. Nevertheless, the global occurrence reveals that early to middle Miocene forms are minor among the foraminiferal fauna. Most cassidulinids have been unnamed, particularly in Japan. Thus, detailed description of Miocene forms is needed to reconstruct the phylogenetic relationships to the latest Cenozoic forms. The most notable evolution can be recognized in the wall structure, which corresponds to the late Miocene geologic events characterized by the polar cooling and subsequent intensified oceanic and atmospheric circulation. At least, cassidulinids might have developed in association with the global cooling after the middle Miocene and an increased primary productivity in the oceans and marginal seas.

During the last fifteen years, I have had several opportunities to examine the holotypes and secondary types of some cassidulinids deposited in the U. S. National Museum, Smithsonian Institution, British Museum of Natural History, and Austrian National Museum, Wien, and some topotype specimens that were kindly sent to me by request. However, it is still insufficient to cover all of the cassidulinids. Thus, the objectives of this paper are intended to report on the Japanese Miocene forms and to discuss factors which led to an adaptive radiation of cassidulinids during the late Miocene and led to further diversified Pliocene to Recent cassidulinids.

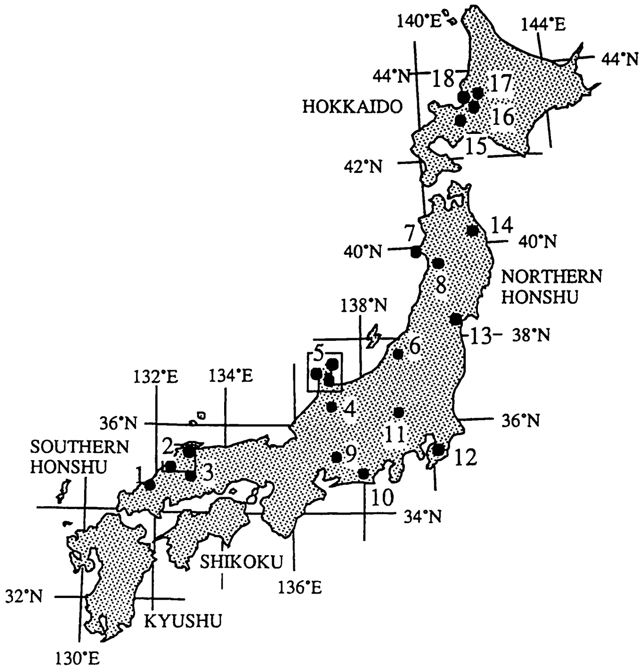


Figure 1. Index map of localities. **1.** Masuda, Shimane Prefecture; **2.** Northeast Shimane, Shimane Prefecture; **3.** Miyoshi and Shobara, Hiroshima Prefecture; **4.** Yatsuo, Toyama Prefecture; **5.** Noto Peninsula, Ishikawa Prefecture; **6.** Niigata, Niigata Prefecture; **7.** Oga Peninsula, Akita Prefecture; **8.** Akita, Akita Prefecture; **9.** Mizunami, Gifu Prefecture; **10.** Kakegawa, Shizuoka Prefecture; **11.** Tomioka, Gunma Prefecture; **12.** Boso Peninsula, Chiba Prefecture; **13.** Hatatate, Miyagi Prefecture; **14.** Sannohe, Iwate Prefecture; **15.** Jozankei, southwestern Hokkaido; **16.** Tsukigata, Hokkaido; **17.** Shintotsugawa, Hokkaido; **18.** Atsuta, Hokkaido.

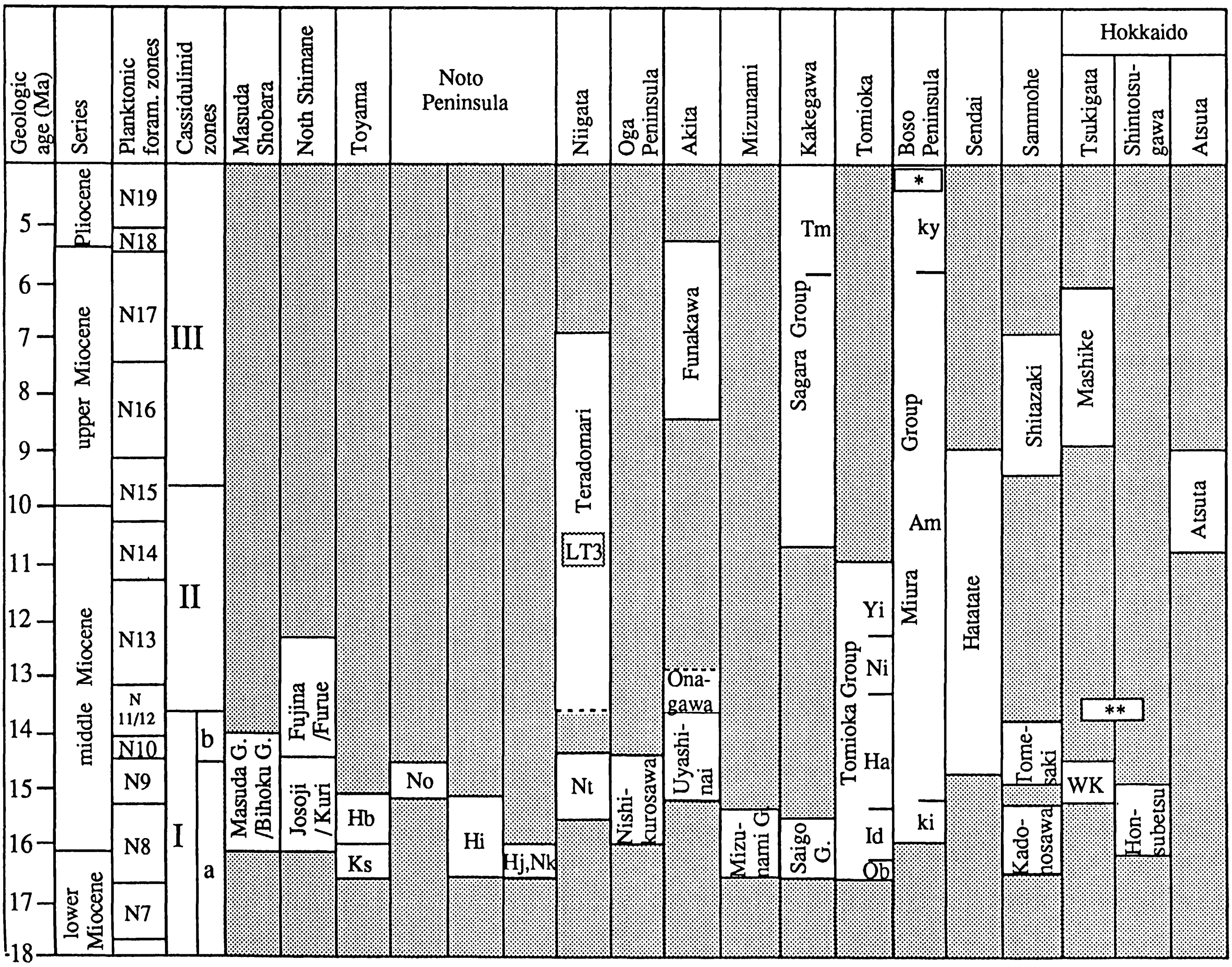
Methods

In order to examine the time and spatial variations of cassidulinid assemblages, many samples were collected from main sections of Miocene basins in the Japanese Islands (Figure 1). Except for a few samples containing highly diversified cassidulinid assemblages, cassidulinids do not dominate middle Miocene foraminiferal assemblages and are usually rare in most basins. This feature of Miocene cassidulinid occurrences differs from Pliocene and Pleistocene cassidulinids, which are characterized by high species diversities. In addition, foraminiferal apertures for Miocene samples are filled with sediment grains, which prevent detailed anatomical observation of internal apertural structure. However, I have tried to get anatomical observations by using a SEM for well preserved specimens. Ontogenetic variation of the cassidulinid aperture presents a key to reconstructing the Late Tertiary cassidulinid phylogeny. Anatomical observations by SEM have been repeatedly used in my studies (e.g., Nomura, 1983c).

Although a secondary overgrowth of calcite occurred in some specimens, the original optical feature of foraminiferal walls was not significantly changed, with an original evidence of radial-granular texture. Optical measurements of crystal units were examined only for the well-preserved specimen. The area and perimeter of each crystal unit were analyzed by using a polarized light microscope at the magnification × 400 to × 1,500. The measurements were carried out by using a public domain program Image (version 1.31) for Macintosh computer (Nomura, 1997).

Occurrence of Miocene Cassidulinids

The stratigraphic positions of the studied lithologic units are summarized in Figure 2, and the biostra-



Am: Amatsu Formation
Ha: Haratajino F.
Hb: Higashibessho F.
Hj: Hojuji F.
Id: Idosawa Formation
Ki: Kinone F.
Ks: Kurosedani F.
Ky: Kiyosumi F.
LT3: Foram. assemblage (Sato et al., 1995)
Ob: Obata Formation
Ni: Niiya F.
Nk: Nakanami F.
No: Nanao Limestone
Nt: Nanatani F.
Tm: Tamari Siltstone
Yi: Yoshii F.
Wk:Wakkauenbetsu F.
* : Anno F. (Pliocene; ~N20)
** : Takinosawa F. (middle Miocene, 13.3-14.2 Ma)

Figure 2. Stratigraphic position of studied lithologic units.

tigraphic and chronostratigraphic remarks are briefly described below:

Atsuta, western Hokkaido

A poorly diversified cassidulinid assemblage occurred in the upper part of the Atsuta Formation distributed in a sea cliff between Kotan and Bekkari.

Ujiié et al. (1977) using magnetobiostratigraphy assigned the Atsuta Formation to a late Miocene diatom zone which is overlain by the *Denticulopsis kamtschatica* Zone. At that time they reported *Cassidulina kasiwazakiensis* and *Globocassidulina subglobosa,* which are herein identified as *Planocassidulina praehelenae* and juvenile specimens of *Cassidulinoides porrectus,* respectively. The Atsuta Formation ranges from the late middle Miocene to early late Miocene (GSJ, 1991; Fukusawa et al., 1992). *Globocassidulina oblongiformis nana* occurred only in this section.

Shintotsugawa, western Hokkaido

Diversified foraminiferal assemblages in association with cassidulinids occurred in mudstone of the Wakkauenbetsu and Mashike Formations distributed along the Wakkauenbetsu-gawa River. The Wakkauenbetsu and Mashike Formations are separated by an unconformity, with the Wakkauenbetsu Formation assigned to the early middle Miocene and the Mashike Formation to the late Miocene (GSJ, 1991; Fukusawa et al., 1992).

The cassidulinid assemblage is mainly composed of *Globocassidulina* and *Rutherfordoides. Planocassidulina praehelenae* occurred rarely in the Wakkauenbetsu Formation, while its occurrence is abundant in the Mashike Formation without any other cassidulinids.

Tsukigata, western Hokkaido

A poorly diversified cassidulinid assemblage is found in the Honsubetsu Formation which is distributed along the Ponsubetsu-gawa River of Tsukigata-machi. It is assigned to the early middle Miocene (Fukusawa et al., 1992) and is characterized by the smaller size of globocassidulinid, evolvocassidulinid, and islandiellid species.

This formation yields the molluscan Takinoue Fauna and is correlated stratigraphically with the early middle Miocene Wakkauenbetsu Formation (Kakimi and Uemura, 1958; Fukusawa et al., 1992).

Jozankei, southwest Hokkaido

The Takinosawa Formation in southern Sapporo is correlated with the middle middle Miocene. The numerical age from the strata correlated to the Takinosawa Formation is 14.2-13.3 Ma (Sawai and Ganzawa, 1988).

A very rare cassidulinid assemblage consisting of *Reissia* sp. was found in this section.

Sannohe, Aomori Prefecture

Multiple biostratigraphic zonation of the Miocene sequence, which consists of the Yotsumata, Kadonosawa, Suenomatsuyama, Tomesaki, and Shitazaki Formations in ascending order, has been studied by Oda et al. (1983, 1984). The Kadonosawa Formation yields a tropical to subtropical shallow fauna, indicating the lower middle Miocene. The Tomesaki Formation is partly correlated with the diatom *Denticulopsis praedimorpha* Zone and the Shitazaki Formation is partly correlated to the *D. dimorpha, D. katayamae* and *Thalassionema schraderi* Zones, indicating early late Miocene (Oda et al., 1983, 1984).

A diversified cassidulinid assemblage occurred in the Shitazaki Formation. Poor assemblages occurred in the underlying the Tomesaki, Suenomatsuyama, and Kadonosawa Formations. *Globocassidulina pseudojaponica* and *G. lenticularis* occurred commonly in the Tomesaki Formation. *Cassidulinoides porrectus* and islandiellids are common in the Shitazaki Formation.

Akita and Oga Peninsula, Akita Prefecture

The Miocene sequence in the eastern part of Akita City consists of the Uyashinai, Onnagawa, and Funakawa Formations in ascending order (Osawa et al., 1981). Maiya (1978) reported the *Globigerinoides sicanus/Praeorbulina glomerosa* Zone, the *Globorotalia peripheroronda/G. quinifalcata* Zone, and the *Globorotalia peripheroronda/G. miozea* Zone, indicating planktonic foraminiferal Zones N8-11. The upper part of the Onnagawa Formation is correlated with the diatom *Coscinodiscus yabei* Zone of the late middle Miocene and the Funakawa Formation is correlated with the diatom *Denticulopsis dimorpha* Zone to the *D. kamtschatica* Zone of the late Miocene (Shiraishi and Matoba, 1992).

Planktonic foraminifera indicating N9 (Saito and Maiya, 1973), and the diatom *Denticulopsis hyalina* Zone and the *D. hustedtii* Zone (without the *D. nikobarica* Zone; Koizumi and Matoba, 1989) are reported from the Nishikurosawa Formation distributed in the southern Oga Peninsula.

A poorly developed cassidulinid assemblage from the Uyashinai Formation consists of small-sized *Globocassidulina, Ehrenbergina,* and *Rutherfordoides.* In contrast, diversified islandiellids and planocassidulinids occurred in the Funakawa Formation, all of which are characterized by larger tests. *Globocassidulina notoensis* occurred rarely in the Nishikurosawa Formation.

Sendai, Miyagi Prefecture

A Miocene marine sequence in the west of Sendai City consists of the Moniwa, Hatatate, and Tsunaki Formations in ascending order. The Moniwa Formation is assigned to the planktonic foraminiferal Zone N8 (Oda and Sakai, 1977) and the Hatatate Formation to N9–14 and the middle middle Miocene based on the diatom *Denticulopsis praedimorpha* Zone (Oda and Sakai, 1977; Oda et al., 1984)

The cassidulinid assemblage from the Hatatate Formation is composed of *Globocassidulina, Ehrenbergina, Paracassidulina,* and *Islandiella. Globocassidulina globosa* is abundant throughout the formation *Globocassidulina pseudojaponica is* abundant in the lower part of the Hatatate Formation, while *G. hatatatensis* occurred commonly in the upper part.

Niigata, Niigata Prefecture

Three zones of planktonic foraminifera (the *Globigerinoides sicanus/Praeorbulina glomerosa curva* Zone, the *Globorotalia peripheroronda / G. quinifalcata* Zone, and the *Globorotalia peripheroronda / G. miozea* (s.l.) Zone) were proposed from the Nanatani Formation, Niigata Prefecture, as the standard planktonic foraminiferal zones in the Sea of Japan borderland (Maiya, 1978). These three zones are correlated with the interval from N8 to lower part of N11–N13 (Maiya, 1978). From late middle Miocene to late Miocene, benthic foraminifera are composed of agglutinated forms and no planktonic foraminifera were found in this area (Matsunaga, 1963; Maiya, 1978)

Cassidulinid foraminifera from the type sections studied by Maiya (1978) are rare and have smaller tests. Of 10 species identified, *Globocassidulina globosa* and *G. oblongiformis* are dominant, indicating the development of a similar cassidulinid assemblage throughout the Nanatani Formation.

The first appearance of *Planocassidulina praehelenae* was found in the upper part of the Nanatani Formation. In general, this occurrence is rare. However, exceptionally, a hundred percent of *P. praehelenae* occurred in the limited level of the lower Teradomari Formation (so-called Blue Zone), which is correlated with the LT3 (the *Cassidulina-Gyroidinoides* assemblage with agglutinated foraminifera) of Sato et al. (1995), or N11 to N13 (Kobayashi and Tateishi, 1992). A clear change of cassidulinid assemblage occurred in association with the event recognized as the planktonic foraminiferal sharp surface (Maiya and Inoue, 1981).

Yatsuo, Toyama Prefecture

The Marine Miocene sequence in this area consists of the Kurosedani, Higashibessho, and the Otogawa Formations, in ascending order. A typical tropical to subtropical fauna (the Yatsuo-Kadonosawa molluscan fauna; Chinzei, 1986; Ogasawara, 1994) and flora have been reported from the Kurosedani Formation deposited in a shallow water environment. The *Denticulopsis praelauta* Zone and the *Actinocyclus ingens* Zone have been reported from the upper part of the Kurosedani Formation, indicating N7–8 (e.g., Fujii et al., 1992). Planktonic foraminiferal and paleomagnetic studies in the Higashibessho Formation indicate the geologic ages assigned to N8–9 (Itoh, 1986; Ogasawara et al., 1990).

Cassidulinid assemblage from the Higashibessho Formation consists of five taxa, of which *Globocassidulina globosa* and *Planocassidulina praehelenae* are common.

Noto Peninsula, Ishikawa Prefecture

Various kinds of marine faunas occur from the Higashi-innai Formation, distributed in the northern part of the peninsula, including foraminifera (Asano, 1953b). The Hojuji and Nakanami Formations are correlated with the Higashi-innai Formation, all of which yield well preserved foraminiferal assemblages (Morozumi and Koizumi, 1981; Hasegawa and Kobayashi, 1986; Fujii et al., 1992). Their geologic ages are assigned to 16–15 Ma (N8–9). The Sekinohana Calcareous Sandstone, distributed in the northwestern part of the peninsula, yields both benthic and planktonic foraminifera, indicating Zone N8 and thus correlated with the Higashi-innai Formation. The Nanao Limestone is assigned to 16–15 Ma (Fujii et al., 1992).

Globocassidulina pseudojaponica and *G. lenticularis* are associated with paracassidulinids in the Sekinohana Calcareous Sandstone and the Nanao Limestone. Except for these calcareous sediments, a similar composition of the cassidulinid assemblage, represented by *G. imamurai, G. oblongiformis,* and *G. globosa,* is found in this area. *Globocassidulina canaliornata* occurred only in the Nakanami Formation.

Boso Peninsula

The Miocene sequence consists of the Sakuma, Kinone, Amatsu, and Kiyosumi Formations and the Pliocene Anno Formation. According to Oda (1977), the early middle Miocene Kinone Formation is assigned to N8. The Amatsu Formation ranges from the middle to late Miocene (N9 to N17). The Kiyosumi Formation ranges from the late Miocene to the Pliocene (N17–19). The Anno Formation is correlated with the early Pliocene (N20).

The cassidulinid diversity of these Miocene formations is very low, only represented by *Globocassidulina globosa. Takayanagia cushmani* occurred in the Anno Formation.

Tomioka, Gunma Prefecture

Lower middle to middle middle Miocene strata in the Tomioka area are divided into the Obata, Idozawa, Haratajino, Niwaya, Yoshii, and Itahana Formations in ascending order (Konda, 1980). The Obata and Idozawa Formation, and the lower part of the Haratajino Formation are assigned to N8. The main Haratajino Formation is assigned to N9. The upper part of the Haratajino Formation comprises N9–12. The upper part of the Yoshii Formation is correlated to N14 (Konda, 1980).

Among them, the Idozawa, the Haratajiro, and the Niwaya Formations yield cassidulinid foraminifera, consisting mainly of *Globocassidulina* and *Paracassidulina*. The last occurrence of *G. oblongiformis* is found in the lower part of the Haratajino Formation, which is correlated with the boundary of the *Praeorbulina glomerosa/Orbulina suturalis* Zone and the *Globorotalia peripheroronda/O. suturalis* Zone (N8/9 boundary). *Planocassidulina praehelenae* occurred in the upper half of the Haratajino and Niwaya Formations and the relative abundance increased in the Niwaya Formation.

Kakegawa, Shizuoka Prefecture

The Saigo Siltstone of the Saigo Group is correlated with the *Globigerinoides sicanus* and *Praeorbulina glomerosa* Zones, indicating N8 (Ibaraki, 1986). In general, the cassidulinid assemblage is very poor in composition and diversity, consisting only of *Globocassidulina*.

The cassidulinid assemblage in the uppermost Miocene Tamari Siltstone (N16–17; Ibaraki, 1986) of the Sagara Group consists of *Cassidulina carinata, Paracassidulina neocarinata, Globocassidulina globosa, G. kakegawaensis,* and *Evolvocassidulina kuwanoi.* Such an assemblage is very similar to that of the Pliocene to Pleistocene Kakegawa Formation.

Mizunami, Gifu Prefecture

The Oidawara Formation of the Mizunami Group yields a diversified foraminiferal assemblage (Seto, 1992) and is assigned to N8 (Shibata and Ishigaki, 1981; Itoigawa and Shibata, 1992).

The cassidulinid assemblage from the Mizunami Group consists of *Globocassidulina notoensis, G. globosa, Ehrenbergina notoensis,* and *Planocassidulina praehelenae.* The assemblage is very similar to that of the Higashibessho Formation, Toyama Prefecture.

Miyoshi and Shobara, Hiroshima Prefecture.

Small patches of the lower middle Miocene Bihoku Group are distributed in isolated basins of the inland area of Chugoku mountain. Planktonic foraminiferal zones in the lower part of this group are correlated to N8–9 (Nomura, 1992a).

The cassidulinid assemblage found in the benthic foraminiferal *Hanzawaia-Heterolepa* Assemblage Zone (Nomura, 1992a) is similar to that of the Mizunami Group, represented by *Globocassidulina globosa, G. notoensis,* and *Planocassidulina praehelenae.* Relative abundance of *P. praehelenae* reaches 35%.

Northern Shimane, Shimane Prefecture

Only *Planocassidulina praehelenae* occurred in the Furue and Fujina Formations, which are assigned to Zones N10–13 (Nomura, 1984; Nomura and Maiya, 1984). *Planocassidulina praehelenae* is usually associated with abundant *Uvigerina* or agglutinated taxa characterized by lower diversity.

A poor cassidulinid assemblage consisting of *Globocassidulina globosa* and *Planocassidulina praehelenae* occurred in the Kuri Formation, which can be assigned to the biostratigraphic units (N9) below the Foram. Sharp Line (Nomura, 1986).

Masuda, Shimane Prefecture

The cassidulinid assemblage from the Masuda Group is similar to that from the Bihoku Group. Both the Masuda and Bihoku Groups share a similar geologic history (Nomura et al., 1993).

Systematic Criteria of Miocene Cassidulinids

Wall Structure

The cassidulinid walls consist of optically radial and granular textures, and there are two variations in each texture (Nomura, 1983a). Miocene cassidulinids with these textures should be primarily the figurative expression resulting from genetic control. However, the variations within the radial and granular textures may be ecophenotypic. For example, the two species *Cassidulina reniforme* and *Cassidulina carinata* which have mosaic-granular walls and jagged granular walls, respectively. They adapt to particular environments by changing their wall structure from the ancestral globocassidulinid species, when speciation occurred. *Cassidulina reniforme* is common in cold water masses, while *C. carinata* occurs in warm water masses. *Rutherfordoides erectus* having the mosaic granular texture usually occurs in argillaceous sediments, while *Globocassidulina pseudojaponica* with jagged-granular walls occurs in arenaceous sediments. Both forms have a different ecological preference as reflected in the different wall texture. Thus, wall structure has been considered as indicating both phylogeny and ecophenotypic variation responding to the microhabitat.

In order to evaluate these textures quantitatively, I carried out an image analysis for the optical textures of crystal units. Each crystal unit is distinguished by com-

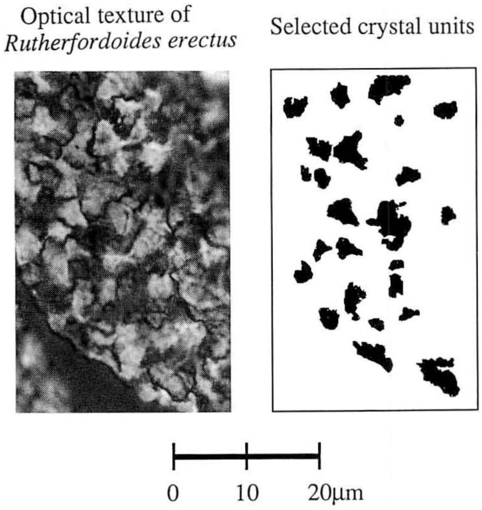


Figure 3. Measurements of crystal units of optically granular walls. Crystal units in polarized feature with inserted gypsum plate showing optically positive or negative states (left). Selection of crystal units was made from one state of positive or negative feature by using image analysis. Solid areas were measured for each area and perimeter (right). Example is mosaic granular texture of *Rutherfordoides erectus.*

plicated suture lines, when the final chamber walls are examined with a polarizing microscope at the magnification over × 400. Each crystal unit consists of a bundle of needle-shaped crystal elements, which are a fundamental constituent (about 0.2μm in width) of the crystal unit. The crystal elements have the same optical axis within the crystal unit. Each crystal unit has a different direction of the optical axis. The optical axis of the crystal unit is inclined to the wall surface in the range of 30–60° (Nomura, 1983a). This presents the complicated nature of the granular texture in polarized light. These crystal units are optically distinguishable at positive or negative state with an accessory gypsum plate inserted into the polarized state, showing ameba-shaped blue and yellow areas. Thus, quantitative analysis of these crystal units is possible by measuring the area and perimeter of the colored units, in either optically positive or negative states (Figure 3). This optical analysis of crystal units gives a good result for the distinction between jagged and mosaic granular textures, which have been hitherto distinguished by an apparent feature of crystal units (Figure 4). Despite the same species, specimens from different localities show different sizes of crystal units, as can be seen in *Rutherfordoides erectus* with the mosaic texture. The mosaic texture shows that the areas of crystal unit are statistically overlapped with those of the jagged texture (Figure 4a). When they are examined by a ratio of the area to the perimeter, however, mosaic and jagged types are effectively distinguishable from each other, giving the median boundary values of 1.5 – 2 (Figure 4b). In this work, I employ this result for the recognition of granular texture of walls.

Apertural Foramen

In Pliocene to Recent forms, I have recognized nine types of apertural morphology (Nomura, 1983a). They

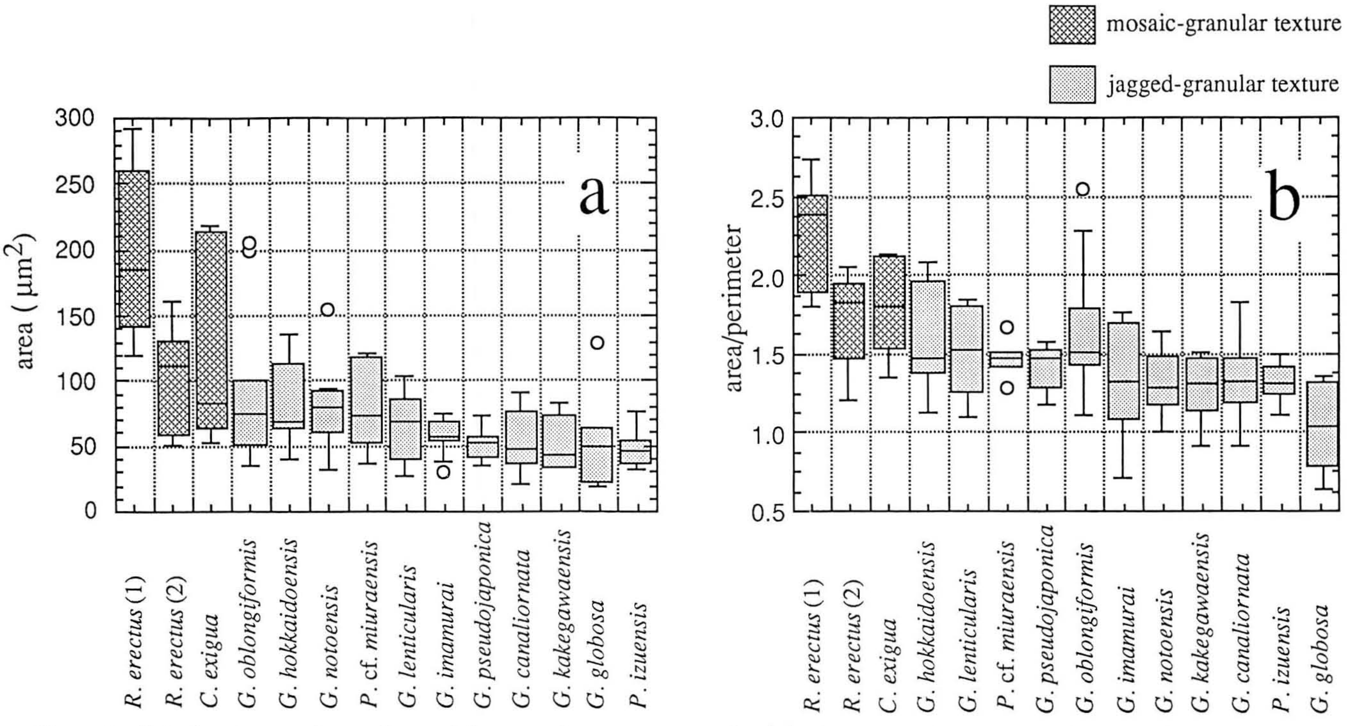


Figure 4. Calculated comparisons of area (a) and perimeter to area ratios (b) of crystal units for the different species with optically granular walls. Note mosaic granular texture differs clearly from jagged granular one, by having larger perimeter to area ratios. Each box accounts for 50% of the crystal units. Circle indicates exceptional value of the unit.

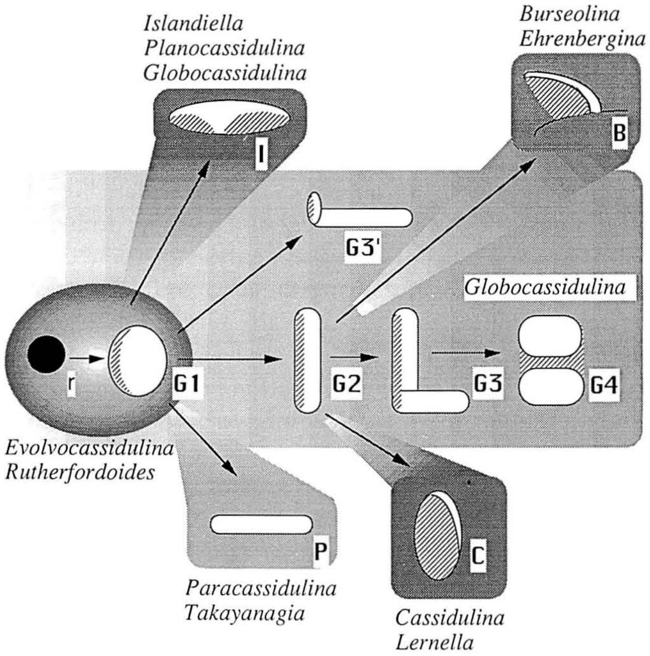


Figure 5. Schematically illustrated apertural types and their development patterns in the Cassidulinidae. The representative genera of each apertural type indicated near the type or assembled types, respectively. Character **r** indicating rounded aperture of proloculus; **G1** indicating oval to rounded triangular aperture; **G2** indicating vertical slit (I-shaped) aperture; **G3** indicating tripartite (L-shaped) aperture; **G3'** indicating tripartite aperture with very short areal slit; **G4** indicating =-shaped aperture; **I** indicating elongate oval with developed cristate tooth and secondary tongue; **P** indicating interiomarginal aperture; **C** indicating oval aperture with developed apertural plate; **B** indicating curved slit aperture with developed apertural flap. Obliquely shaded area indicating apertural modifications such as cristate tooth and secondary tongue. Apertural types of Nomura (1983a) and Nomura (1984) are revised in this figure.

are also recognized in Miocene forms showing oval (including rounded triangular; **G1**-type), vertical slit-shaped (**G2**-type), tripartite (L-shaped; **G3** and **G3'**-types), elongate oval with developed toothplate (**I**-type), interiomarginal slit aperture (**P**-type), elongate oval with apertural plate (**C**-type), and curved slit with apertural flap (**B**-type) (Figure 5). Many varied shapes of apertures are particularly found in the Genus *Globocassidulina* (**G1**-, **G2**-, **G3**-, **I-**, and **G3'**-type; **G4**-type aperture is only found in *G. biora* (Crespin); Nomura, 1984). These apertural types vary through the ontogeny, and are a key to reconstructing the heterochronic phylogeny of the cassidulinid taxa. The apertural structure of Miocene cassidulinids is commonly represented by primitive forms, such as *Globocassidulina notoensis* that is devoid of protruded cristate tooth. Such a primitive shape as **G1**-and **G2**-types can be observed in the younger generation of the Pliocene to Recent forms.

Toothplate

Recently Revets (1993) reviewed the concept of the foraminiferal toothplate and suggested a limitation in comparing morphology among the foraminifera using the toothplate, particularly for the difference between rotaliaceans and buliminids. He discussed the toothplate from the view point of morphology and lamellarity.This should be important in discussing a higher level of systematic classification, because it is needed to evaluate whether the toothplate (including formation process) is a consistent systematic criterion or not. The toothplate originally referred to a free structure of wall that formed near the apertural opening, and has been best illustrated in the Buliminidae (Hölund, 1947). Hölund (1947) noted this structure only as a tongue. However, its interpretation expanded to include multifarious taxa having apertural modifications, as shown in Hofker's Order Dentata (Hofker, 1951a, b). Moreover, Hansen and Reiss (1971, 1972) and Hansen (1979) regarded the toothplate as consisting of a bilamellar structure, to be included in the rotaliaceans. Revets (1989, 1993) stressed that the toothplate consisting of an inner layer of bilamellar walls is a feature most characteristic of the Buliminidae. Thus, there have been two ideas for the toothplate structure, which may have different processes in the toothplate formation. Because of the difficulty in tracing the layer structure of walls in cassidulinids, the lamellar structure of the toothplate is still unclear (Nomura, 1983a).

The toothplate, herein, is used as a morphological comparison only and is not related to the lamellar walls. Setting aside the question of whether the cassidulinids walls are bilamellar or not, I believe the cassidulinid toothplate has the same functional significance and formation as the buliminid toothplate.

Some observations suggest that apertural shape and surface ornamentation of test walls reflect protoplasmic movement (Kitazato, 1992). The toothplate may possibly work as a rudder for the protoplasmic flow out of the aperture, as speculated before (Nomura, 1983a). Biserial chamber arrangement may also be controlled by the toothplate for the movement of cytoplasm. The **G1**-type aperture consisting of a rounded opening is sometimes devoid of the internal free tongue, but such specimens usually form an uncoiled or loosely coiled tests. The **I**-type aperture with a developed cristate tooth and tongue is usually in large and biserially enrolled tests. Such a difference of chamber arrangement is surely reflected in the apertural structure, particularly in the toothplate morphology.

The toothplate of Miocene cassidulinids supports my suggestion that it is morphologically variable in character, and the presence or absence of toothplate itself is not useful for distinguishing between generic and suprageneric level of taxa. This is against the view of Hofker (1951a, b) who regarded it as a homologous character.

For comparative work, the morphological variations, such as cristate tooth, primary tongue and secondary tongue, respectively, should be noted. In general, more primitive forms or ontogenetically immature forms show the less developed tongues and tooth.

Perforations

Pores on test walls are basically divided into two types, round and slit. The shape of pores varies in accordance with subsequent layering on test walls. Thus, various shapes of pores can be found on the earlier portion of the external test walls (just below the final apertural face). The typical slit-type pore was found in *Globocassidulina canaliornata*. Other Miocene cassidulinid species show the rounded or irregular type of pores.

Ornamentation

In general, few Miocene cassidulinids have surface ornamentation, in spite of many varied ornamentations recognized in Pliocene and Recent forms. *Globocassidulina arata* has weak reticulate costae, which are a primitive form of the well developed reticulation as found in *G. decorata*. Character change from indistinct to distinctly developed ornamentation may be partly related to the ecology of species. However, its evolutionary significance is not clear.

Zonation of Miocene Cassidulinids

Japanese Miocene sequences were developed in different basins with different geologic histories. Uplift of the Japanese backbone range at ~15 Ma divided the previously formed basins into smaller local basins and produced a different stratigraphic history for the Sea of Japan and the Pacific borderlands. In the Sea of Japan borderland, oceanic circulation at deeper depths became reduced, so that calcareous benthic fauna disappeared and in turn the strata with either agglutinated foraminifera or no foraminifera were formed (e.g., Nomura,

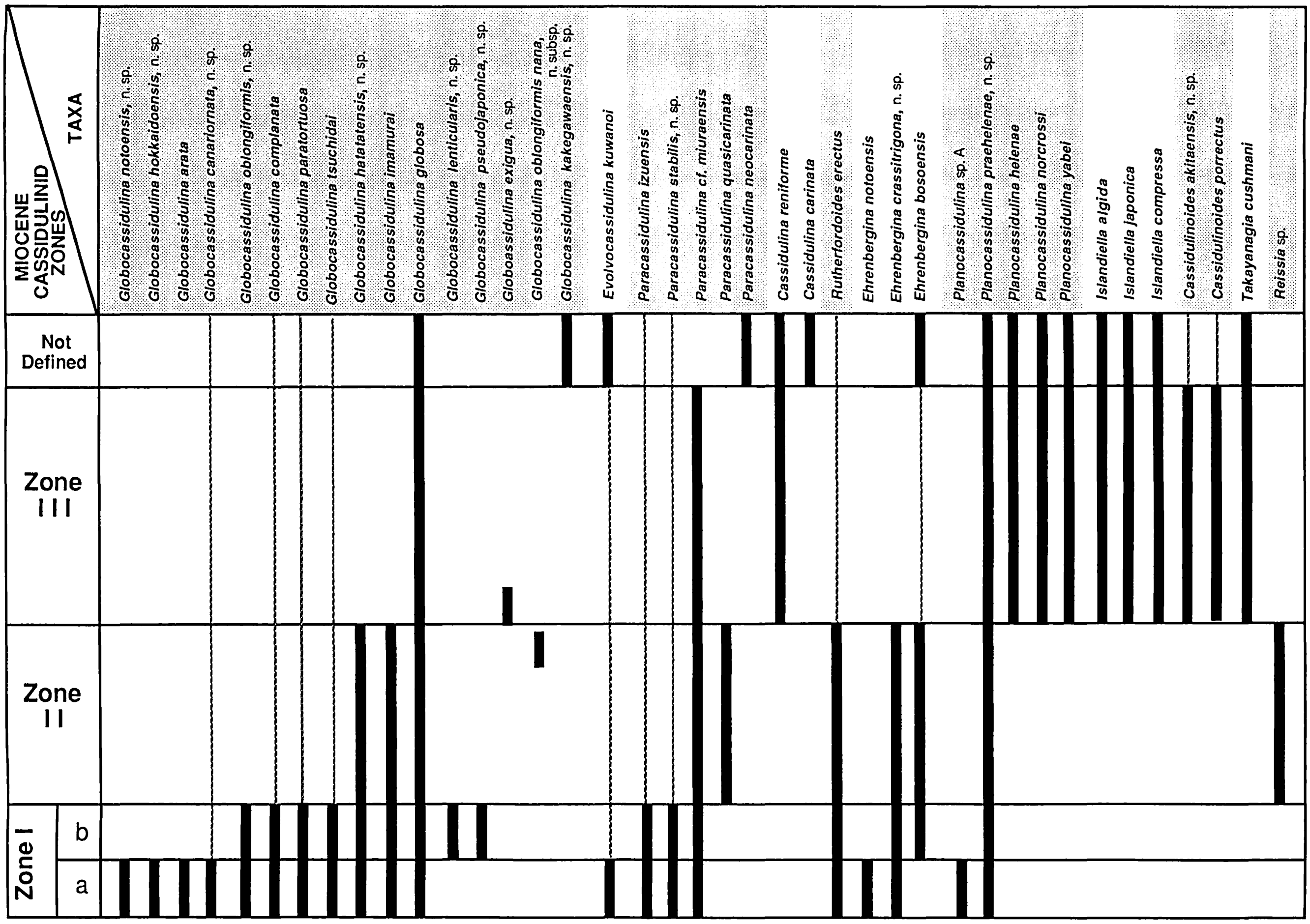


Figure 6. Stratigraphic distribution of cassidulinids and indicated Miocene cassidulinid three zones (I, II, and III) and two subzones (Ia and Ib).

1992a, b). In addition to such different geologic histories in the Japanese Islands, cassidulinid foraminifera do not always characterize middle Miocene foraminiferal assemblages as compared with the Pliocene cassidulinids. They were rather limited in number compared to the main components of the foraminiferal fauna. However, the explosive evolution of the cassidulinid assemblages from the late Miocene is intimately related to the physicochemical changes of regional marine water in concert with global paleoceanographic changes. These Miocene geologic and paleoceanographic events should be reflected in the scheme of cassidulinid zonation.

The zonal scheme used in this study is in accordance with an interval zone as defined by the first and last occurrences of marker species (ISSC: International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy, 1994). In consequence, three Miocene cassidulinid zones and two subzones are recognized. Some taxa applied to this zonation form a phylogenetic lineage (Figure 6). The assemblages in southern Honshu show more or less similar composition, though the cassidulinid assemblages in northern Honshu and Hokkaido are differentiated from those of southern Honshu. Thus, based on the similarity of assemblage, the interval zones within a limited area can be represented by lineage zones, particularly in early middle Miocene globocassidulinid assemblages. However, such lineage zones can not be applied to the extended geographic area, because the paleoceanographic environment as well as regional geologic history changed critically from the middle middle Miocene on, as stated above.

The proposed cassidulinid zones are correlated with the published bio-and chronostratigraphic zones described in the stratigraphic section, which are based on Berggren et al.'s age model (1985). The ages are also referred to the revised model of Berggren et al. (1995). Numerical ages without any citation are described as the age model of Berggren et al. (1985). Evolutionary trends of selected species, which are nominated for the marker in this zonation, are shown in Figure 7.

1. Cassidulinid I Zone

Definition:- Interval from the first occurence of *Globocassidulina oblongiformis* to the last occurrence of *Globocassidulina pseudojaponica* and *G. lenticularis.*

Type sequence:- Higashi-innai Formation, Toyama Prefecture

Age:- Latest early Miocene to early middle Miocene.

Remarks:- This zone is characterized by diverse globocassidulinid species. The most common species are: *G. globosa, G. oblongiformis* and *G. imamurai.* This zone is further divided into two subzones based on the total range, and first and last occurrences of the marker spe-

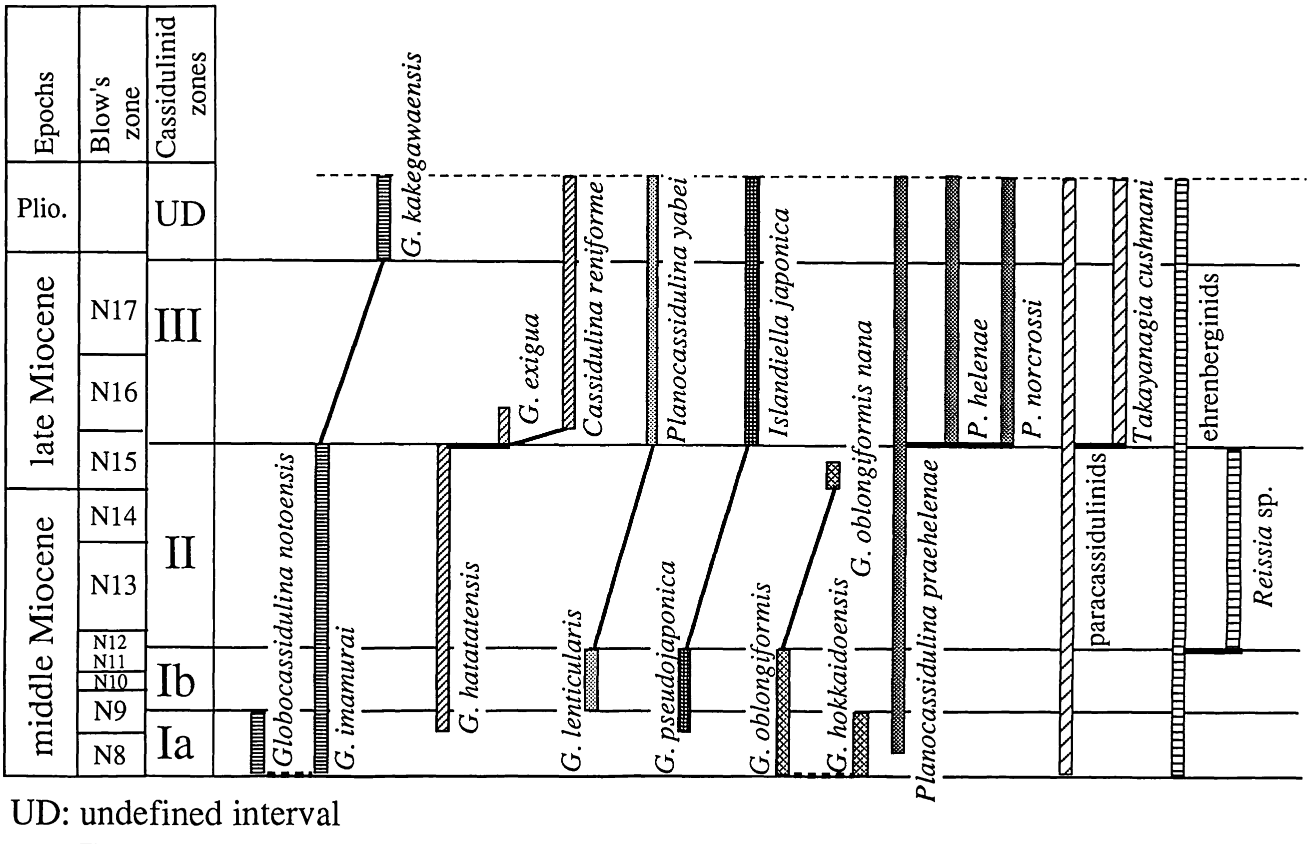


Figure 7. Phylogeny of some Miocene cassidulinids and the stratigraphic distribution (see also Figures 11 and 12).

cies.

Cassidulinid Ia Subzone

Definition:- Interval from the first occurrence of *Globocassidulina oblongiformis* to the last occurrence of *Globocassidulina notoensis* and *Globocassidulina hokkaidoensis.*

Type sequence:- Hojuji Formation, Noto Peninsula.

Age:- Latest early Miocene to early middle Miocene.

Remarks:- This zone is characterized by usually small-sized globocassidulinid species. *Globocassidulina imamurai* is common in this subzone.

This subzone is nearly correlated with N7-N9 of planktonic foraminiferal zones which ages are ~17-14.8Ma (Berggren et al., 1985, 1995).

Cassidulinid Ib Subzone

Definition:- Interval from the last occurrence of *G. notoensis* to the last occurrence of *G. pseudojaponica* and *G. lenticularis.*

Type sequence:- Nanao Limestone, Noto Peninsula.

Age:- Early middle Miocene.

Remarks:- This zone is also characterized by diversified globocassidulinid species. This subzone is nearly correlated with the interval of late N9 to N11/12.

2. Cassidulinid II Zone

Definition:- Interval from the last occurrence of *Globocassidulina oblongiformis* to the first occurrence of *Planocassidulina helenae* and *Islandiella japonica.*

Type sequence:- Middle to upper part of the Hatatate Formation, Miyagi Prefecture.

Age:- Middle middle Miocene.

Remarks:- This zone is represented by the Hatatate Formation and the Tomioka Group, Gunma Prefecture. Although this zone in the Sea of Japan borderland is mostly occupied by agglutinated foraminifera, *Planocassidulina praehelenae* is found in the limited level of the Teradomari Formation, Niigata Prefecture and the Furue and Fujina Formations, Shimane Prefecture. From the Pacific borderland, Konda (1980) reported the assemblage consisting of *Planocassidulina praehelenae* (as *Cassidulina norcrossi*) in the Niwaya Formation, which is correlated with planktonic foraminiferal zone N10-13 (mostly N12-13) and included in this Zone.

This zone corresponds in extent to the interval ranging from N11/12 to N15 which suggests an age of ~ 13.8-10.2Ma (Berggren et al., 1985) and 12.8-10.9Ma (Berggren et al., 1995).

3. Cassidulinid III Zone

Definition:- Interval from the first occurrence of *Planocassidulina helenae* and *Islandiella japonica* to the first occurrence of *Cassidulina carinata.*

Type sequence:- Shitazaki Formation, Aomori Prefecture.

Age:- Late Miocene.

Remarks:- This zone is characterized by the diversified islandiellid and planocassidulinid species. The base of this zone is assigned to N15 and is nearly correlated with the middle and late Miocene boundary (10.4Ma of Berggren et al., 1985 and 11.2Ma of Berggren et al., 1995).

4. Undefined Pliocene Zone

Undefined cassidulinid zone is recognized in the latest Miocene to early Pliocene Kakegawa Group. The base of this zone is marked by the first occurrence of *Cassidulina carinata.* Because of limited numbers of samples, the detailed zonal definition is not discussed in this paper. The faunal composition of this zone is close to Pliocene to Recent faunas of the southern Pacific borderland of Japan.

Paleobiogeography of Cassidulinid Assemblages and the Relation to Wall Structure

Distribution of Pleistocene and Recent cassidulinids in and around the Japanese Islands led to recognition of two biogeographic provinces, the Japan Sea and the Pacific Provinces (Asano and Nakamura, 1937). The Japan Sea Province is characterized by a common occurrence of islandiellid species, while the Pacific Province is dominated by diversified globocassidulinid and paracassidulinid species. This differentiation is more clearly recognized from the view point of the wall structure; forms with optically radial walls are main components in the Japan Sea Province and those with optically granular walls are dominant in the Pacific Province (Nomura, 1984a). Asano and Nakamura's discussion on these cassidulinid provinces was based on rather limited information at that time. They examined assemblages from shelf deposits but no cassidulinid assemblages from northeastern Honshu of the Pacific borderland were taken into account in the recognition of these provinces. However, recent researches on the modern distribution indicate that islandiellid species occur in the Pacific

Ocean off Northeast Honshu (Matoba, 1976) and in upper Miocene deposits of Sannohe area (this study). Thus, the original definition of the two provinces should been modified to the Japan Sea Province and the Pacific Province except for northern Japan. Such a biogeographic pattern is otherwise recognizable as showing a latitudinal differentiation at a boundary around 35° North latitude, and is more exactly expressed as the northern cassidulinid province and southern cassidulinid province. When the depth distribution is superimposed on this biogeography, a different biogeographic feature can be seen. The modern islandiellid species are very abundant at the depths of 140–600 m in the Sea of Japan, where an intensified seasonal upwelling occurs (Inoue, 1980; Nomura and Ikehara, 1987). However, they are not so abundant in the Pacific Ocean off Northeast Honshu as compared with the Sea of Japan area and they are limited to bathyal depths (Ikeya, 1971; Matoba, 1976; Kaiho and Hasegawa, 1986).

Nomura (1984) recognized temperature control for the cause of such differentiation of the cassidulinid biogeography. The reported temperature ranges for islandiellid and planocassidulinid species are mostly 10°–20°C, although there are wide variations in the ranges. Contrary to this, globocassidulinid species prefer to live in higher temperature ranges. Based on such a correspondence between the geographic occurrence and the temperature range of water masses, wall structure having optically radial texture is judged to be an adapted morphocharacter to colder water masses, while granular texture to warmer water masses. Thus, the cassidulinid biogeography should be interpreted as an indicator of the Japan Sea Proper water mass and the cold Oyashio Current, and the warm Kuroshio Current, respectively. Such a consistent relationship between the wall character and the water mass character can be applied to Miocene cassidulinid assemblages to reconstruct paleowater masses. I have analyzed the wall character of Miocene cassidulinids for three different zones (Figures 8–10).

The cassidulinid I Zone is generally represented by the taxa with intricate granular walls consisting mostly of the genus *Globocassidulina* (Figure 8). The dominance of *Globocassidulina* is related to the development of warm water mass over the Japanese Islands. This zone is assigned to the period that the marine transgression occurred at ~ 17–16 Ma. A neritic environment developed in many places on the Japanese Islands, yielding shallower tropical to subtropical faunas. Exceptionally, *Planocassidulina praehelenae* with optically radial walls

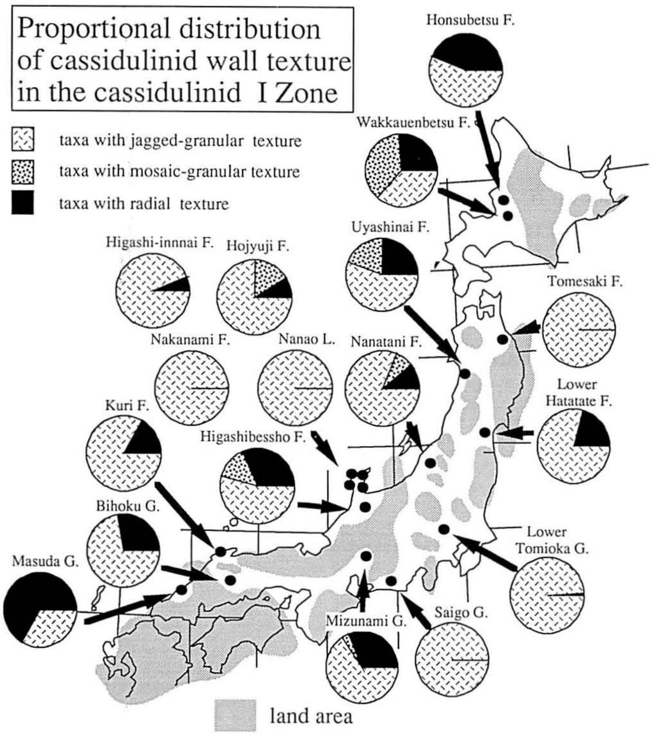


Figure 8. Geographic distribution of three wall types of cassidulinids in the cassidulinid I Zone. Each wall type is calculated from proportional ratios of individuals forming assemblages within lithologic units. Note that globocassidulinid and paracassidulinid species with jagged-granular walls are common in this zone. Exceptionally, cassidulinid with radial walls was found in the Sea of Japan borderland. Hatched pattern indicates supposed land areas during the early middle Miocene (planktonic foraminiferal N8-9) (After Chinzei, 1986; Maiya, 1988; GSJ, 1991).

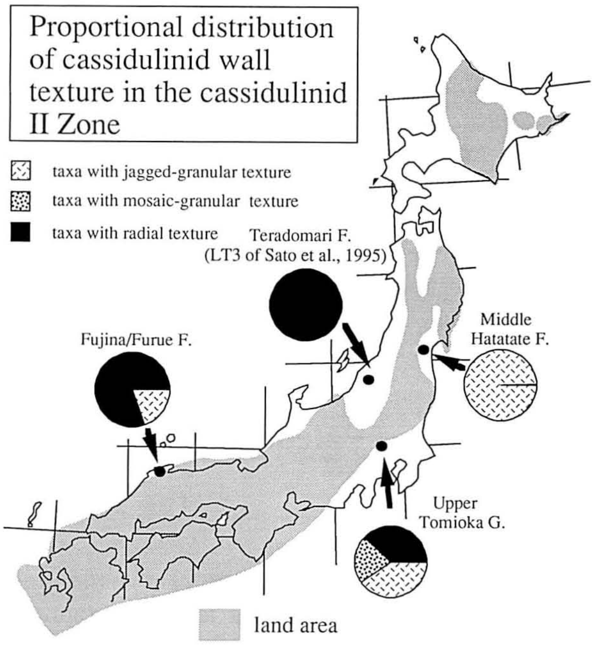


Figure 9. Geographic distribution of three wall types of cassidulinids in the cassidulinid II Zone. Each wall type is calculated from proportional ratios of individuals forming assemblages within lithologic units. Note that calcareous foraminifera in this zone are rare in occurrence, but exceptionally *Planocassidulina praehelenae* with radial walls dominates in the Sea of Japan borderland. Hatched pattern indicates supposed land areas during the middle middle Miocene (planktonic foraminiferal N12–15) (After Chinzei, 1986; Maiya, 1988; GSJ, 1991).

accounts for a maximum 58–85% of the cassidulinid assemblage in some samples from the Masuda and Bihoku Groups of Southwest Honshu and Higashibessho Formation of Central Honshu, and the assemblages from the Uyashinai Formation of Northeast Honshu and the Wakkauenbetsu Formation of Hokkaido.

Cassidulinid assemblages in the cassidulinid II Zone are less developed in the Japanese Islands (Figure 9). This is related to tectonic history of the Japanese Islands, in which Miocene basins were further divided into several smaller basins during the middle to late middle Miocene. Differential vertical movement appeared in Miocene basins during this time. The foraminiferal fauna indicates such a differentiated tectonic history in the respective basins (Nomura, 1992a, b; Sato et al., 1995). The sediments assigned to this zone yield mostly agglutinated assemblages lacking in hyaline calcareous foraminifera in the sedimentary basins developed in the Sea of Japan borderland. An exception is the LT3 zone (*Cassidulina-Gyroidinoides* assemblage with agglutinated foraminifera) of Sato et al. (1995) or the so called "blue zone" of informal lithostratigraphic units in the Niigata sedimentary basin yields a hyaline calcareous assemblage, that is dominated by *Planocassidulina praehelenae* (100% for the cassidulinid assemblage). *Planocassidulina praehelenae* occurred in this zone in the Tomioka (the Niwaya Formation) and northern Shimane areas (the Fujina and Furue Formations), with maxima of 44% and 85% of the cassidulinid assemblage, respectively. These assemblages were formed at upper bathyal depths, while shallower assemblages such as the Hatatate Formation were dominated by the optically granular-walled taxa such as *Globocassidulina hatatatensis.* Species diversity decreased distinctly from the I Zone to the II Zone. The optically radially walled taxa found in the LT3 zone (the "blue zone") indicate the colder water masses developed in the Sea of Japan. Its water mass developed particularly in the deeper part of sedimentary basins.

Cassidulinid assemblages in the cassidulinid III Zone are distinctly differentiated from those of the lower two zones (Figure 10). The assemblages are dominated by diversified islandiellid and planocassidulinid species in the northern part of Japan, such as the Atsuta, the Funakawa and the Shitazaki Formations. The cassidulinid assemblage in southern Japan is dominated by the species of optically granular walls. Thus most distinct geographic differentiation of cassidulinid assemblages occurred in this zone, despite that the paleodepth range of each of the sedimentary basins is nearly the same. *Cassidulina reniforme* is noted as a colder water element and commonly associated with islandiellid species in the modern Sea of Japan. *Cassidulina reniforme* occurs also in the Oyashio Current area off Northeast Honshu and Hokkaido. This species developed in this zone and represents the granular walled taxa adapted to colder water masses, in association with *Globocassidulina exigua.* The occurrence of *C. reniforme* in the III Zone from the Boso Peninsula indicates that colder water intruded into this area during the late Miocene. In general, such a pattern is similar to the modern geographic distribution of cassidulinid foraminifera.

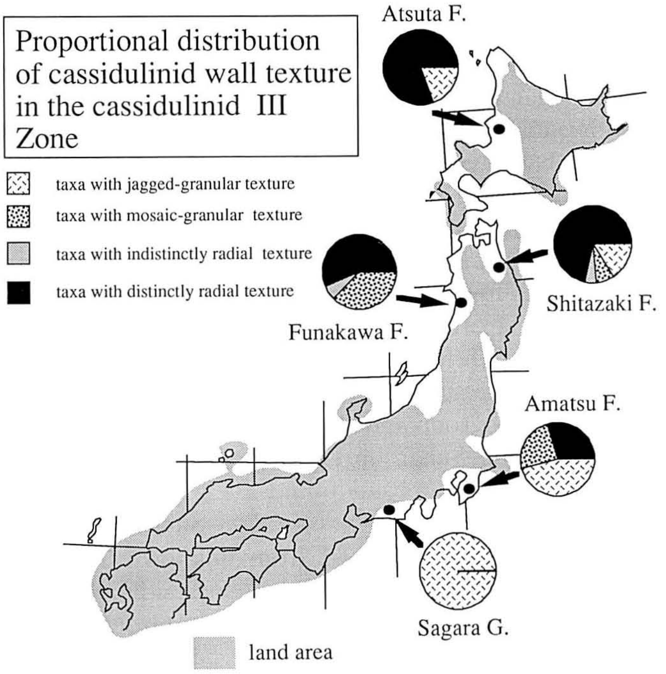


Figure 10. Geographic distribution of three wall types of cassidulinids in the cassidulinid III Zone. Each wall type is calculated from proportional ratios of individuals forming assemblages within lithologic units. Note that cassidulinids (*Islandiella* and *Planocassidulina*) with radial walls are common in northern Japan, while those of granular walls are common in southern Japan. Hatched pattern indicates supposed land areas, which is referred to early Pliocene paleogeographic map (After Chinzei, 1986; Maiya, 1988; GSJ, 1991).

Evolutionary Trend of Miocene Cassidulinids

Evolution of smaller foraminifera has been recognized mainly in the variation of chamber arrangement and test size (e.g., Galloway, 1933; Cushman, 1948a; Glaessner, 1963; Scott, 1974; Haynes, 1981). Among others, Hofker (1951a, b) used the toothplate to reconstruct the suprageneric phylogeny, although he did not reveal the ontogenetic variation of the toothplate of a particular taxon. The ontogenetic information of apertural structure is still limited in phylogenetic reconstruction. The apertures with or without the toothplate show a wide variation in Pleistocene to Recent cassidulinid foraminiferal species, and they vary also through the ontogeny (Nomura, 1983a, b; Figure 5). Besides the apertural structure, synthesized systematic criteria such as wall structure and ontogenetic changes of chamber arrangement have permitted the recognition of 12 phylogenetic groups in the upper Pliocene to Recent Cassidulinidae (Nomura, 1983b).

The *Islandiella* Group has been recognized as consisting of both globular and lenticular forms (Nomura, 1983b). However, both forms may form a different phylogeny. Lenticular forms have longer stratigraphic ranges from the early Miocene (maybe from the Oligocene) on, while the first occurrence of globular type is found in the late Miocene. In addition, occurrences of morphologically similar forms such as *Globocassidulina lenticularis* to *Planocassidulina yabei* and *G. pseudojaponica* to *Islandiella japonica* respectively, suggest that each of these forms has a more intimate phylogenetic relationship. Similar apertural structure (I-type) between globocassidulinid and islandiellid / planocassidulinid would indicate that there is no significant difference in habitat, despite a different wall structure. Evolution from optically granular to radial texture in the crystalline structure is possible for these taxa having similar apertural structure. Thus, morphologically two different forms of lenticular and globular test are herein defined as forming a subgroup; that is the *Islandiella* Subgroup and the *Planocassidulina* Subgroup. The *Islandiella* Subgroup is monophyletic and evolved from Miocene globocassidulinids (e.g., *G. hatatatensis* Group), though the *Planocassidulina* Subgroup consists of two phylogenies derived from unknown Paleogene globocassidulinids and Miocene globocassidulinids (e.g., *G. lenticularis* from *G. hatatatensis* Group). The apertural development of the *Islandiella* Subgroup shows **r→ G1→ I**, and that of the *Planocassidulina* Subgroup shows **r → G1** (e.g., *P. norcrossi*) and **r → G1 → I** (e.g., *P. yabei*) (Figure 5)

Table 1. Ontogeny of the Miocene globocassidulinid aperture. Each globocassidulinid taxon has a different apertural type through the ontogeny, indicated by arrows.

Ontogenetic development of apertural type	*Globocassidulina*
r -> G1	*hokkaidoensis, notoensis*
r -> G1 -> G2	*arata, paratortuosa, globosa, canaliornata, oblongiformis, oblongiformis nana*
r -> G1 -> I	*hatatatensis, lenticularis, pseudojaponica,*
r -> G1 -> G3'	*complanata, imamurai, kakegawaensis,*
r -> G1 -> G2 -> G3	*exigua, tsuchidai*

r: rounded aperture of proloculus, **G1**: oval to rounded trinagular aperture,
G2: vertical slit (I-shaped) aperture, **G3**: tripartite (L-shaped) aperture,
G3': basically L-shaped, but with low areal branch,
I: elongate oval with cristate tooth and secondary tongue.

The so called globocassidulinid group has been considered as consisting of the *G. subglobosa* Group and the *G. bisecta* Group (Nomura, 1983b). So far as an apertural development, the **G3**-type aperture (L-shaped aperture) of the *G. bisecta* Group has the **G1**- or **G2**-type aperture of the *G. subglobosa* Group in the earlier ontogenetic stages. However, three Miocene globocassidulinids such as *G. hatatatensis, G. pseudojaponica,* and *G. lenticularis* have the **I**-type aperture, which has been recognized only in the *Islandiella* Group. A discovery of the **I**-type aperture indicates that the supposed phylogeny of globocassidulinids is not as simple as previously reconstructed. This apertural type needs a reexamination of the phylogeny within globocassidulinid taxa. Ontogenetic changes of aperture indicate that the forms having the **I**-type aperture constitute the different phylogeny from the *G. bisecta* and *G. subglobosa* Groups (Figure 5; Table 1). I herewith refine the globocassidulinid phylogeny in the following three groups: the *G. subglobosa* Group, the *G. bisecta* Group, and the *G. hatatatensis* Group.

The *G. subglobosa* Group is composed of the Miocene *G. globosa, G. canaliornata, G. arata, G. paratortuosa, G. oblongiformis, G. hokkaidoensis, G. oblongiformis nana,* and they are characterized by having the ontogenetic development of **r → G1** or **r → G1 → G2** (Table 1). This group should be derived from the forms having the **G2**-type aperture in Paleogene forms. I have found that *G. globosa* having the **G2**-type aperture occurred in the earliest Eocene in the Indian Ocean (Nomura, 1991) and many reported occurrences of *G. globosa* (as *G. subglobosa*) suggest the first occurrence in the latest Paleocene (e.g., Boltovskoy and Boltovskoy, 1989). Thus the **G2**-type aperture of *Globocassidulina* may represent one of the primitive forms of the Cassidulinidae.

The *G. bisecta* Group includes the following Miocene and early Pliocene forms: *G. notoensis, G. imamurai, G. kakegawaensis, G. obtusa,* and *G. tsuchidai,* all of which are characterized by the ontogenetic development from oval aperture (including rounded triangular) to tripartite one. They are assigned to one of three ontogenetic types as **r→ G1, r → G1 → G3'**, and **r → G1 → G2 → G3** (Table 1). One of these types might have linked to the typical forms such as Pleistocene *G. bisecta* (Nomura, 1983a) by the development of both areal and basal branches of the aperture. This phylogeny will be discussed in more detail in the next section.

The *G. hatatatensis* Group is characterized by having an aperture with a protruded cristate tooth and secondary tongue (**I**-type aperture). The ontogenetic variation of the aperture is **r → G1 → I** and **r → G1 → G2 → G3** (Table 1). Further development of the cristate tooth produces the apertural plate, which is a diagnostic of the genus *Cassidulina.* This feature can be traced to *G.*

exigua and its ancestoral species *G. hatatatensis.* This phylogeny will be discussed in more detail in the next section. The ancestor of *G. pseudojaponica* and *G. lenticularis* has a stem in this group, and then they may have evolved into the *Islandiella* and some of the *Planocassidulina* Subgroups, by changing the wall structure from optically granular to radial textures.

The *Cassidulina* Group, represented by *C. reniforme,* should have evolved from the *Globocassidulina* Group by increasing the size of the cristate tooth, as will be discussed in the next section. The ontogenetic variation of the aperture is **r** → **G1** → **G2** → **C.** I propose that *G. exigua* may be an ancestor of this Group, which evolution is attained by heterochrony occurred in the late Miocene.

No distinct changes of the apertural structure were found in the *Cassidulinoides* Group, which might have evolved from coiled globular forms. Both uncoiled forms such as *C. akitaensis* and *C. porrectus* occurred first from the late Miocene, which level is characterized by the first appearance of globular type islandiellids.

The Miocene *Paracassidulina,* the *Evolvocassidulina* and the *Rutherfordoides* Groups show the same morphology as those of Pliocene to Recent forms. Their ancestors have already appeared in the Paleogene.

The first appearance of the *Takayanagia* Group, represented by *T. cushmani* (separated from *T. delicata* in this paper) is confirmed in the cassidulinid III Zone of the late Miocene. As previously pointed out, this group might have derived from the *Paracassidulina* Group by changing the crystalline wall structure during the late Miocene. This evolutionary hypothesis is similar to the explosive evolution of islandiellid and planocassidulinid in the cassidulinid III Zone.

The Miocene *Reissia* Group is first found in the cassidulinid II Zone. Previously this genus has been only represented by Recent *R. hystrix* (Loeblich and Tappan, 1964a, 1987). However, an ancestral form goes back to the middle middle Miocene. No changes of the apertural structure were observed in this group. Functional significance of the aperture may be a conservative character for the *Reissia* and for the *Ehrenbergina* Groups with the **B** -type aperture.

Heterochronic Evolution of *Globocassidulina hatatatensis, G. exigua* and *Cassidulina reniforme* Phylogeny, and *Globocassidulina notoensis, G. imamurai, G. kakegawaensis* and *G. obtusa* Phylogeny

A clear evidence of aforementioned evolutionary trends is shown in some species of Miocene cassidulinids from the viewpoint of aperture, indicating a heterochronic evolution. Based on the ontogenetic observation, globocassidulinid apertures change from a simple rounded opening to a slit or tripartite opening with or without developed toothplate, which suggests the validity of recapitulation (in a limited sense of morphologically graded changes) for some species (Nomura, 1983b).

The heterochrony is interpreted as the morphological changes through time in the appearance or rate of development of ancestral characters (Gould, 1977; Alberch et al., 1979; McNamara, 1982, 1986). The morphological changes through time can be recognized in a number of ontogenetic variations, such as different rates of morphological development, different ages for the onset of growth (in the sense of maturity), and different timing of sexual maturation. Thus, they are best summarized in two opposite ontogenetic and phylogenetic relationships: paedomorphosis and peramorphosis, respectively. The former is defined as "retention of ancestral juvenile characters in the descendant adult phase" and the latter is defined as "the occurrence of the ancestral adult morphology in a descendant juvenile stage of development" (McNamara, 1986). Although no information on the onset age of sexual maturity with respect to the test size of foraminifera is available, mature stages may be discriminated from immature stages by shape change of the aperture through the ontogeny (Figures 11 and 12). The morphologic changes of the mature globocassidulinid and cassidulinid showing I-shape, L-shape and apertural plate can be traced through the ontogeny and phylogeny in the following two processes.

The *Globocassidulina hatatatensis, G. exigua* and *Cassidulina reniforme* phylogeny is represented by an orthogenetic trend from cristate tooth to apertural plate (Figure 11). The aperture of *G. hatatatensis* from the cassidulinid I Zone is an oblique slit opening with a small rudimentary cristate tooth on the posterior side in the immature stages. The cristate tooth grows without

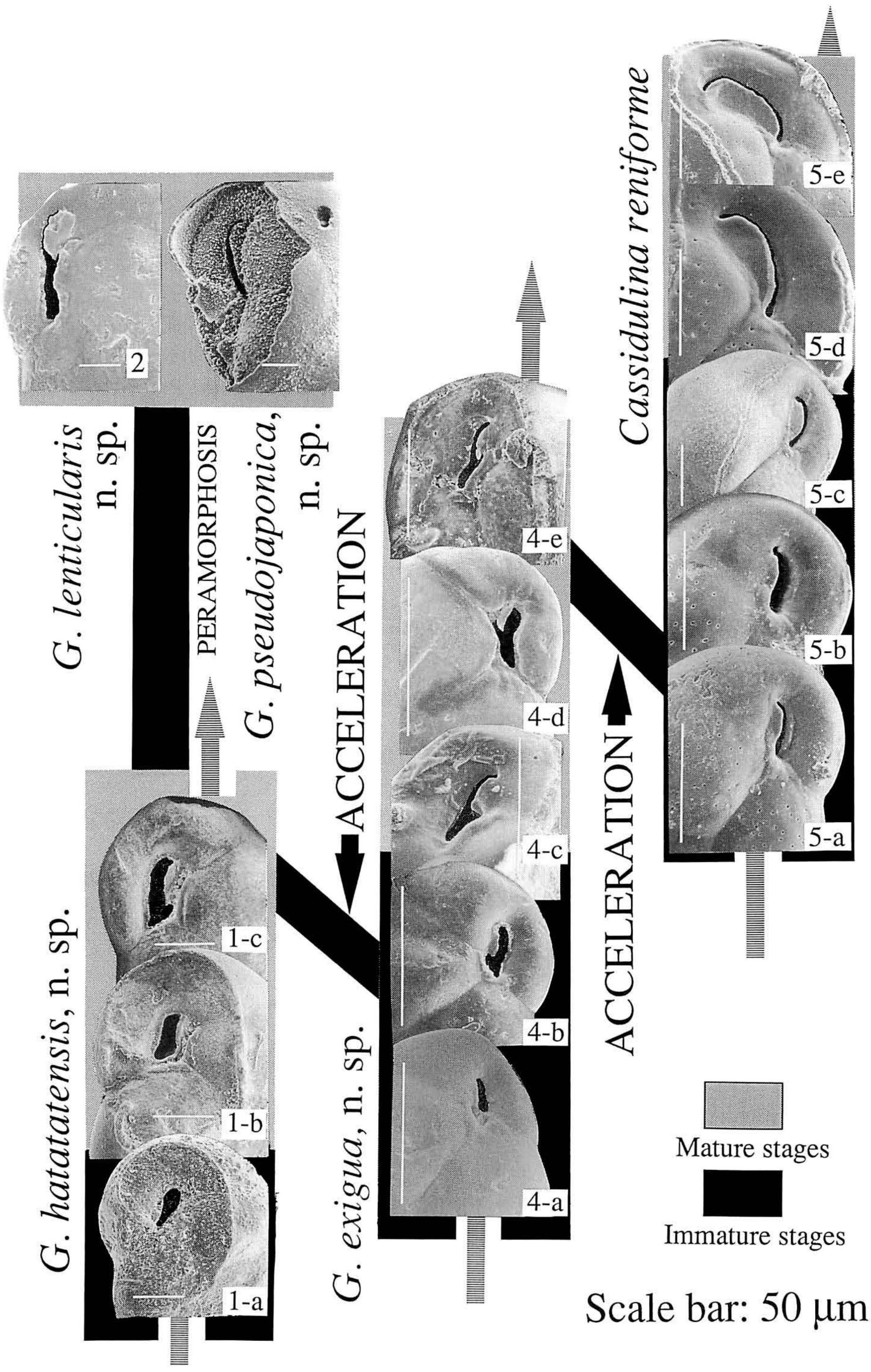


Figure 11. Morphological changes of the aperture through ontogeny. Arrow in each figure indicating the increasing test size. Solid area indicating immature stages and half-tone area indicating mature stages.

1a-c: *Globocassidulina hatatatensis,* 1-a, 60µm, 1-b, 1-c, 50µm. **2:** *G. lenticularis,* 75µm. **3:** *G. pseudojaponica,* 86µm. 4a-e: G. exigua, 4-a, 23µm, 4-b, 30µm, 4-c, 20µm, 4-d, 27µm, 4-e, 30µm. **5a-e:** *Cassidulina reniforme,* 5-a, 5-b, 27µm, 5-c, 50µm, 5-d, 30µm, 5-e, 43µm.

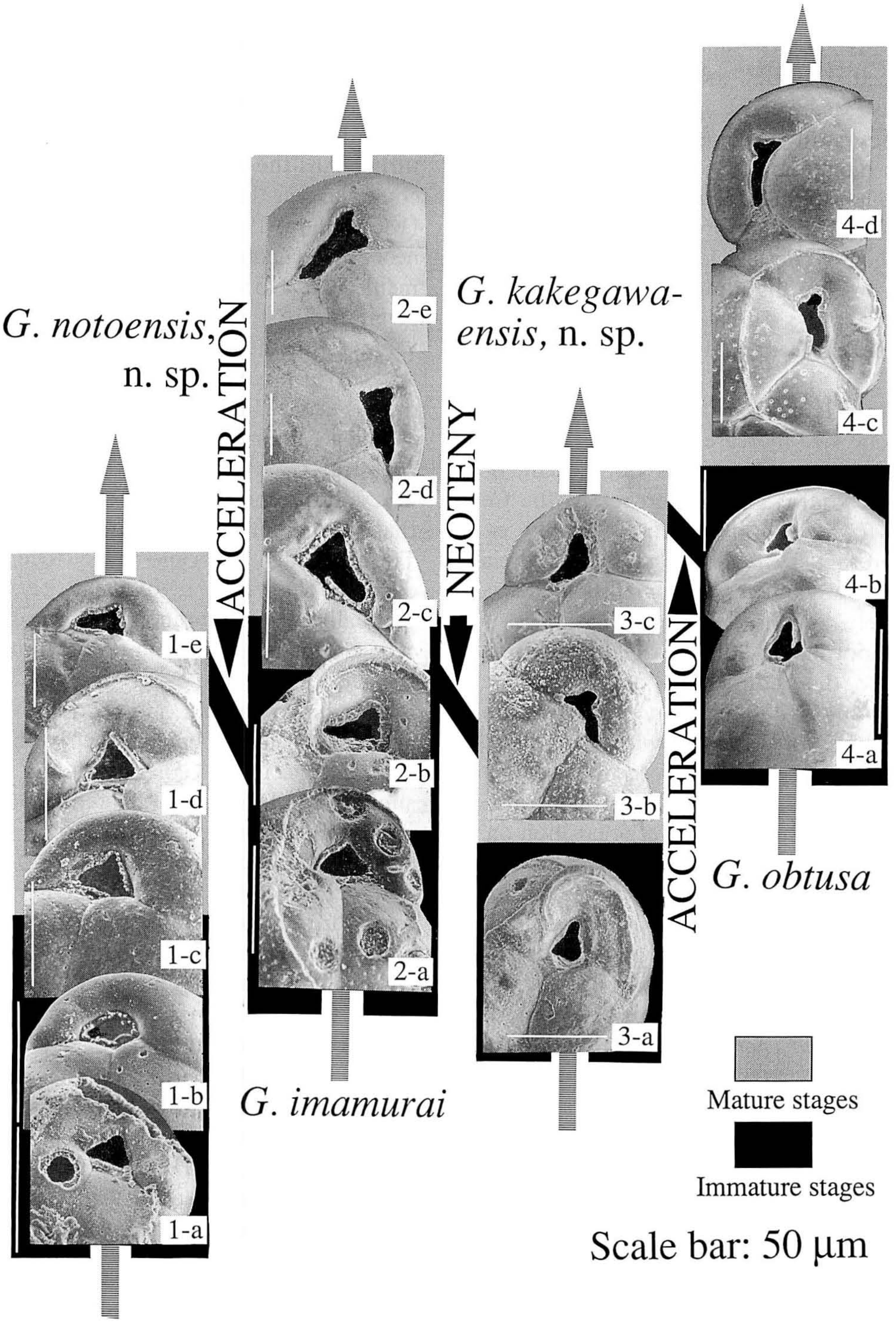


Figure 12. Morphological changes of the aperture through ontogeny. Arrow in each figure indicating the increasing test size. Solid area indicating immature stages and half-tone area indicating mature stages.
1a-e: *Globocassidulina notoensis,* 1-a, 1-b, 25µm, 1-c, 30µm, 1-d, 27µm, 1-e, 43µm. **2a-e:** *G. imamurai,* 2-a, 30µm, 2-b, 38µm, 2-c, 27 m, 2-d, 2-e, 50µm. **3a-c:** *G. kakegawaensis,* 3-a, 3-b, 3-c, 30µm. **4a-d:** *G. obtusa,* 4-a, 38µm, 4-b, 30µm, 4-c, 38µm, 4-d, 43µm.

conspicuous morphological changes in the mature stage (Figure 11, nos. 1a-c). *Globocassidulina exigua* in the lower cassidulinid III Zone is small in test size, but it has a more developed cristate tooth than that of *G. hatatatensis* for its test size. The apertural morphology of *G. exigua* in the immature stage is very similar to that of *G. hatatatensis* in the mature stage in having a less developed cristate tooth (Figure 11, nos. 4a-e). This evolutionary process should be interpreted as an acceleration in the peramorphosis. The acceleration may result in a larger size of the descendant adult than that of the ascendant, which is due to the increased rate of development and the accelerated onset of maturity. However, dwarfing occurred in test size from *G. hatatatensis* to *G. exigua*. This feature is contrary to the traditionally assumed phylogenetic size increase driven by the adaptive advantages of larger size (known as Cope's Rule). On this phylogenetic causality, with reference to the Cenozoic planktonic foraminiferal evidence, Arnold et al. (1995) mentioned that size change is not causally related to the phylogenetic advantages, but small bodied species are more adaptively responsive to biotic crises.

The apertural morphology of *G. exigua* in the mature stage is similar to the rudimentary apertural plate of *Cassidulina reniforme*. No significant difference can be seen in the apertures of *C. reniforme* from those of *Globocassidulina*. The apertural plate developed from a cristate tooth by changing its basal position from the posterior part of the apertural wall to the position on the previous chamber walls (Nomura, 1983a). This feature is observable in the ontogeny of *C. reniforme* (Figure 11, nos. 5a-e). The peramorphosis between *G. exigua* and *C. reniforme* is considered as an example of the acceleration process. The mature test of *C. reniforme* becomes large, compared with that of *C. exigua* in this process.

The *Globocassidulina notoensis*, *G. imamurai*, *G. kakegawaensis* and *G. obtusa* phylogeny is represented by the orthogenetic trend of an aperture characterized by a large triangular opening (**G1**-type aperture) to an L-shaped one (Figure 12). The aperture of the immature form of *G. notoensis* changed from a rounded opening to a triangular opening without the protruded cristate tooth through the ontogeny (Figure 12, nos. 1a-e). The mature form of *G. imamurai* from the cassidulinid Ib Subzone further develops the basal part of its triangular opening, but the aperture in the immature stages resembles that of mature *G. notoensis* (Figure 12, nos. 2a-e). This peramorphic process is regarded as the acceleration.

The large triangular shaped opening which appeared in the mature stages of *G. imamurai* is observable in the earlier aperture of mature *G. kakegawaensis* from the cassidulinid III Zone (Figure 12, nos. 3a-c). In fully mature stages of *G. kakegawaensis*, the aperture is characterized by an almost equal length of basal and areal opening, but its basal opening is not so large in comparison with the mature aperture of *G. imamurai*. The rate of apertural development is clearly reduced in *G. kakegawaensis*. This evolutionary process is regarded as a neoteny represented by the paedomorphosis. The neotenic process stresses the earlier onset of sexual maturity, thus the descendant in the mature stage may become larger than the ancestor in its mature stage (McNamara, 1986). However, such a size change is not necessarily a common feature for foraminifera as already mentioned. No definite conclusion for the dwarfing is given in this study, despite several reports indicating advantages for the delayed maturation and growth to large test size of larger foraminifera in nutrient-deficient conditions (e.g., Hallock, 1985).

The peramorphic process can also be detected between ancestral *G. kakegawaensis* and descendant *G. obtusa*. The aperture of a mature *G. kakegawaensis* is similar to that of an immature *G. obtusa* (Figure 12, nos. 4a-d). The descendant Pliocene to Pleistocene *G. obtusa* further develops the basal slit of tripartite opening and has a vertically set areal branch of the opening in the mature stages. This type of peramorphic process is regarded as the acceleration.

The heterochrony, mostly represented by the peramorphosis, is recognized clearly in these Miocene to Pliocene species of *Globocassidulina* and *Cassidulina*. It should be intimately related to the global paleoceanographic changes occurred during the middle Miocene to Pliocene. McNamara (1997) mentioned that the heterochronic changes mean the modulation of life history ("life history strategy") for various environmental conditions. He discussed the heterochrony in relation to the *r-K* continuum (Pianka, 1970). Caron and Homewood (1983) proposed the evolutionary strategy of planktonic foraminifera by means of the *r*- or *K*-selections. In the period of the colder, unstable and highly convective oceans (oligotaxic oceanic conditions), foraminiferal fauna favors *r*-selected species with rapid growth, a high reproduction potential and high tolerance. In contrast, *K*-selected species with a higher potential to exploit resources favor the warmer, stable and sluggish oceans (polytaxic oceanic conditions). Thus the heterochrony in terms of the *r-K* continuum theoretically indicates the dominance of paedomorphic species (i.e., progenesis) in the *r*-selected faunas and the dominance of peramorphic ones (i.e., hypermorphosis) in the *K*-selected faunas. The cassidulinid I Zone in the early middle Miocene was a time characterized by a warmer ocean with a higher sea level (polytaxic conditions). The accelerated species relation (from *G. notoensis* to *G. imamurai*) is found in this zone and supports the *r-K* continuum theory. However, the accelerated species relations (from *G. exigua* to *C. reniforme*, *G. kakegawaensis* and *G. obtusa*) are also found in the cassidulinid III Zone (oligotaxic conditions). The same ontogenetic strategy works in the different environmental conditions, which suggests the limits of a simplified model of the cassidulinid heterochronic trends with respect to environmental changes.

Miocene Cassidulinid and Paleoceanography: Strategy for the Evolution

Explosive Evolution Related to an Increased Input of Marine Organic Matter

Micro- and macro-paleontological evidence suggests that the early middle Miocene sequence of Japan is characterized by warm water faunas. Tropical to subtropical shallow sea faunas developed on the pre-Tertiary basements or early Miocene non-marine sediments. Planktonic foraminiferal species of this interval indicate N8/N9 zones (~17–15 Ma), which have been noted as the warm climatic optimum. Tropical to subtropical planktonic foraminifera appeared in both the Sea of Japan and Pacific borderlands at this time (Oda, 1977; Maiya, 1978), and similar benthic faunas developed on both sides of the Japanese Islands. Subsequently, Miocene basins became deep and the shallow sea fauna changed to deeper one in association with bathyal benthic foraminifera. Late Miocene sequences are characterized by diatomaceous sediments in association with cold and deep water faunas. Particularly in Northeast Honshu and Hokkaido, an upwelling commonly occurred, which is related to the formation of these siliceous and organic-rich sediments in the Sea of Japan borderland. Thus the Japanese Miocene sequences are represented by environmental changes ranging from warm to cold and from shallow to deep water. Planktonic and benthic faunas changed in response to these environmental changes. Chinzei (1986) reconstructed such changes in three different paleobiogeographic maps with an indication of cold and warm water currents.

Appearance and disappearance of many cassidulinid species also occurred in response to these regional and global environmental changes. Particularly, the explosive evolution of the islandiellid/planocassidulinid species corresponds to the significant changes from the middle to late Miocene. These changes should be represented by potential changes of primary productivity. I suppose that islandiellids and planocassidulinids developed by adapting their habitat preferences to areas high in organic matter.

In order to examine the relationship between the islandiellid/planocassidulinid species and the organic matter content of the modern sediments, I have studied individual numbers of well preserved *Islandiella japonica* and *Planocassidulina helenae* from a volume of sediment off Shimane and Tottori Prefectures, Southwest Honshu,

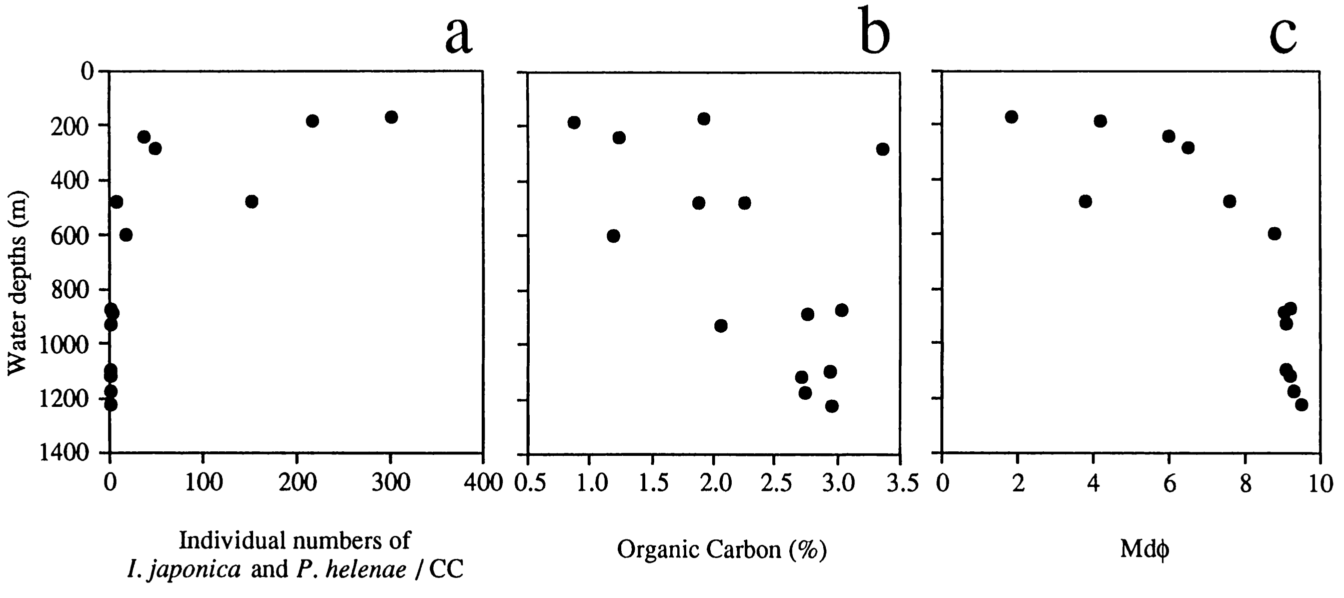


Figure 13. Three figures indicating the relationship between water depth and the individual numbers of *I. japonica* and *P. helenae* per sediment volume (a), organic carbon contents (%) of the modern sediment (b), and grain size (MdΦ) of the modern sediment (c), respectively. The negative relation between organic carbon content and abundance of the two species is an apparent feature due to easier decomposition of organic matter in coarser grained sediments in shallower depths. Samples were from off San'in (off Tottori and Shimane Prefectures).

where these species are very common (Figure 13a). Particularly, they occur dominantly in fine-grained sediments at about 200 to 500 m depths. Their upper depth limits are situated at about 135 m depth off the San'in area (Nomura and Ikehara, 1987) and their occurrences gradually decrease in abundance through about 400 m to deeper depths characterized by muddy sediments. Organic carbon content in the sediments increases generally to deeper depths, though the content shows wide variation on the shelf and upper slope of 130-500 m. Apparently this feature shows the reverse relationship between the islandiellids/planocassidulinids abundance and the organic carbon content, and is against my supposition. However, this reverse relationship may have resulted from the preservation potential of organic matter. Preservation of organic matter is controlled by several factors such as deep water oxygen content, substrate condition, and the flux of particulate organic matter to the sediments as a result of primary productivity. Poorly preserved islandiellid and planocassidulinid specimens are found in sandy-mud to silty-mud sediments, some of which may be dissolved by carbonic acid (bicarbonate ion) with a progressive decomposition of organic matter. It should be noted that the organic matter content varies on the shelf to upper slope but the variations are small on the lower slope, off Southwest Honshu (Figure 13b). They are clearly related to grain size of sediments as previously suggested (Emery and Uchupi, 1972; Kamada and Kondo, 1981). The increasing trend of organic carbon content correlates with the increasing trend of median phi of the sediments (Figure 13b, c), which is also related to the increase of clay content in the sediments at deeper depths (Ikehara et al., 1990). Thus, the lower organic carbon content at shallower depths is due to the lower amounts of clay minerals (meaning poor absorption effect) and the oxidation of organic matter in the sediments, in comparison with that at the deeper depths.

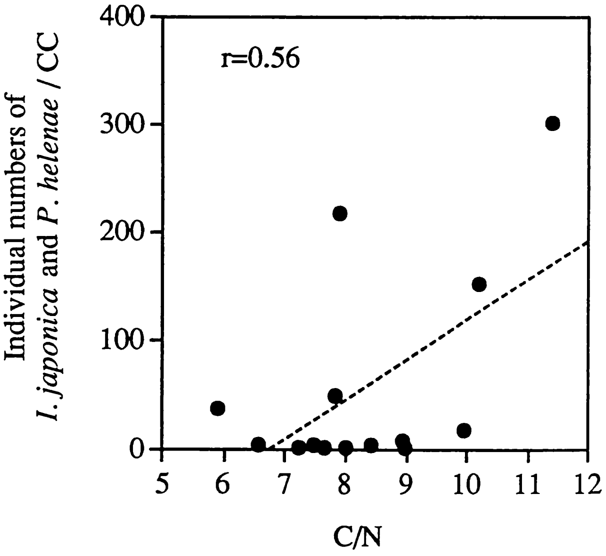


Figure 14. Relationship between the individual numbers for *I. japonica* and *P. helenae* per sediment volume and carbon to nitrogen ratios (C/N ratios), indicating that islandiellid and planocassidulinid abundance is constant for the distribution of C/N ratios. C/N ratios of 6–9 indicate the organic matter of marine phytoplankton (see text).

On the other hand, no distinct variation was found in the C/N ratios deeper than 150 m, indicating the values of about 6–10 (Figure 14). It shows rather that the islandiellids/planocassidulinids abundance indicates a positive correlation to C/N ratios (r=0.56; significant at a 5% level of significance). Although some samples which may have been introduced from the land area have higher C/N ratios at shallower depths (50–150m), islandiellid/planocassidulinid occurrence is basically related to marine organic matter. In general, C/N values of marine plankton with higher amount of protein are 6–9, while those of land plants with higher amount of carbon are >9 (Terashima et al., 1995). The lower C/N ratios from the outer shelf and slope thus suggest the organic matter was introduced by primary productions in the surface water. Abundant diatom and radiolarian remains are usually observed in the samples containing islandiellid/planocassidulinid specimens. This evidence strongly supports that islandiellid/planocassidulinid species are intimately related to the coastal upwelling with the supply of increased organic matter to the sediment surface.

Miocene Paleoceanography as a Cause of Cassidulinid Evolution

Productivity and temperature changes through the Miocene can be examined from the viewpoint of oxygen and carbon isotopes (Figure 15). Oxygen isotopic studies of Miocene sequence show lower $\delta^{18}O$ values during 17–14.5 Ma and a general increase of the values with several positive shifts from the middle middle to late Miocene. The reverse distribution pattern can be seen in the carbon isotopes, which ratios are high during 17–14 Ma and gradually decrease from the middle middle to the late Miocene. The critical changes of $\delta^{13}C$ values have been noted at about 16 Ma and 6 Ma, which are called the Chron-16 carbon shift represented by a positive shift and the Chron-6 carbon shift represented by a negative shift (Vincent and Berger, 1985). The $\delta^{18}O$ distribution indicates that global temperature decrease of marine water occurred at about 15–14 Ma, which continued throughout the middle to late Miocene. This timing is correlated with the expansion of the Antarctic ice sheets (e.g., Kennett, 1977; Kennett and Baker, 1990; Flower and Kennett, 1994). Before the Antarctic glaciation, marine temperature was warm and the sea levels were high, as noted by the warm climatic optimum (17–14.5 Ma). This warm climatic optimum is mostly correlated

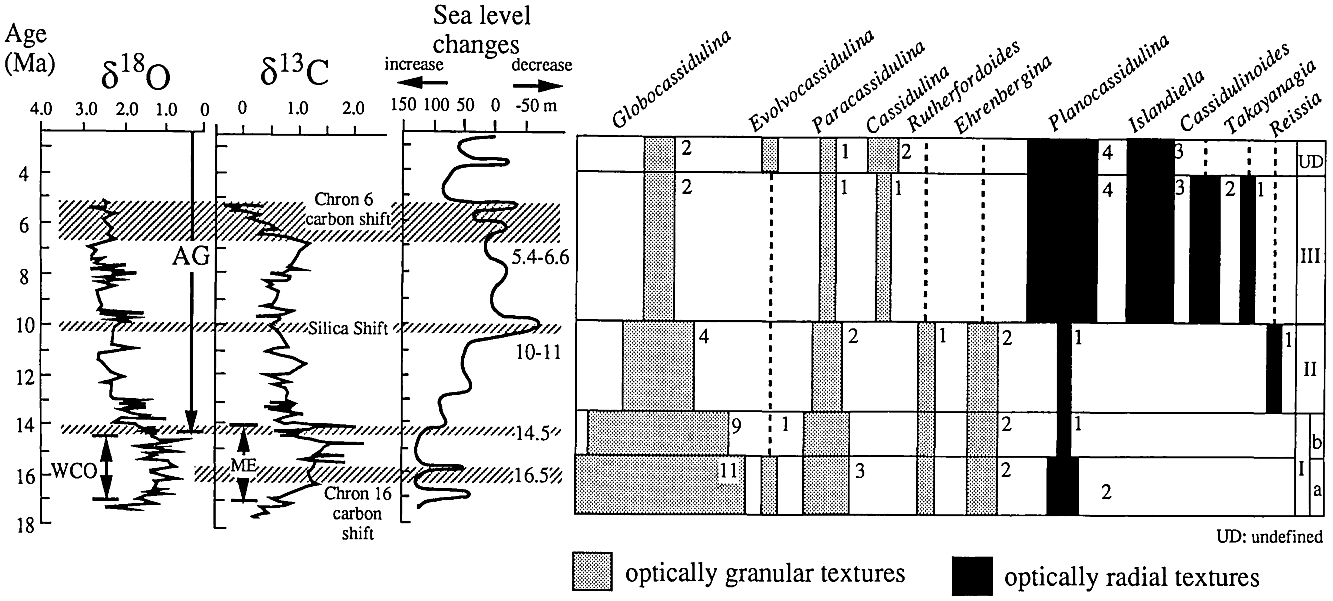


Figure 15. Stratigraphic distribution of species number of each genus (right side) and oxygen and carbon isotopic changes (DSDP Site 286; Woodruff and Savin, 1989) and sea level changes (Haq et al., 1988). Numerical ages (Ma) on the sea level curve are paleoceanographic events introduced from the oxygen and carbon isotopic critical changes (Loutite et al., 1984). Note the significant change of cassidulinid evolution occurred from the Zone II to the Zone III, which is nearly correlated with the silica shift and further paleoceanographic temperature decrease with the development of the Antarctic glaciation and the decrease of δ^{13} C values. Marine productivity and an input of organic matter to the ocean increased in the North Pacific after the silica shift. Decrease of sea level change is also critical during the Miocene. The cassidulinid I zone, characterized by abundant globocassidulinids, is mostly correlated with the warm climatic optimum and the interval of higher sea levels. The cassidulinid I zone is also correlated with the interval of higher δ^{13} C values, noted by the Chron-16 carbon shift in association with an increased input of organic matter into marginal seas (e.g., the Monterey Carbon Excursion; Vincent and Berger, 1985). The cassidulinid evolution corresponds to these oceanographic events, as indicated by a reciprocal distribution of radially walled taxa and granular walled taxa in the Miocene. AG: Antarctic glaciation. WCO: Warm climatic optimum. ME: Monterey carbon excursion.

with the carbon isotopic positive shift (Chron-16 Carbon shift) occurred in the early middle Miocene, which climax (the most increased $\delta^{13}C$) is about 1-2 m.y. before the cooling event. During the high $\delta^{13}C$ interval, the extraordinary deposits of organic matter content, as recognized in the Monterey Formation (Ingle, 1981) and as represented by the Monterey Carbon Excursion (Vincent and Berger, 1985; Flower and Kennett, 1993) were developed in continental margin, which caused the fractionation of light carbon from the ocean. These organic-rich sediments were formed by strengthened thermal gradients between high and low latitudes in association with the development of the Antarctic ice sheet (Woodruff, 1985, 1992; Vincent and Berger, 1985; Woodruff and Savin, 1989). Some hypotheses propose nutrient input from land area to the ocean, with an uplift of the Himalayas and the Tibetan plateau (Richter et al., 1992; Raymo, 1994). These processes might have enhanced the oceanic fertility. After this shift, δ^{13}C gradually decreased in value, suggesting a continuation of the high nutrient oceanic water.

Increased organic accumulation occurred along the coast of continents and marginal seas in the North Pacific. At about 10 Ma, primary production became more distinct in the northern Pacific Ocean, by shifting the increased primary production from the Atlantic to the Pacific (Keller and Barron, 1983; Woodruff and Savin, 1989). Deep-sea foraminiferal fauna changed during the early to middle Miocene in relation to changes of deep-water sources and surface water productivity (Miller et al., 1992; Nomura, 1995). This paleoceanographic event is correlated with the boundary of the cassidulinid II and III Zones. Along with this increased input of organic matter into the deep ocean, global sea level lowering (Haq et al, 1988) occurred at about 10 Ma (Figure 15), which may have further contributed to the continental organic matter to the ocean, with the distinct decrease of $\delta^{13}C$ (Loutite et al., 1984).

In addition to these global paleoceanographic events, at about 15-14 Ma, the Miocene basin was divided into several parts by different tectonic movement. The Japanese backbone ranges uplifted in Southwest Honshu (Nomura, 1992a) and Northeast Honshu (Sato et al., 1991). Many islands in the shallow seas in Southwest Honshu disappeared and the main sedimentary basins migrated to borderland areas of the Sea of Japan. The benthic fauna developed independently in the Sea of Japan and in the Pacific Ocean borderland from this time on. A distinct change in benthic foraminiferal assemblages occurred in the Sea of Japan borderland, which biostratigraphic level has been recognized as the Foraminiferal (Foram) Sharp Line (Tai, 1963, 1988; Nomura, 1992a, b). In the Sea of Japan, the calcareous faunas above this level were poorly developed, but in turn the agglutinated faunas thrived (Chiji, 1961; Matsunaga, 1963). Some sequences above the Foram Sharp Line are characterized by barren intervals. Development of the agglutinated faunas in the Pacific borderland area is not distinct as compared with that of the Sea of Japan borderland. Such a distinct faunal change occurred at 14.4 Ma (14.8 Ma according to Berggren et al., 1995) in Southwest Honshu and in the Sea of Japan (Nomura, 1992b). Thus, the cassidulinid I Zone characterized by higher diversity of globocassidulinids is limited to the strata containing high amount of organic matter before 14.4 Ma and mostly assigned to the warm climatic optimum. The Foram Sharp Line indicates the faunal change related to the development of deficient oxygen content of bottom water, which can be explained by a silled basin model (Nomura, 1992a) or inflow of poor oxygen intermediate water into the Sea of Japan area (Tada, 1994, 1995). The paleoenvironment derived from such models shows an undesirable bottom water condition for calcareous hyaline foraminifera including the cassidulinid assemblage, as indicated by poor diversity of the cassidulinid II Zone. The sedimentological information from several basins in the Sea of Japan borderland of Northeast Honshu indicates a dysaerobic or anoxic paleoenvironment. No foraminifera or very poor agglutinated faunas in association with calcareous assemblages with low oxygen tolerance were reported from the Teradomari Formation, Niigata sedimentary basin (Sato et al., 1995). Low oxygen condition was also reported from the Onnagawa Formation, Akita and Aomori sedimentary basin, based on geochemical analyses using sulfides, carbonate, phosphate, and their relations (Tada, 1991, 1995; Watanabe et al., 1995). In the ODP Sites 794 and 797, a less diversified assemblage occurred in the lithological unit IV represented by claystone or silty clay (Tamaki et al., 1990). However, the lithological unit III consisting of diatomaceous ooze sometimes contains a calcareous assemblage transported from a shallower environment (Nomura, 1992b). The distinct environmental change might have occurred from the lithological unit IV and the unit III.

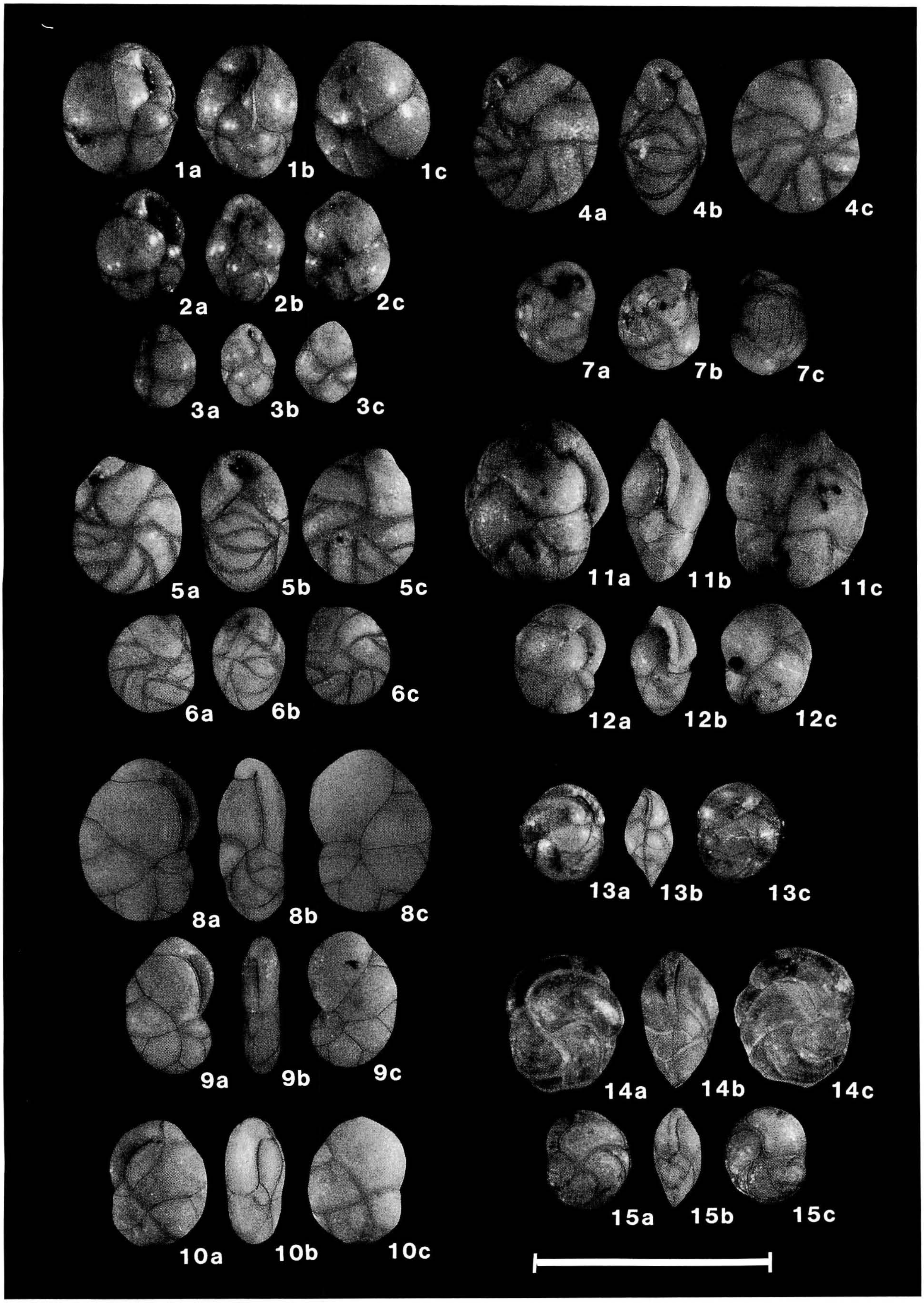
The base of the lithological unit III has been recognized at about 10.7 Ma at Site 795, in the northern Sea of Japan. The lithological interpretation of the unit III suggests the environmental changes from sluggish bottom water to the active circulation of bottom water, which might have caused the active upwelling along the Sea of Japan coast. The timing of the development of the diatomaceous sediments corresponds well to that of the silica shift (Keller and Barron, 1983; Woodruff and Savin, 1989). An increased accumulation of biogenous materials occurred locally in the Sea of Japan borderland of Northeast Honshu after 10–9 Ma and their sediments are related to the initiation of upwelling (Watanabe et al, 1995). Bottom water change from suboxic to oxic condition occurred at about 10 Ma is significant for benthic faunal evolution, particularly in the Sea of Japan borderland. The cassidulinid III Zone in the late Miocene might have developed in association with such a paleoenvironmental change from suboxic bottom water to oxic one. Thus, enhanced inputs of organic matter to the sediment surface as well as circulation of higher oxygenated bottom water could trigger the adaptive radiation of islandiellid/planocassidulinid assemblages. This feature can be ascertained by deep sea benthic foraminiferal observation, showing that the benthic assemblages (opportunistic species) exploit phytodetritus and are able to develop the population size when a sufficient food source is supplied to the deep sea (Gage and Tyler, 1991; Gooday, 1988, 1993, 1994). The islandiellids and planocassidulinids with gregarious occurrences (i.e., *r*-selected species) are found in such a high organic matter input area (upwelling area). I propose that the cassidulinid assemblages have succeeded in utilizing the organic matter (phytodetritus) for their food resources and in adapting to cold water environment.

Systematic Classification

In the systematics of the Superfamily Cassidulinacea, I follow the recent systematics of Loeblich and Tappan (1992) for the suprageneric classification. The genus *Rutherfordoides* that is classified in the Superfamily Fursenkoiniacea, Family Fursenkoinidae is included in the Superfamily Cassidulinacea. For the generic classification of the Japanese Miocene forms, the following key to genera is proposed:

1. Optically granular texture of walls (both jagged and mosaic ones).··· ································· 3

Figure 16. **1a-c, 2a-c, 3a-c.** *Globocassidulina hokkaidoensis* Nomura, n. sp., WAK-65. **4a-c, 5a-c, 6a-c.** *Globocassidulina paratortuosa* (Kuwano), TM-39. **7a-c.** *Globocassidulina arata* (Finlay), NOTO-10. **8a-c, 9a-c.** *Paracassidulina* cf. *miuraensis* (Higuchi), NANA. **10a-c.** *Paracassidulina izuensis* (Aoki), ISW-19. **11a-c, 12a-c.** *Paracassidulina quasicarinata* Nomura, TM-186. **13a-c.** *Paracassidulina neocarinata* (Thalmann), KK-15. **14a-c, 15a-c.** *Takayanagia cushmani* (Stewart and Stewart), AN-76. Scale bar=0.5 mm


1a
1b
1c
2a
2b
2c
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3b
3c
4a
4b
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15a
15b
15c

Figure 16.

2. Optically radial texture of walls (both distinctly and indistinctly ones). ································11
3. Test globular or angled periphery. ················· 4
Others. ··9,10
4. Test coiled throughout ontogeny. ················· 5
Others. ··· 6
5. Aperture with or without toothplate.
··*Globocassidulina*
Others. ··7,8
6. Test with coiled early portion and uncoiled later potion. ······························*Evolvocassidulina*
7. Aperture with apertural plate. ············*Cassidulina*
8. Aperture long narrow slit at the base of apertural face, without toothplate.···············*Paracassidulina*
9. Test triangular with loosely coiled earlier portion and uncoiled later portion.···············*Ehrenbergina*
10. Test spear shaped with slightly curved earlier portion.································*Rutherfordoides*
11. Test triangular with coiled earlier portion and uncoiled later portion. ····························*Reissia*
Others.··12
12. Crosier-shaped test with curved earlier portion and uncoiled later portion. ···········*Cassidulinoides*
Others. ··13
13. Test globular throughout ontogeny. ······*Islandiella*
Test lenticular with angled or keeled periphery.
···14, 15
14. Aperture with toothplate. ···········*Planocassidulina*
15. Aperture with long narrow slit without toothplate.
··*Takayanagia*

Class Foraminiferea J. J. Lee, 1990
Order Buliminida Fursenko, 1958
Superfamily Cassidulinacea d'Orbigny, 1839
Family Cassidulinidae d'Orbigny, 1839
Subfamily Cassidulininae d'Orbigny, 1839

Genus *Globocassidulina* Hantken, 1875

Globocassidulina Voloshinova, 1960, p. 58.

Cassilongina Voloshinova, 1960, p. 58 (type, *Cassidulina oblonga* Reuss, 1850, p. 376).

Cassidulita Sellier de Civrieux, 1969, p. 156 (type, *Cassidulina norcrossi* Cushman subsp. *australis* Phleger and Parker, 1951).

Smyrnella Saidova, 1975, p. 331 (type, *Cassidulina subglobosa* Brady var. *subcalifornica* Drooger, 1953).

Cassidulinitella Saidova, 1975, p. 329 (type, *Cassidulinitella salebrosa* Saidova, 1975).

Cassisphaerina Saidova, 1975, p. 336 (type, *Cassisphaerina globulosa* Saidova, 1975).

Bradynella Saidova, 1975, p. 344 (type, *Cassidulina subglobosa* Brady, 1881).

Sphaeroislandiella Saidova, 1975, p. 324 (type, *Sphaeroislandiella notalnella* Saidova, 1975).

Type species:- *Cassidulina globosa* Hantken, 1875, p. 64, pl. 16, figs. 2a, b.

Remarks:- Globocassidulinds are the major constituents in middle Miocene cassidulinid assemblage, and they are abundant in the cassidulinid I and II Zones. Globocassidulinds are rather less common in the cassidulinid III Zone of the late Miocene. In general, Miocene globocassidulinids are usually characterized by a small-sized test.

Globocassidulina arata (Finlay, 1939)

Figures 16-7a-c

Cassidulina arata Finlay, 1939, p. 112, pl. 14, figs. 74, 75.

Apertural structure:- The aperture is vertical slit with very short basal slit at the base of the apertural face; small curled cristate tooth and triangularly protruded small lip can be seen; copula without free primary tongue attached to the preceding anterior part of the aperture. Apertural openings in immature stages elongate oval in shape.

Hypotype:- Figure 16, nos. 7a-c, NFL9501, sample NOTO-10, Higashi-innai Formation, Ishikawa Prefecture, early middle Miocene.

Test size:- Test width 0.14-0.23 mm, test length 0.17-0.24 mm, test thickness 0.15-0.20 mm, sample NOTO-10.

Occurrence:- Nakanami Formation (NAKA), Higashi-innai Formation (NOTO-10), Hojuji Formation (NOTO-27), Sekinohana Limestone (SEKI).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in southern Honshu.

Remarks:- The holotype figure of this species has been insufficient to understand the diagnoses of this species, despite that Finlay (1939) originally noted the costae of this species, as the most diagnostic feature. I have examined the paratype specimens deposited in the U. S. National Museum (USNM 689134), which are described from the Hutchinsonian Stage (early Miocene), New Zealand, and found weak bifurcating reticulate costae on the test surface. In appearance, however, the costae of paratypes are inconspicuous and are not well developed as those of *G. decorata*. Nevertheless, the bifurcating pattern of these costae is the same as those of *G. decorata*, suggesting that this species is the ancestor of Pliocene to Recent *G. decorata*.

Finlay (1939) also described this species as having the vertical slit similar to the aperture of *Globocassidulina*

Figure 17. **1a-c, 2a-c.** *Globocassidulina pseudojaponica* Nomura, n. sp., IW-1. **3a-c.** *Globocassidulina kakegawaensis* Nomura, n. sp., KK-16. **4a-c, 5a-c.** *Globocassidulina notoensis* Nomura, n. sp., NOTO-27. **6a-c, 7a-c, 8a-c.** *Globocassidulina imamurai* (Tai), H-9A. **9a-c, 10a-c, 11a-c.** *Globocassidulina tsuchidai* Nomura, TM-35. **12a-c, 13a-c. 14a-c, 15a-c.** *Globocassidulina exigua* Nomura, n. sp., IW-12. **16a-c.** *Globocassidulina canaliornata* Nomura, n. sp., NAKA. Scale bar=0.5 mm

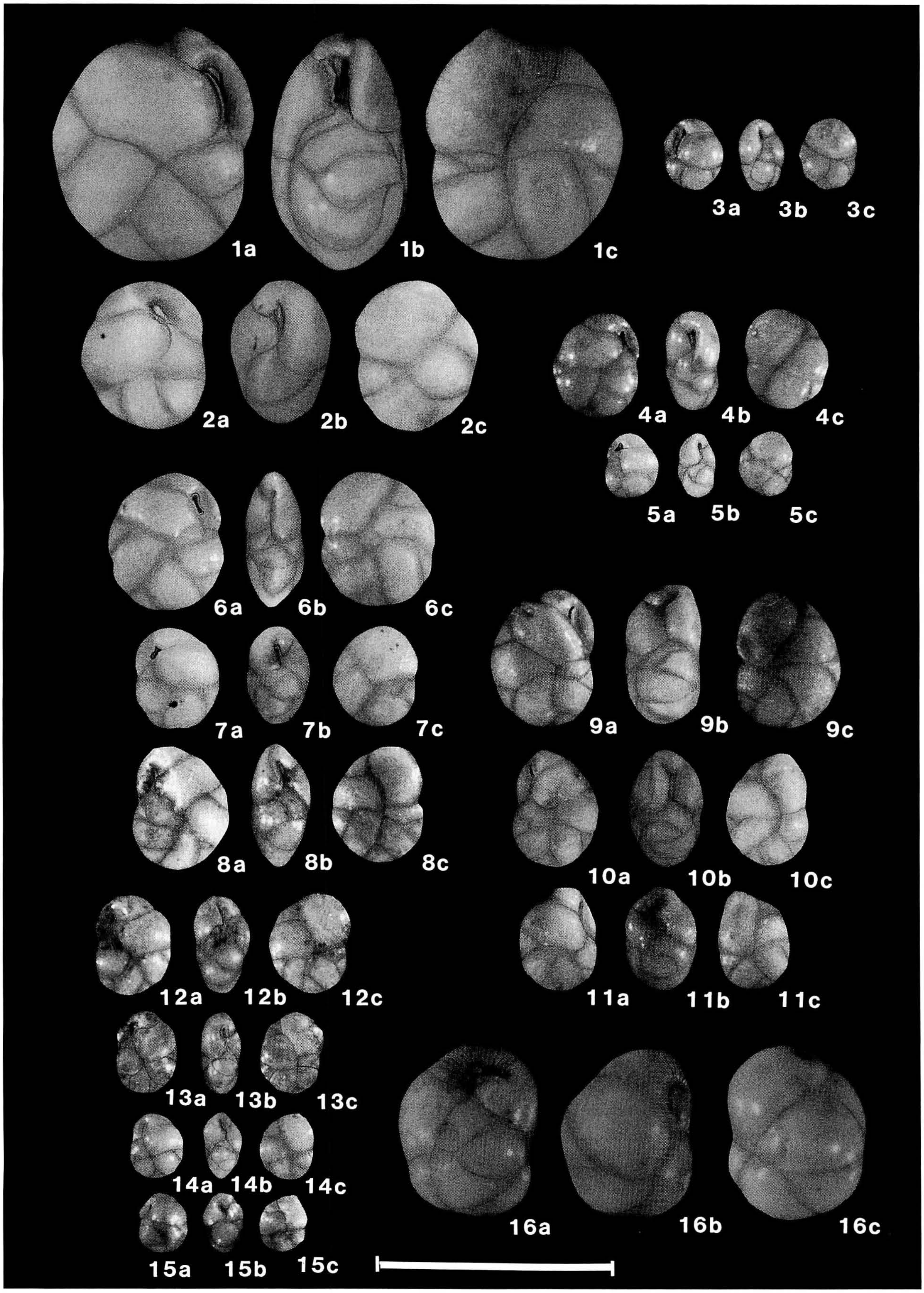
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Figure 17.

subglobosa. However, a short basal slit is observed in these paratypes, with a small cristate tooth. No structural difference of the aperture between *G. arata* and *G. decorata* is found, excepting for the difference of reticulate costae and test size. Thus, the development of the costae and the increasing of the test size are the evolutionary feature for these intimately related species.

Globocassidulina arata is first recognized in Japan and occurs from the middle Miocene of the Tomioka and Niigata areas.

Globocassidulina canaliornata
Nomura sp. nov.

Figures 17-16a-c, 21-10

Globocassidulina gemma (Todd). Nomura, 1983b, p. 22, pl. 2, figs. 10a, b, 11; Loeblich and Tappan, 1994, p. 115, pl. 223, figs. 9, 10; Hasegawa and Nomura, 1995, p. 19, figs. 5-1a-c.

Islandiella subglobosa (Brady). Poag, 1981, p. 70, pl. 17, fig. 3.

Not *Globocassidulina gemma* (Todd). Akimoto, 1990, p. 200, pl. 18, figs. 3a, b.

Diagnosis:- Large globular test with rounded-triangular last chamber positioned at an high angle to the axis of symmetry; elongate and somewhat curved aperture perpendicular to the base of apertural face, with well developed numerous apertural grooves

Holotype:- IGPS (Institute of Geology and Paleontology, Tohoku University, Sendai) 97188A, sample OK-21, Shinzato Formation, Okinawa Island, Pliocene; hypotype, Figure 17, nos. 16a-c, NFL9505, sample NAKA, Nakanami Formation, Ishikawa Prefecture, early middle Miocene.

Test size:- Test width 0.16-0.31 mm, test length 0.19-0.39 mm, test thickness 0.17-0.32 mm, sample NAKA.

Occurrence:- Nakanami Formation (NAKA).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in Noto Peninsula; Pleistocene form found in Okinawa Island.

Remarks:- In the description of *G. gemma*, Nomura (1983b) noted the distinct apertural grooves and the elongate aperture oblique to the axis of symmetry and the absence of sutural grooves (Figure 21-10). Recently, I examined both the holotype and paratypes of *Cassidulina subglobosa* var. *horizontalis* Cushman and Renz (Cushman Coll. 35879 for holotype and 45993 for paratypes) and those of *Cassidulina gemma* Todd (USNM 548668 for holotype and 369243 and 548669 for paratypes), deposited in the U. S. National Museum. *Cassidulina subglobosa* var. *horizontalis* is characterized by the large test and elongate aperture. However, no sutural grooves of this form developed and the apertural grooves are not conspicuous, with very fine striations around the aperture. *Cassidulina gemma* is also characterized by the large test with distinct sutural grooves and the vertical slit aperture at the base of apertural face. The test walls of *C. gemma* are transparent, showing many pore lining and pervious chambers inside. The apertural grooves are not distinct as may be seen in original figures, although some specimens of paratypes have distinct grooves around the aperture. These diagnostic features of both *C. subglobosa* var. *horizontalis* and *C. gemma* are different from those of Nomura's *gemma*. For these reasons, the specimens described by Nomura (1983b) and the Miocene specimens are described as the new species *Globocassidulina canaliornata*.

The specific name is from the Latin *canalis* meaning groove and ornatus meaning decoration, referring to the aperture of this species.

Globocassidulina complanata
(Ujiié and Kusukawa, 1969)

Figures 18-17a-c, 23-6

Cassidulina complanata Ujiié and Kusukawa, 1969, p. 766, pl. 1, figs. 1a-c, 2a-c.

Cassidulina (?) *jamesoni* McCulloch, 1977, p. 390, pl. 164, figs. 15a-c.

Globocassidulina jamesoni (McCulloch). Nomura, 1983b, p. 33, pl. 3, figs. 7a-c, 8a, b, pl. 19, figs. 1, 2.

Not *Cassidulina complanata* Voloshinova, 1952, p. 95, pl. 4, figs. 7a, b.

Hypotypes:- Figure 18, nos. 17a-c, NFL9502, sample NOTO-8, Higashi-innai Formation, Ishikawa Prefecture, early middle Miocene.

Test size:- Length 0.18 mm, width 0.14 mm, thickness 0.08 mm, sample NOTO-8.

Occurrence:- Hojuji Formation (NOTO-27), Higashi-innai Formation (NOTO-8), Haratajino Formation (TM-159, 205).

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone in southern Honshu; Pleistocene to Recent form found in southern Honshu and shallower Pacific Ocean.

Remarks:- This species has been described from Recent sediments from Miyako and Yamada Bays, Iwate Prefecture, Northeast Honshu. In the original description, the test morphology is given as slightly compressed lenticular. However, I confirmed that the test shape of this species is highly compressed for the genus in the holotype deposited in the National Science Museum, Tokyo, and that *Globocassidulina jamesoni* by Nomura (1983b) is a junior

Figure 18. **1a-c, 2a-c, 3a-c.** *Globocassidulina lenticularis* Nomura, n. sp., SEKI. **4a-c, 5a-c, 6a-c, 7a-c.** *Globocassidulina oblongiformis* Nomura, n. sp., NOTO-27. **8a-c, 9a-c.** *Globocassidulina oblongiformis nana* Nomura, n. subsp., AT-22. **10a-c, 11a-c, 12a-c, 13a-c.** *Globocassidulina hatatatensis* Nomura, n. sp., HTTO-7. **14a-c, 15a-c.** *Globocassidulina globosa* (Hantken), H-3A. **16a-c.** *Globocassidulina globosa* (Hantken), NANA. **17a-c.** *Globocassidulina complanata* (Ujiié and Kusukawa), NOTO-8. **18a-c, 19a-c.** **Cassidulina reniforme** Nørvang, FUNA-11. Scale bar=0.5 mm

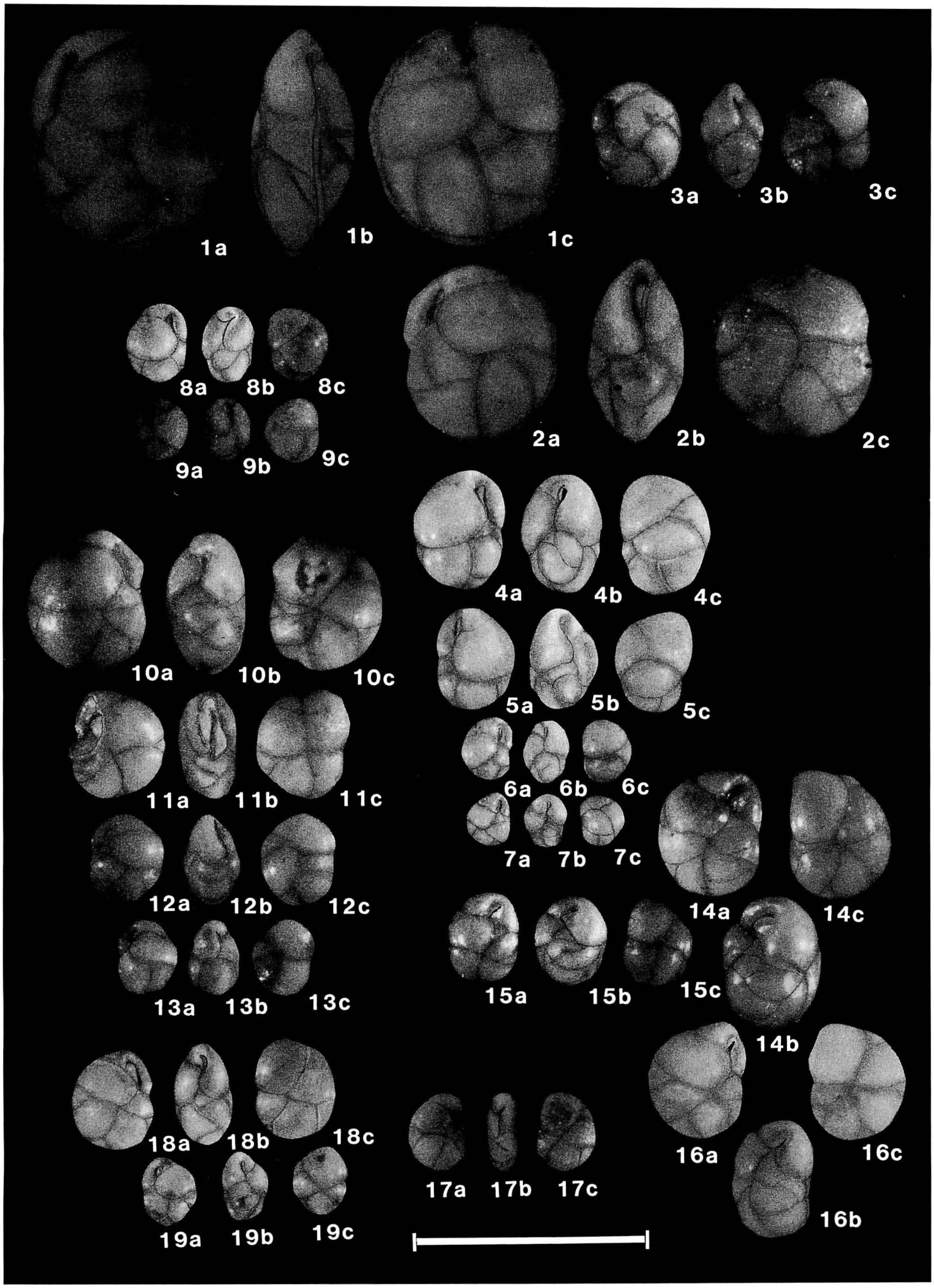
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Figure 18.

synonym to *G. complanata*. The holotype is allocated to the growth stage between No.8 and No. 9 of Nomura (1983b), showing a trend of uncoiled chamber arrangement.

I confirmed also that the aperture of this species given as "aperture elongate, extending slightly upward from the base of the apertural face, and nearly paralleling the anterior margin with narrow bordering lip" is assignable to the E4 type of Nomura (1983a).

Globocassidulina complanata is rarely found in Miocene sediments.

Globocassidulina exigua
Nomura sp. nov.

Figures 17-12a-c, -13a-c, -14a-c, -15a-c, 21-7, -8, -9

Diagnosis:- Small compressed test; aperture small slit with protruded cristate tooth.

Description:- Test very small, circular in side view and compressed oval in edge view; periphery narrowly rounded, very slightly lobulate; chambers distinct, not inflated, four pairs in last whorl; sutures distinct, slightly limbate and depressed, radial toward periphery; umbilical region closed; aperture comma-shaped, oblique to the base of final apertural face, with fragile protruded cristate tooth on the posterior side of aperture; wall smooth, polished, very finely perforate, translucent.

Optical structure:- Wall mosaic-granular texture.

Apertural structure:- Aperture is provided with the cristate tooth and lip; cristate tooth is comb-shaped, fan-shaped; lip smooth and sometimes with small knobs; secondary tongue is indistinct, but formed on the preceding chamber; copula attached to the anterior portion of the preceding aperture near the opening; primary tongue undeveloped (Figures 21-7-9).

Holotype:- Figure 17, nos. 12a-c, NFL9517, sample IW-12, late Miocene, Shitazaki Formation, Iwate Prefecture; paratypes and hypotypes, Figure 17, nos. 13a-c, 14a-c, 15a-c, NFL9518.

Test size:- Holotype maximum test length 0.20 mm, test thickness 0.13 mm, sample IW-12; paratypes maximum test length 0.12 to 0.20 mm, test thickness 0.07 to 0.13 mm, sample IW-12.

Occurrence:- Shitazaki Formation (IW-10, -12).

Stratigraphic and paleogeographic distribution:- Part of the cassidulinid III Zone in northern Honshu.

Remarks:- This new species is found only in the late Miocene Shitazaki Formation, Sannohe, Aomori Prefecture, where its occurrence is common. Because this species is small in test size, no information on this species has been reported.

Detailed apertural structure of this species is beyond the limits of binocular microscope, but SEM figures show the development of the cristate tooth, which conceals most of the opening. The position of the cristate tooth indicates the close relationship of this species to *Globocassidulina hatatatensis*, whose cristate tooth is formed near the base of the apertural opening, and to *Cassidulina reniforme*, whose apertural plate in immature stage resembles the cristate tooth.

This new species is named from the Latin *exigua*, meaning small and little, with reference to the small test.

Globocassidulina globosa (Hantken, 1875)

Figures 18-14a-c, -15a-c, -16a-c, 19, 21-11, -12

Cassidulina globosa Hantken, 1875, p. 64, pl. 16, figs. 2a, b; Cushman, 1925b, p. 56, pl. 9, figs. 25, 26; Cushman, 1927a, p. 167, pl. 26, fig. 13; Beck, 1943, p. 609, pl. 108, figs. 7, 13, 14; Cushman and Simonson, 1944, p. 202, pl. 34, fig. 7; Detling, 1946, p. 358, pl. 51, figs. 3a, b; Cushman, R. E. and K. C. Stewart, 1947, p. 103, pl. 12, fig. 14; Asano, 1952, p. 42, pl. 4, figs. 3a-c; Graham and Classen, 1955, p. 26, pl. 4, figs. 14a, b; Smith, 1956, p. 100, pl. 14, figs. 2a-c; Todd, 1957, pl. 73, fig. 15; Mallory, 1959, p. 226, pl. 33, figs. 11a, b; Todd and Low, 1960, p. 847, pl. 257, figs. 3a, b; Kleinpell and Weaver, 1963, p. 180, pl. 13, figs. 5a, b.

Globocassidulina globosa (Hantken). Fairchild et al., 1969, p. 69, pl. 22, figs. 15a, b; Kaiho, 1984, p. 71, pl. 7, figs. 1a-c; Grünig, 1985, p. 273, pl. 10, fig. 3; Nomura, 1991a, pl. 5, fig. 16; Nomura, 1991b, pl. 5, fig. 9; Kaiho, 1992a, p. 378, pl. 2, figs. 11a-c, pl. 5, fig. 17a, b; Bolli, Beckmann, and Saunders, 1994, p. 131, fig. 35, 11.

Globocassidulina subglobosa (Brady). Kleinpell, 1954, p. 56, pl. 2, figs. 12a, b; Boltovskoy and Boltovskoy, 1989, pl. 2, figs. 11, 12; Boltovskoy and Watanabe, 1994, pl. 1, fig. 19 (part); Lidz and Bralower, 1994, p. 329, pl. 11, figs. 239-241.

Not *Globocassidulina globosa* (Hantken). McDougall, 1980, p. 46, pl. 26, fig. 3.

Hypotypes:- Figure 18, nos. 14a-c, 15a-c, NFL9503, sample H-3A, Higashibessho Formation, Toyama Prefecture, early middle Miocene; Figure 18, nos. 16a-c, NFL9504, sample NANA, Nanao Limestone, Noto Peninsula, Ishikawa Prefecture, early middle Miocene.

Test size:- Test width 0.16-0.18 mm, test length 0.2-0.29 mm, test thickness 0.16-0.21 mm, sample NANA; test width 0.17-0.24 mm, test length 0.21-0.29 mm, test thickness 0.17-0.23 mm, sample H-3A.

Occurrence:- Masuda Group (MS-10), Josoji Formation (JS-1), Bihoku Group (SHO-21, -23, FU-5, -8, SB-6), Uyashinai Formation (AK-3, -6), Anno Formation (AN-67, -74, -76), Higashibessho Formation (H-3A, -4A, -5, -6A, -7A, -9B, -10B), Honsubetsu Formation (HON-31, -32), Hatatate Formation (HTTO-7, ISW-16, -19), Tomesaki Formation (IW-1), Shitazaki Formation (IW-12), Kiyosumi Formation (KI-54), Saigo Group (KK-117, -120), Sagara Group (KK-16, -17, -18, -19, -20), Mizunami Group (MIZU), Nakanami Formation (NAKA), Nanao Limestone (NANA), Nanatani Formation (NG-2, -4, -6, -9, -12, -13, -14, -18, -19, -20, -23, -25, -27), Higashi-innai Formation (NOTO-3, -8, -10, -15, -16), Hojuji Formation (NOTO-27), Nishikurosawa Formation (OGA), Sekinohana Sandstone (SEKI), Niwaya Formation (TM-11, -186), Haratajino Formation (TM-3, -4, -9, -153, -159, -204), Idosawa Formation (TM-34, -39),

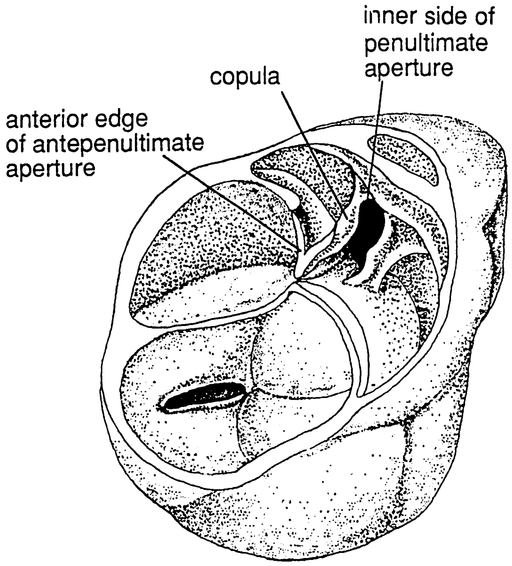

Figure 19. Internal structure of *Globocassidulina globosa*.

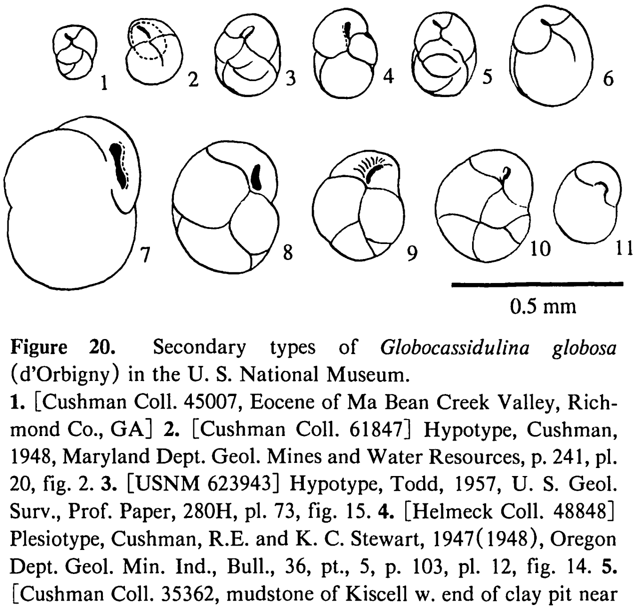

Figure 20. Secondary types of *Globocassidulina globosa* (d'Orbigny) in the U. S. National Museum.
1. [Cushman Coll. 45007, Eocene of Ma Bean Creek Valley, Richmond Co., GA] **2.** [Cushman Coll. 61847] Hypotype, Cushman, 1948, Maryland Dept. Geol. Mines and Water Resources, p. 241, pl. 20, fig. 2. **3.** [USNM 623943] Hypotype, Todd, 1957, U. S. Geol. Surv., Prof. Paper, 280H, pl. 73, fig. 15. **4.** [Helmeck Coll. 48848] Plesiotype, Cushman, R.E. and K. C. Stewart, 1947(1948), Oregon Dept. Geol. Min. Ind., Bull., 36, pt., 5, p. 103, pl. 12, fig. 14. **5.** [Cushman Coll. 35362, mudstone of Kiscell w. end of clay pit near Budapest, Hungary] **6.** [Cushman Coll. 6997, Oligocene of *Clavuline Szaboi,* Kleinzell, Hungary] **7.** [Cushman Coll. 48977] Hypotype, Cushman and Stone, 1947, Cushman Found. Foram. Res., Spec. Publ., 20, p. 23, pl. 3, fig. 8. **8.** [USNM 547718] Hypotype, Rau, 1951, Jour. Pal., vol. 25, p. 449, pl. 67, figs. 3-5. **9.** [Cushman Coll. 9557, Klein Teller Tegel b. oben Hungary] **10.** [Cushman Coll. 38609, Oligocene] Hypotype, Cushman and Simonson, 1944, Jour. Pal., vol. 18, p. 202, pl. 34, fig. 7. **11.** [Cushman Coll. 22342] Hypotype, Cushman, 1935, U. S. Geol. Surv., Prof. Paper, 181, p. 49, pl. 20, fig. 20.

Wakkauenbetsu Formation (WAK-69/71).

Stratigraphic and paleogeographic distribution:- Cassidulinid I to III Zones in the Japanese Islands; global in Paleogene to lower Tertiary sequences.

Remarks:- This species is characterized by having a small globular test. The aperture of this species is a vertical slit at the base of apertural face, which situated in the middle of apertural face. Scanning electron micrograph shows the lip and lip-like cristate tooth surround the slit of the aperture. In some specimens having a rather inflated apertural face, a very short basal slit can be seen. Inner structure of the aperture is rather simple. The proximal part of the cristate tooth connects internally to the anterior part of preceding lip, without forming a free part of the primary tongue (Figures 19, 21-11-12). The anterior part of the aperture connects to the early formed chamber. Such apertural structures keep this species compact-globular in shape.

Since Hantken described this species from the lower Oligocene of Hungary, species *globosa* has been repeatedly described from Paleogene and Neogene sediments. However, no detailed information about the holotype and paratypes has been obtained until now. Thus many confusions of this species concept have been occurred as shown in the secondary specimens (=reported specimens) deposited in the U. S. National Museum (Figure 20). As seen in these figures, there are several types of aperture. I found three slides of *globosa* from Hungary in the collection. The first slide is from the Eocene (Keinzeller Tegel, b. oben) (Cushman Coll. 9557), the second one is from the Eocene (Mudstone of Kiscell W. end of clay pit near Budapest) (Cushman Coll. 35362), the third one is from the Oligocene (*Clavulina szaboi,* Keinzell bei Ofen) (Cushman Coll. 6997). The first slide is labeled as topotype and includes two specimens, though one of the two shows inflated chambers and distinct apertural grooves out of curved slit aperture. Such features of the specimen are out of Hantken's original concept. It indicates some other species and may be conferrable to *Globocassidulina canaliornata* described in this paper. The final chamber of the other specimen is broken, and thus no details are obtained. The second and third slides contain the specimens similar to one another. They are globular test and their test diameters range from 0.2 to 0.3 mm as described in the original designation. Those characters of very compact test without the chamber inflation and the flushed sutures (though they are somewhat indistinct), are in agreement with the original description. The aperture of these specimens is consistently a vertical slit without tripartite feature. For these reason, I suppose the true species concept of *globosa* is found in these specimens contained in the second and third slides. The locality and stratigraphic level described on the label of the third slide are identical with those given by Hantken (1875).

Globocassidulina globosa has been sometimes reported as *G. subglobosa* from Paleogene deep sea sediments. Paleogene specimens are characterized by a small test. I have compared these deep sea specimens from the Indian Ocean with holotype of *subglobosa* that is deposited in the British Museum of Natural History, and concluded that

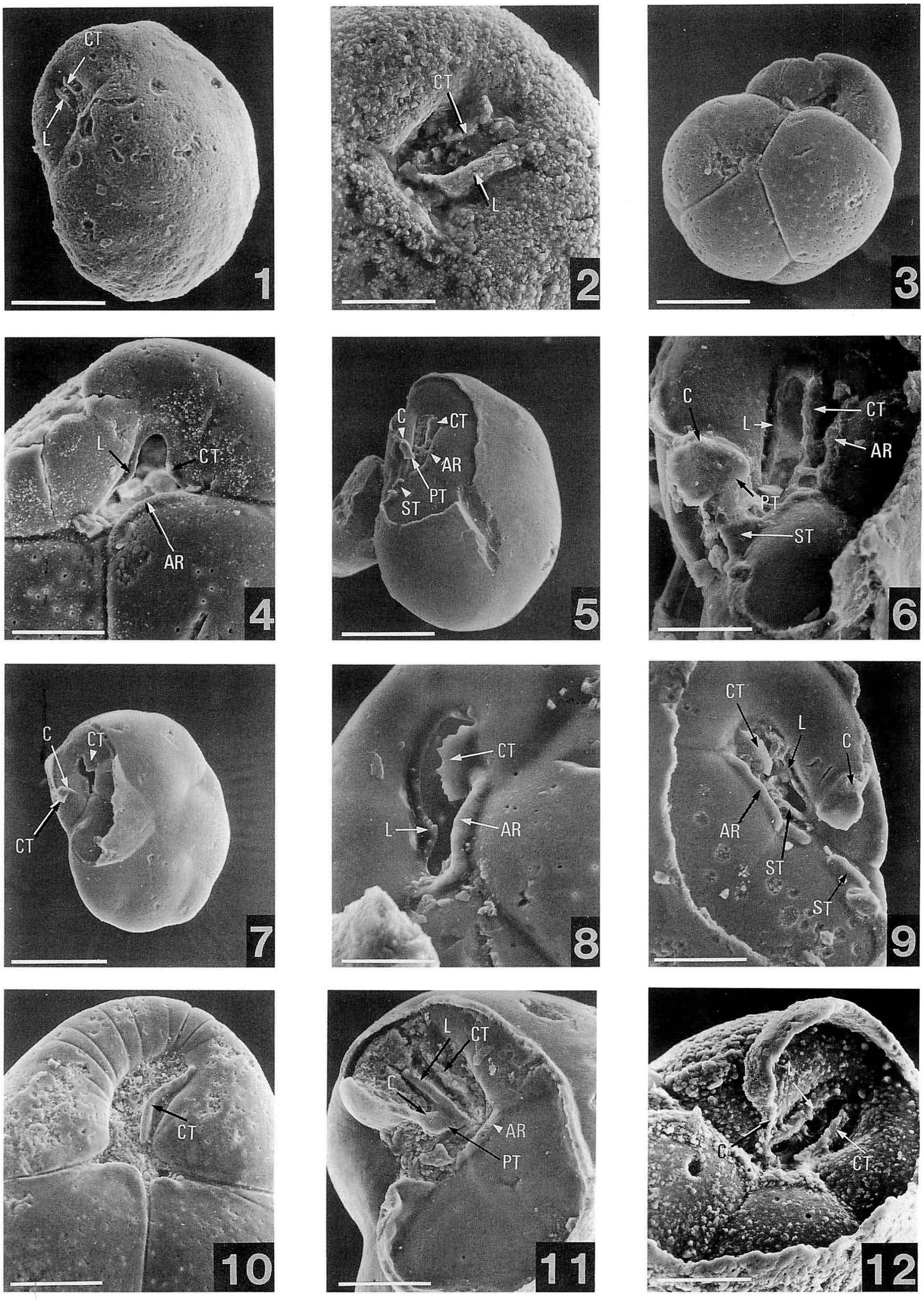
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Figure 21.

the Paleogene deep-sea specimens should not be identified with *G. subglobosa,* but should be included in the range of variation of *G. globosa.* In addition to the size difference, the vertical slit of aperture in *subglobosa* is opened in the upper part of the base of apertural face, while that of *globosa* is in the middle part of the base of the face. These differences are sufficient to distinguish the two species.

This species is abundant in the early middle Miocene of Japan.

Globocassidulina hatatatensis
Nomura sp. nov.

Figures 18-10a-c, -11a-c, -12a-c, -13a-c, 21-5, -6, 22

Diagnosis:- Test compressed; short slit-shaped aperture parallel to the base of apertural face, with small cristate tooth.

Description:- Test small, circular in side view, compressed oval with both parallel sides in edge view; periphery compressed-rounded, not lobulate; chambers distinct, not inflated, four pairs in final whorl, with small triangular opposing chamber on periphery; sutures flush with surface, almost straight toward periphery, radially arranged; umbilical region closed; aperture a short slit paralleling to the base of final apertural face, with a small cristate tooth and secondary tongue occupying most of the apertural opening; wall smooth, polished, very finely perforate, translucent.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture with the cristate tooth, lip and secondary tongue; copula attached to the preceding apertural face near the opening; internal free part of the primary tongue undeveloped; secondary tongue formed internally on the preceding chamber and in the adult specimen it is externally fused to the proximal portion of the cristate tooth (Figures 21-5-6, 22).

Holotype:- Figure 18, nos. 10a-c, NFL9506, sample HTTO-7, middle middle Miocene, Hatatate Formation, Miyagi Prefecture; paratypes and hypotypes, Figure 18, nos. 11a-c, 12a-c, 13a-c, NFL9507, sample HTTO-7.

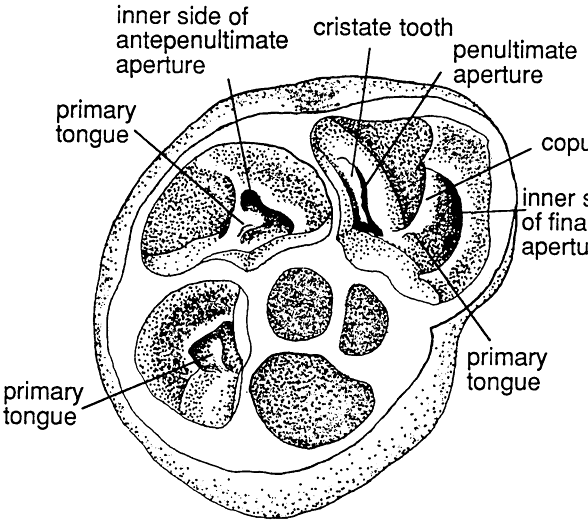


Figure 22. Internal structure of *Globocassidulina hatatatensis,* n. sp.

Test size:- Holotype, maximum test diameter 0.32 mm, test thickness 0.19 mm, sample HTTO-07; paratypes, maximum test length 0.16 to 0.32 mm, test thickness 0.13 to 0.19 mm, sample HTTO-7.

Occurrence:- Hatatate Formation (HTTO-7, ISW-16, -19).

Stratigraphic and paleogeographic distribution:- Cassidulinid I and II Zones in northern Honshu.

Remarks:- This new species is characterized by having the cristate tooth filling the slit-shaped apertural opening. The apertural structure of this species is classified as the **I** -type (**B** type of Nomura, 1983a), which is common in islandiellid species. However, this species is generally small in test size with a shorter slit in comparison with islandiellids.

This new species is similar to *Globocassidulina exigua* and *G. obtusa* in its compressed test. However, *G. hatatatensis* has larger test than *G. exigua,* and is distinguishable from this species in having more flat umbilicus. As for the apertural structure, nevertheless, this species

Figure 21. **1.** Side view of *Globocassidulina paratortuosa* showing cristate tooth (CT) and lip (L). Note the short vertical-slit of aperture at the base of apertural face. Scale bar=100μm. **2.** Details of the final tripartite aperture of *Globocassidulina paratortuosa* showing cristate tooth (CT) and lip (L) in areal branch. Scale bar=30μm. **3.** Side view of *Globocassidulina kakegawaensis.* Scale bar=60μm. **4.** Detail of 3 showing curved tripartite aperture consisting of indistinct cristate tooth (CT), lip (L), and apertural ridge (AR). Scale bar=27μm. **5.** Side view of *Globocassidulina hatatatensis* with dissected final chamber. copula (C), primary tongue (PT), and secondary tongue (ST) of the final aperture, cristate tooth (CT) and apertural ridge (AR) of penultimate aperture. Scale bar=100μm. **6.** The final cristate tooth (CT), primary tongue (PT), copula (C), and secondary tongue, and penultimate cristate tooth (CT), lip (L), apertural ridge (AR) of *Globocassidulina hatatatensis.* The proximal position of copula is attached to the preceding apertural face. Scale bar=27μm. **7.** Side view of *Globocassidulina exigua.* showing cristate tooth (CT) of the final and penultimate aperture and copula (C) of the final aperture. Scale bar=75μm. **8.** The final aperture of *Globocassidulina exigua* showing comb-like cristate tooth (CT), lip (L) and apertural ridge (AR). Scale bar=20μm. **9.** Penultimate aperture of *Globocassidulina exigua* showing cristate tooth (CT), lip (L), secondary tongue (ST) and apertural ridge (AR), and secondary tongue (ST) and copula (C) of the final aperture. Scale bar=43μm. **10.** Close view of *Globocassidulina canaliornata.* Note numerous grooves on the apertural face, and also distinct grooves on the sutures. These features are characteristics of this species. CT=cristate tooth. Scale bar=60μm. **11.** Penultimate aperture with dissected final chamber wall of *Globocassidulina globosa.* Note the vertical slit with lip-like cristate tooth (CT) and lip (L) at the base of the apertural face. Copula (C) with primary tongue (PT) attached to the proximal portion of preceding lip. L=lip, AR=apertural ridge. Scale bar=50μm. **12.** Penultimate aperture with dissected final chamber wall of *Globocassidulina globosa.* C=copula, CT=cristate tooth. Scale bar=38μm.

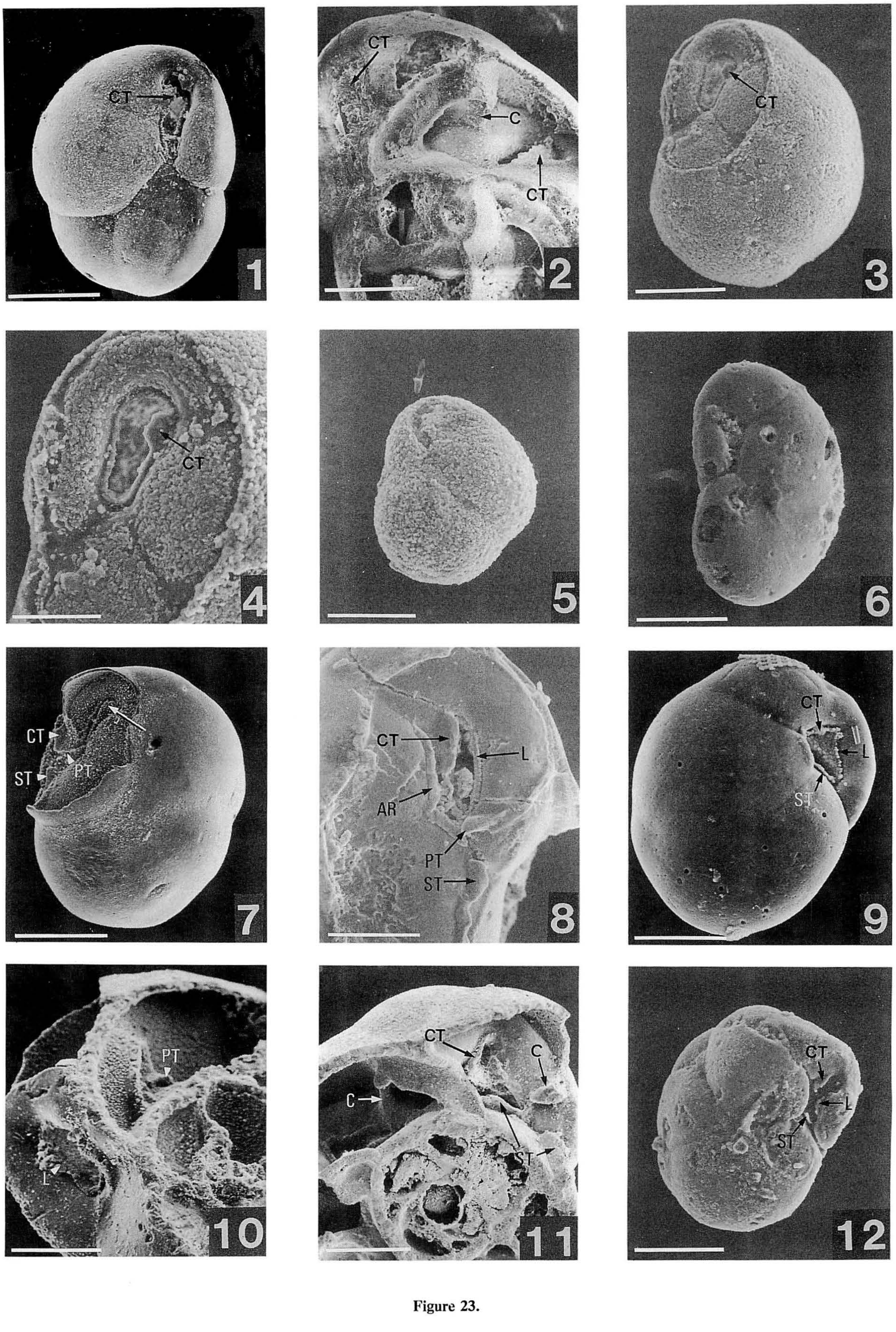

CT
1
CT
C
CT
2
CT
3
CT
4
5
6
CT
ST
PT
7
CT
L
AR
PT
ST
8
CT
L
ST
9
PT
L
10
CT
C
C
ST
11
CT
L
ST
12

Figure 23.

may form the same phylogeny with these allied species. Particularly, this new species evolved into *G. exigua* with relative development of the cristate tooth in the test.

Globocassidulina hatatatensis is common in the Hatatate Formation, though this new species has not been previously recognized as a distinct species. This new species is named for the type locality, Hatatate, Miyagi Prefecture.

Globocassidulina hokkaidoensis
Nomura sp. nov.

Figures 16-1a-c, -2a-c, -3a-c, 23-3, -4, 24

Diagnosis:- Globular test with large apertural opening and with small cristate tooth at the base of the posterior side.

Description:- Test medium, circular in side view and oval in edge view; periphery rounded, not lobulate; chambers broad, very slightly inflated, four pairs with small triangular portion in last whorl; sutures distinct, very slightly depressed and limbate, gently curved toward periphery; umbilical region closed, slightly depressed; aperture an elongate oval, parallel to the base of apertural face, showing a small cristate tooth at the base of the posterior side; wall smooth, polished, very finely perforate, translucent.

Optical structure- Wall jagged-granular texture.

Apertural structure:- Aperture simple with very small cristate tooth and lip, surrounding the opening; copula with very small cristate tooth attached to the preceding apertural face apart from the opening; secondary tongue may be formed, but usually indistinct on the preceding chamber wall. The aperture in young stages is oval, with indistinct cristate tooth (Figures 23-3-4, 24).

Holotype:- Figure 16, nos. 1a-c, NFL9508, sample WAK-65, early middle Miocene, Wakkauenbetsu Formation, Hokkaido; paratypes and hypotypes, Figure 16, nos. 2a-c, 3a-c, NFL9509.

Test size:- Holotype, test width 0.28 mm, test length 0.31 mm, test thickness, 0.23 mm, sample WAK-65; paratype, test width 0.16-0.28 mm, test length 0.18-0.31 mm, test thickness 0.13-0.23 mm, sample WAK-65.

Occurrence:- Wakkauenbetsu Formation (WAK-65, WAK-69/74).

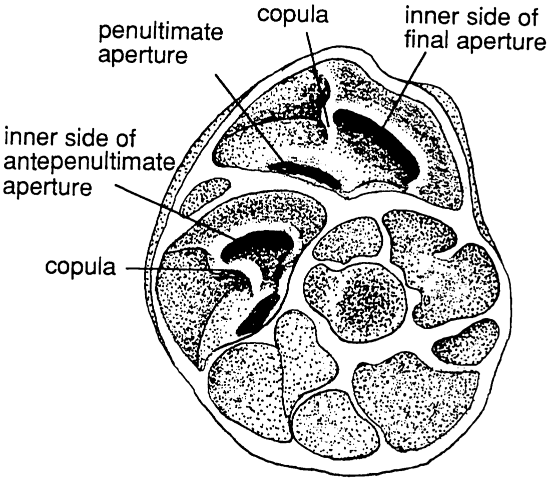


Figure 24. Internal structure of *Globocassidulina hokkaidoensis*, n. sp.

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in southern Hokkaido.

Remarks:- This species is most characterized by its large simple apertural opening with incipient cristate tooth formed at the base of the apertural face. No free structure of the internal aperture is the diagnostic feature of this species. This feature is similar to that of *G. notoensis* and *G. imamurai*, which are common in southern Japan. However, *Globocassidulina hokkaidoensis* is larger and more globular in comparison with those species. The oblique aperture (Figure 23, no. 4) is rather related to that of *G. oblongiformis*, despite the small cristate tooth of this species.

This new species occurs only in Hokkaido. The specific name refers to the geographic name, from where specimens were obtained.

Globocassidulina imamurai (Tai, 1959)

Figures 17-6a-c, -7a-c, -8a-c, 23-11, -12

Cassidulina imamurai Tai, 1959, p. 389, pl. 42, figs. 2a, b.
Cassidulina margareta Karrer. Asano, 1953b, pl. 3, figs. 11a, b.

Figure 23. **1.** Side view of *Globocassidulina oblongiformis*. Note the elongate narrow apertural opening with protruding cristate tooth (CT). Scale bar=86μm. **2.** *Globocassidulina oblongiformis* showing cristate tooth (CT) of the final and antepenultimate aperture, and internal view of penultimate aperture with copula (C). Scale bar=60μm. **3.** Penultimate aperture of *Globocassidulina hokkaidoensis* showing small cristate tooth (CT). Scale bar=75μm. **4.** Close view of 3. Scale bar=38μm. **5.** Side view of *Globocassidulina oblongiformis nana* showing small cristate tooth covering the apertural opening. Secondary calcite overgrowth occurred on test surface. Scale bar=75μm. **6.** Side view of *Globocassidulina complanata* showing crescent apertural opening. Scale bar=60μm. **7.** Penultimate aperture with cristate tooth (CT), and primary tongue (PT), cristate tooth (CT) and secondary tongues (ST) of the final aperture in *Globocassidulina pseudojaponica*. Note that the apertural structure of this species is similar to that of *Islandiella japonica*. Scale bar=176μm. **8.** Details of penultimate aperture showing cristate tooth (CT), lip (L), and apertural ridge (AR), and the final aperture showing primary tongue (PT) and secondary tongue (ST) in *Globocassidulina pseudojaponica*. Scale bar=86μm. **9.** Side view of *Globocassidulina notoensis* showing large apertural opening surrounded by lip (L), indistinct cristate tooth (CT), and indistinct secondary tongue (ST). Scale bar=60μm. **10.** Internal view of *Globocassidulina notoensis* showing primary tongue (PT) in penultimate aperture. Lip (L) of the final aperture also shown. Scale bar=60μm. **11.** Details of internal structure of *Globocassidulina imamurai*. Note cristate tooth (CT) and secondary tongue (ST) of penultimate aperture and copula of the final and antepenultimate aperture. Scale bar=60μm. **12.** Side view of *Globocassidulina imamurai* showing cristate tooth (CT), secondary tongue (ST) and lip (L) of penultimate aperture. Scale bar=60μm.

Redescription:- Test small, circular in side view and compressed oval in edge view; periphery very slightly lobulate; chambers distinct, four pairs making up the last whorl, with small triangular tips of alternating chambers on periphery; sutures distinct, very slightly depressed, nearly straight; umbilical region showing a small stellate area; aperture low L-shaped, occupying about one half of the final apertural face, with indistinct cristate tooth; wall smooth, polished, very finely perforate; translucent.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture is simple without distinct free structure; lip and cristate tooth is noded; primary tongue is small; copula attached to the anterior part of the preceding aperture near opening; internal part of the secondary tongue is very small on the preceding chamber (Figures 23-11-12). The apertural opening is low rounded-triangular to rounded-oval in immature stage.

Hypotypes:- Figure 17, nos. 6a-c, 7a-c, 8a-c, NFL9510, sample H-4A, Higashibessho Formation, Toyama Prefecture

Test size:- Maximum test diameter 0.16 to 0.36 mm, test thickness 0.12 to 0.20 mm, sample H-4A.

Occurrence:- Higashibessho Formation (H-3A, -4A, -6A, -9B, -10B), Hatatate Formation (ISW-16), Saigo Group (KK-117, -120), Mizunami Group (MIZU), Nanao Limestone (NANA), Nanatani Formation (NG-12, -18, -19), Higashi-innai Formation (NOTO-8, -10), Niwaya Formation (TM-11), Haratajino Formation (TM- 4, -153, -186, -205), Idosawa Formation (TM-34, -39).

Stratigraphic and paleogeographic distribution:- Cassidulinid I and II Zones in southern Honshu.

Remarks:- I have examined *G. imamurai* deposited at Hiroshima University, which is close to the holotype figure of that species, despite no documentation on the slide. The specimen is characterized by a small compressed test with relatively larger apertural opening, five pairs of chambers per whorl and broad apertural foramen. The apertural opening is surrounded by both tube-like lip and cristate tooth as described herein. The aperture of Tai's specimen is somewhat oblique to the base of the apertural face, though it is usually broad and triangularly shaped opening. Moreover, the figured specimen shows the stellate umbilical area as described by Tai, though the population of this species is characterized by the closed umbilicus.

This species is similar to *Globocassidulina margareta* (Karrer) in having compressed test and four pairs of chambers. I have compared *G. imamurai* with the holotype of *Cassidulina margareta,* described from the Miocene of Baden, Austria, which is deposited in the Austrian National Museum, Wien, and distinguished *G. imamurai* from *C. margareta* in having a smaller test and larger aperture to the test size. The apertural opening of *G. margareta* is characterized by more downward-curved slit to the base of the apertural face.

Globocassidulina kakegawaensis Nomura sp. nov.

Figures 17-3a-c, 21-3, -4

Diagnosis:- Small compressed test with sutural grooves; aperture loosely curved L-shape with almost the same-sized basal and areal slit.

Description:- Test small, circular in side view and compressed oval in edge view; periphery narrowly rounded, very slightly lobulate; chambers distinct, not inflated, four pairs in last whorl; sutures distinct, depressed, appearing as a line when dyed, almost straight to periphery; umbilical region closed; aperture tripartite, consisting of same sized basal and areal slit, without a conspicuous toothplate; wall smooth, polished, very finely perforate, translucent.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture is provided with poorly developed cristate tooth and lip; cristate tooth is small and tube-shaped; lip smooth, without decoration; secondary tongue is indistinct; copula attached to the anterior portion of the preceding aperture near basal branch; primary tongue undeveloped (Figures 21-3-4).

Holotype:- Figure 17, nos. 3a-c, NFL9519, sample KK-16, Tamari Formation, Sagara Group, Shizuoka Prefecture, late Miocene to Pliocene; paratypes, NFL9520, sample KK-16.

Test size:- Holotype, maximum test diameter 0.17 mm, test thickness 0.12 mm, sample KK-16; paratypes, maximum test diameter 0.14 to 0.17 mm, test thickness 0.10 to 0.12 mm, sample KK-16.

Occurrence:- Anno Formation (AN-74), Sagara Group (KK-16, -17, -18, -19).

Stratigraphic and paleogeographic distribution:- Lower Pliocene in southern Honshu.

Remarks:- This new species resembles Recent *G. obtusa* and may be the ancestor of *G. obtusa* in having a compressed test, sutural grooves, and in having tripartite aperture. However, the basal slit of tripartite aperture of *kakegawaensis* is shorter in comparison with that of *obtusa* 's aperture. This feature indicates that the juvenile aperture of *obtusa* suggests the heterochronic evolution of these two species (Figure 12).

Because of the similarity of this species to *G. obtusa,* I should discuss the species concept of *G. obtusa* (Williamson). As stated in the remarks of *Cassidulina reniforme, G. obtusa* has been repeatedly described as the species name of *crassa.* Because earliest workers such as Brady described this species as having a tripartite aperture, most later workers believed a tripartite aperture and compressed test as diagnostic of *crassa.* Some later workers have also noted *crassa* as characterized by the prominent cristate tooth out of the aperture, because d'Orbigny's original figures showed the prominent feature in the aperture. I found such a confusion in identifying *crassa* in ear-

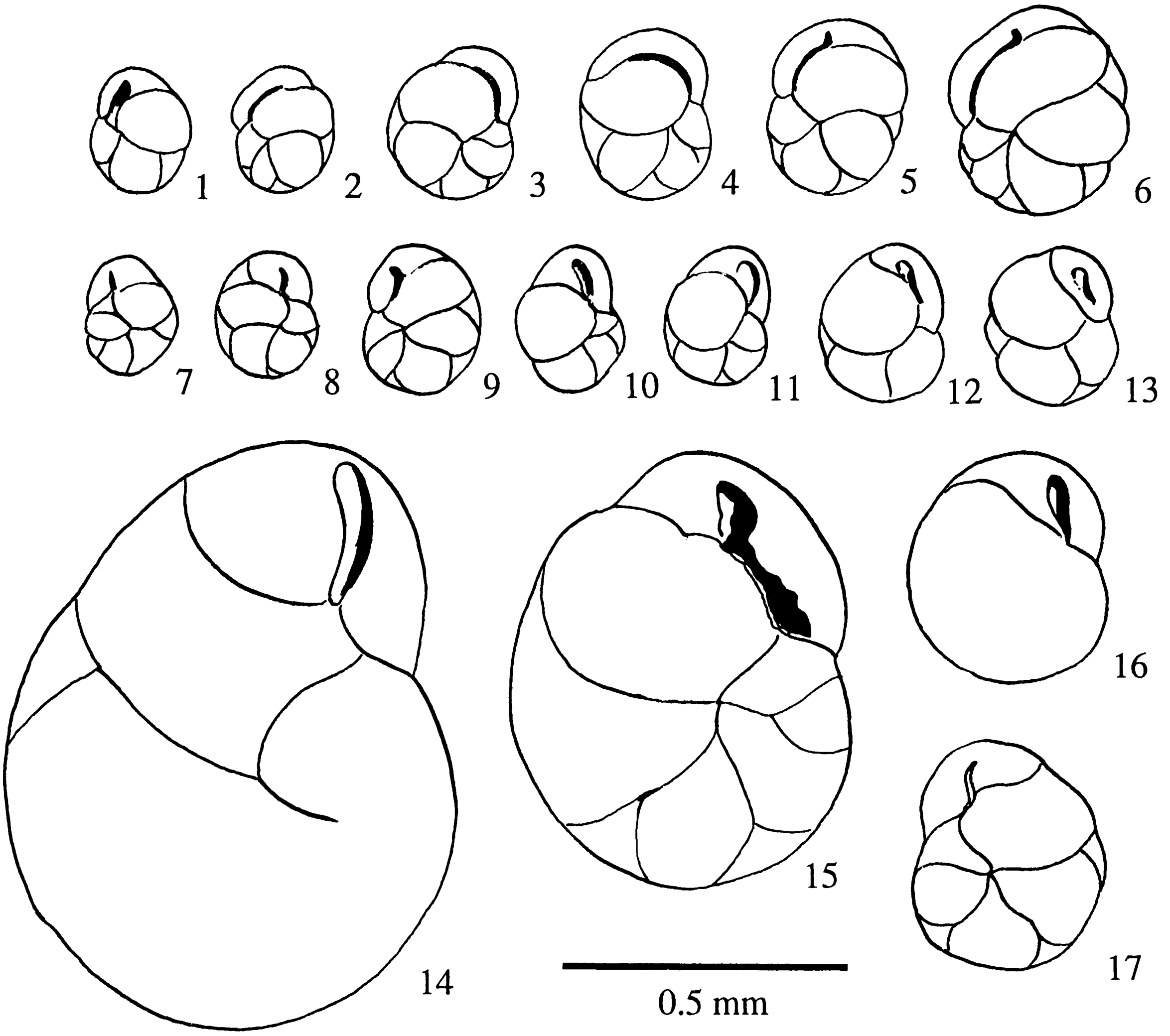


Figure 25. Secondary types of *Globocassidulina crassa* (d'Orbigny) in the collection of the U. S. National Museum.
1. [Cushman Coll. 18702, Miocene] (=*Globocassidulina hokkaidoensis,* Nomura, n. sp.) **2.** [Cushman Coll. 37877] Hypotype, Cushman and Henbest, 1940, U. S. Geol. Surv., Prof. Paper, 196-A, pl. 10, fig. 9. **3.** [USNM 377134] Hypotype, Phleger, Parker and Peirson, 1953, Swedish Deep Sea Exp., vol. 7, pl. 10, fig. 1. **4.** [USNM 377133] Hypotype, Phleger and Parker, 1951, Mem. Geol. Soc. Am., 46, p. 26, pl. 14, figs. 4a, b. **5.** [USNM 377135] Hypotype, Parker, 1958, Repts. Swed. Deep Sea Exped., vol. 8, no. 4, pl. 4, fig. 12. **6.** [USNM 377132] Hypotype, Parker, 1948, Bull. Mus. Comp., 2001, vol. 100, no. 2, p. 237, pl. 6, fig. 5. **7.** [USNM 497522] Hypotype, Cushman and Carhill, 1933, U. S. Geol. Surv., Prof. Paper, 175, p. 32, pl. 12, figs. 2a-c. **8.** [Cushman Coll. 37815] Dorsey, 1948, Bull. 2, Maryland Dept. Geol. Mines and Water Resources, pl. 38, fig. 2. **9.** [USNM 27992] Hypotype, Cushman and Wickenden, 1929, Proc. U. S. Nat. Museum, vol. 75, Art 9, pl. 5, fig. 5. **10.** [Cushman Coll. 60699] Hypotype, Renz, 1948, p. 124, pl. 9, fig. 13. **11.** [USNM 377138] Hypotype, Cushman, 1930, Florida Surv., Bull. 4, p. 50, pl. 11, figs. 6a, b. **12.** [Cushman Coll. 60553] Hypotype, Renz, 1948, p. 124, pl. 12, fig. 23. **13.** [USNM 27928] Hypotype, Cushman, 1948, Cushman Lab. Foram. Res., Spec. Publ., 23, p. 74, pl. 8, fig. 9. **14.** [USNM 689586, Topotype of Discovery Exped., St. 388] **15.** [USNM 628559] Hypotype, Smith, 1964, U. S. Geol. Surv., Prof. Paper, 429B, p. 39, pl. 3, fig. 4. **16.** [Cushman Coll. 14330] Hypotype, Cushman, 1929, Cushman Lab. Foram. Res., vol. 5, p. 100, pl. 14, fig. 10. **17.** [Cushman Coll. 222889] Cushman, 1936, Geol. Soc. Am., Bull., vol. 47, p. 434, pl. 5, fig. 12.

lier worker's specimens deposited in the U. S. National Museum. There are no consistent figures for *crassa* except for the tripartite aperture and compressed test. They are distributed in several different genera, based on my classification scheme. Some of these specimens are shown in Figure 25. Among them, there are specimens to be included in the genus *Paracassidulina,* without any tripartite feature of the aperture, and specimens to be included in the genus *Islandiella.* There are also several variations of tripartite feature in aperture, which are recognized in different species of *Globocassidulina* (Nomura, 1983a, b). Thus, the species *obtusa* is sometimes confused with *G. bisecta* or *G. norvangi* (Ujiié, 1995) and *Takayanagia delicata* (Xu and Ujiié, 1994).

Sejrup and Guilbault (1980) and Rodrigues et al. (1980) independently questioned these previous workers results and suggested that the form having a tripartite aperture of long basal slit and short areal slit is synonymous with *obtusa.* D'Orbigny's original *crassa* was described from the recent sediments off Falkland Island. Heron-

Allen and Earland (1932) refigured *crassa* from this area, and they stated that their specimens are much less delicate and the markings (cristate tooth ?) are generally more obscure than that of d'Orbigny's. I have found such a feature of *crassa* in the specimen (off Falkland, 137m) at the U. S. National Museum (Figure 25-14), which was donated by Earland to Cushman's collection. The aperture of this species is never tripartite, but oblique slit to the base of apertural face, and it is associated with no protruding and curled cristate tooth on the posterior side of the aperture. Some topotypes of Discovery Reports St. 388 (USNM 689586) were donated by Boltovskoy to the U. S. National Museum, which show the same feature of the Earland's specimen. Thus the concept of d'Orbigny's *crassa* can not be applied to specimens having wide varied tripartite apertures (**G3**- and **G3**'-type in here).

The species *obtusa* was described as having a narrow periphery instead of keeled periphery and only the basal slit of the aperture was shown in the original figure. However, Murray (1971) and Sejrup and Guilbault (1980) clearly showed the tripartite aperture consisting of a short areal slit in Recent specimens including off the British Islands. The detailed description based on Japanese specimens was given by Nomura (1983b).

The specific name refers to Kakegawa City, Shizuoka Prefecture, from where this species occurred.

Globocassidulina lenticularis Nomura sp. nov.

Figures 18-1a-c, -2a-c, 3a-c, 26, 30-1, -2

Diagnosis:- Large lenticular test with acute to keeled periphery; aperture with distinct cristate tooth; optically granular texture.

Description:- Test large, circular in side view and lenticular in edge view; periphery acute to keeled, slightly lobulate; chambers distinct, elongate rhomboid, not inflated, four pairs in the last whorl; sutures indistinct, slightly limbate, flush with surface; umbilical region inflated, stellate; aperture elongate, at the base of final apertural face, occupying a half of apertural face, with distinct cristate tooth on the posterior side; wall smooth, polished, very finely perforated, translucent.

Optical structure:- Walls basically jagged-granular texture; some portion of the walls may be indistinctly radial in texture.

Apertural structure:- Aperture with the large fan-shaped cristate tooth on the posterior side and secondary tongue developed on the preceding chamber at the base of apertural opening; copula attached to the preceding anterior apertural face with the primary tongue; primary tongue developed on the anterior portion of the preceding apertural face; gap is usually formed. The aperture in the immature stage is oval oblique to the base with a rudimentary cristate tooth; secondary tongue is indistinct (Figures 26, 30-1-2).

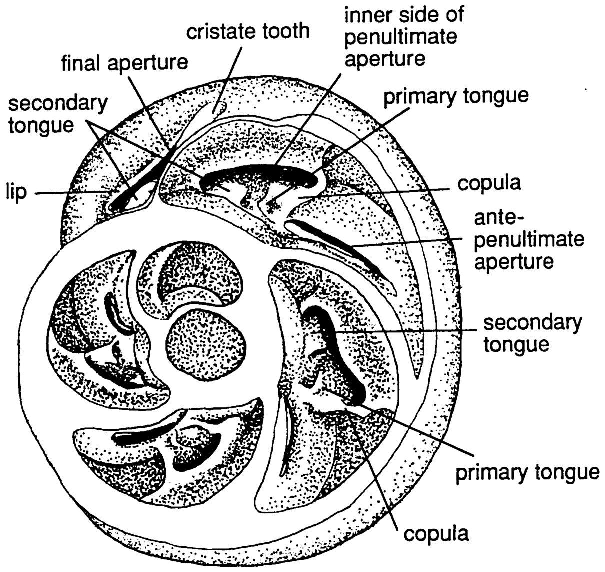


Figure 26. Internal structure of *Globocassidulina lenticularis*, n. sp.

Holotype:- Figure 18, nos. 1a-c, NFL9525, sample SEKI, Sekinohana Limestone, Noto Peninsula, Ishikawa Prefecture, early middle Miocene; paratypes and hypotypes, Figure 18, nos. 2a-c, 3a-c, NFL9526.

Test size:- Holotype, maximum test diameter 0.52 mm, test thickness 0.25 mm, sample SEKI; paratype, maximum test diameter 0.24 to 0.52 mm, test thickness 0.16 to 0.25 mm, sample SEKI.

Occurrence:- Tomesaki Formation (IW-1), Nanatani Formation (NG-20), Higashi-innai Formation (NOTO-16), Sekinohana Limestone (SEKI).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ib Subzone in Honshu.

Remarks:- This species is found only in early middle Miocene calcareous sandstone of Noto Peninsula and Northeast Honshu, although it is very abundant, accounting for maximum 33% of the cassidulinid assemblage. The occurrence of this species is usually associated with *G. pseudojaponica*. An external and internal apertural structure of this species is basically the same as that of *Planocassidulina yabei*, which is abundant in Pleistocene deposits of northern Japan. However, this species has the walls of optically granular texture, which is distinguished from *P. yabei* with a radial texture. As mentioned before, the radial-granular wall can be used as a generic level criterion for foraminiferal classification. Thus the same or very similar morphology of foraminifera may appear in different genus, as a result of homeomorphic evolution.

The specific name is referred to the Latin *lenticularis* meaning lenticular, which is the diagnosis of this species.

Globocassidulina notoensis Nomura sp. nov.

Figures 17-4a-c, -5a-c, 23-9, -10, 27

Diagnosis:- Small compressed test with large triangular apertural opening.

Description:- Test small for the genus, circular in side view and compressed oval in edge view; periphery subacute, not lobulate; chambers broad and elongate, three to four pairs of chambers making up last whorl; sutures radial, flush with surface, not limbate, unclear for earlier portion of the whorl; umbilical region closed; aperture distinct, large for the test size, triangular opening occupying one-third of last apertural face; wall smooth, polished, finely perforate, translucent.

Optical structure:- Wall jagged granular texture.

Apertural structure:- Apertural structure is very simple; triangular opening surrounded by knobbed lip, small cristate tooth and small secondary tongue. Cristate tooth with poorly developed internal free part; copula attached to anterior portion of the preceding aperture near opening; secondary tongue is small on the previous chamber wall. Aperture is on oval opening somewhat oblique to the based of apertural face in immature stage (Figures 23-9-10, 27).

Holotype:- Figure 17, nos. 4a-c, NFL9511, sample NOTO-27, Hojuji Formation, Noto Peninsula, Ishikawa Prefecture; Paratypes and hypotype, Figure 17, nos. 5a-c, NFL9512, sample NOTO-27.

Test size:- Holotype, maximum test length 0.20 mm, test thickness 0.12 mm, sample NOTO-27; paratypes maximum test length 0.13 to 0.20 mm, test thickness 0.09 to 0.12 mm, sample NOTO-27.

Occurrence:- Bihoku Group (FU-5, SB-6), Higashi-bessho Formation (H-4A, -7A), Mizunami Group (MIZU), Nakanami Formation (NAKA), Higashi-innai Formation (NOTO-3, -8, -10, -15, -16), Hojuji Formation (NOTO-27), Nishikurosawa Formation (OGA).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in Honshu.

Remarks:- *Globocassidulina notoensis* resembles the immature *G. imamurai* described from early middle Miocene deposits (the Bihoku Group) of Southwest Honshu. A similar apertural structure and chamber arrangement can be found in the test of mature *G. notoensis* and immature *G. imamurai*, indicating that *G. notoensis* is the ancestor of *G. imamurai*. However, the mature *G. imamurai* has consistently four pairs of chambers in last whorl and an L-shaped aperture, while mature *G. notoensis* has three to four pairs of chambers and triangular opening of the aperture.

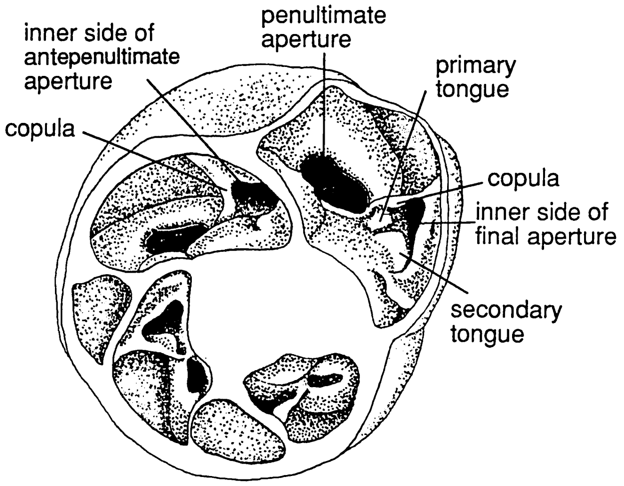


Figure 27. Internal structure of *Globocassidulina notoensis*, n. sp.

The last occurrence of *Globocassidulina notoensis* defines the upper boundary of the cassidulinid Ia Subzone. This species is very common in southern Honshu, such as the Noto Peninsula and Mizunami. The specific name refers to the Noto Peninsula, from where well preserved specimens were obtained.

Globocassidulina oblongiformis
Nomura sp. nov.

Figures 18-4a-c, -5a-c, -6a-c, -7a-c, 23-1, -2, 28

Diagnosis:- Oval test, with broad last pair of chambers; slit aperture oblique to the base of apertural face.

Description:- Test small to medium in size, oval in side view and compressed oval in edge view; periphery rounded, lobulate; chambers broad and inflated, particularly in last pair, which involute a half of test, three pairs in last whorl, with small opposing triangular portion on periphery; umbilical region appearing slightly depressed, because of inflated last chambers; sutures depressed, slightly limbate, moderately curved; aperture a curved slit oblique to the base of apertural face, with a small cristate tooth on the posterior side; wall smooth, polished, very finely perforate, translucent.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture with the protruded cristate tooth and knobbed lip; secondary tongue is indistinct; copula without a primary tongue attached to the preceding apertural face, somewhat apart from the opening. The aperture in immature stage is small, comma-shaped with a

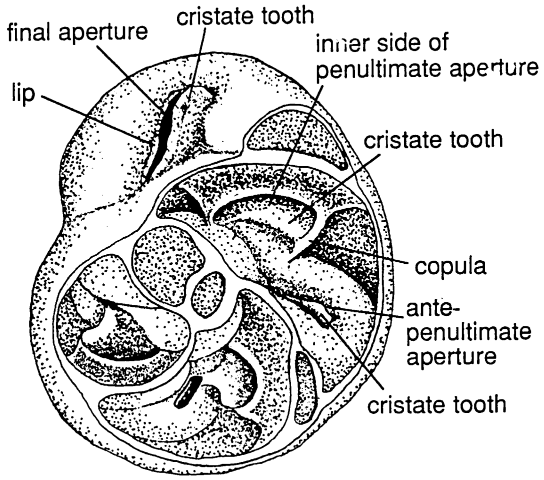
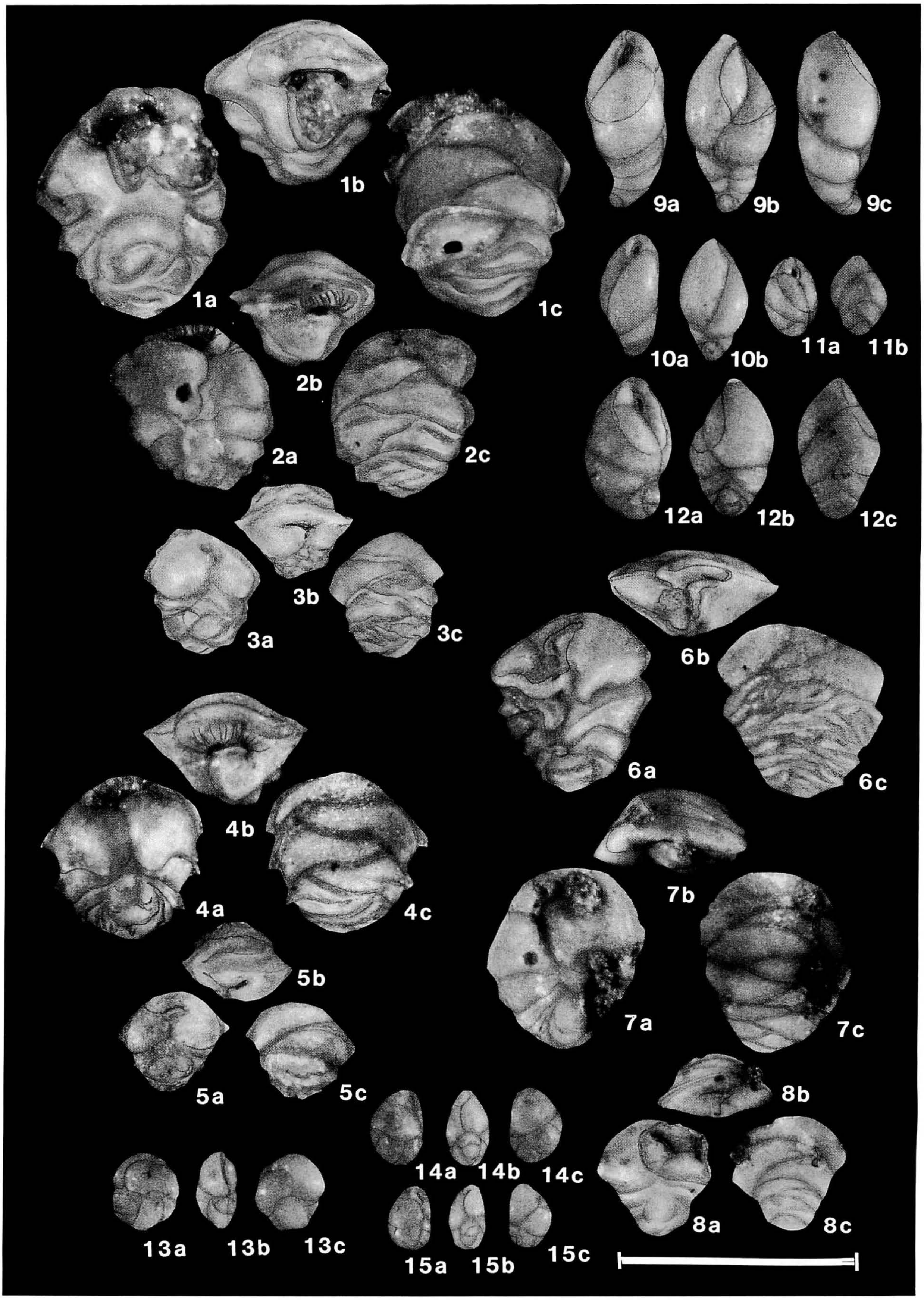


Figure 28. Internal structure of *Globocassidulina oblongiformis*, n. sp.


1a
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9b
9c
10a
10b
11a
11b
12a
12b
12c
13a
13b
13c
14a
14b
14c
15a
15b
15c

Figure 29.

small cristate tooth (Figures 23-1-2, 28).

Holotype:- Figure 18, nos. 4a-c, NFL9513, sample NOTO-27, early middle Miocene, Hojuji Formation, Noto Peninsula, Ishikawa Prefecture; paratypes and hypotypes, Figure 18, nos. 5a-c, 6a-c, 7a-c, NFL9514.

Test size:- Holotype, test width 0.18 mm, test length 0.24 mm, test thickness 0.16 mm, sample NOTO-27; paratypes, test width 0.11-0.18 mm, test length 0.13-0.24 mm, test thickness 0.11-0.16 mm, sample NOTO-27.

Occurrence:- Bihoku Group (SHO-23, FU-5), Higashi-bessho Formation (H-7A), Saigo Group (KK-120), Mizunami Group (MIZU), Nanatani Formation (NG-2, -9, -12, -14, -18, -19, -20, -23, -27), Higashi-innai Formation (NOTO-8, -10), Hojuji Formation (NOTO-27), Haratajino Formation (TM-3, -153, -159, -204, -205), Idosawa Formation (TM-34), Wakkauenbetsu Formation (WAK-65), Kurosedani Formation (KURO).

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone in Honshu and Hokkaido.

Remarks:- In appearance, this new species is similar to *Cassidulina oblonga* Reuss from the Tertiary of Austria, in having an ovate test. Detailed apertural structure and wall structure of *C. oblonga* were not described in the original description and subsequent studies. However, this new species differs from *C. oblonga* in having larger apertural face, and three and half paired chambers in the last whorl, instead of the four pairs of *G. oblonga.*

Globocassidulina oblongiformis is abundant in lower middle Miocene deposits of Japan, and is characteristic of the cassidulinid I Zone. The Pliocene *Globocassidulina kattoi* (originally *Cassidulina kattoi* Takayanagi (1953) in the Nobori Formation, Kochi Prefecture) may be a descendant of *Globocassidulina oblongiformis.*

The specific name of this species refers to the similarity to *C. oblonga* Reuss.

Globocassidulina oblongiformis nana
Nomura subsp. nov.

Figures 18-8a-c, -9a-c, 23-5

Diagnosis:- Small-oval test with three pairs of chamber; final pair of chamber occupying a half of test; aperture slit-shaped, with small cristate tooth.

Description:- Test very small, oval in side view and somewhat compressed oval in edge view; periphery rounded, lobulate; chambers distinct, three pairs in last whorl, inflated in final pair which occupies half of the test; earlier chambers not inflated; sutures depressed between the final pair and earlier chambers, gently curved; aperture a curved slit, oblique to the base of last apertural face, with small cristate tooth; wall smooth and polished, very finely perforate, translucent.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Because of bad preservation, internal apertural structure could not be examined.

Holotype:- Figure 18, nos. 8a-c, NFL9515, sample AT-22, late Miocene, Atsuta Formation, Hokkaido; paratype and hypotype, Figure 18, 9a-c, NFL9516.

Test size:- Holotype, test width 0.15 mm, test length 0.17 mm, test thickness 0.12 mm, sample AT-22; paratype, test width 0.12-0.15 mm, test length 0.15-0.17 mm, test thickness 0.11-0.12 mm, sample AT-22.

Occurrence:- Atsuta Formation (AT-22).

Stratigraphic and paleogeographic distribution:- Part of the cassidulinid II Zone in Hokkaido.

Remarks:- *Globocassidulina oblongiformis nana* is discriminated from *G. oblongiformis* in having a smaller and more compact test. Except for the apertural structure, an immature *G. oblongiformis* is very similar to *G. oblongiformis nana.* This subspecies is only found in the Atsuta Formation, but it may represent a dwarfing in the *G. oblongiformis* phylogeny.

This species is named from the Latin *nanus,* meaning dwarf, with reference to the small test.

Globocassidulina paratortuosa (Kuwano, 1954)

Figures 16-4a-c, -5a-c, -6a-c, 21-1, -2

Cassidulina paratortuosa Kuwano, 1954, p. 34, figs. 4-6.
Cassidulinitella salebrosa Saidova, 1975, p. 330, pl. 88, fig. 13.
Globocassidulina paratortuosa (Kuwano). Nomura, 1983a, p. 28, pl. 2, fig. 19; Akimoto, 1990, p. 200, pl. 18, figs. 8a, b.

Hypotypes:- Figure 16, nos. 4a-c, 5a-c, 6a-c, NFL9521, sample TM-39, Idosawa Formation.

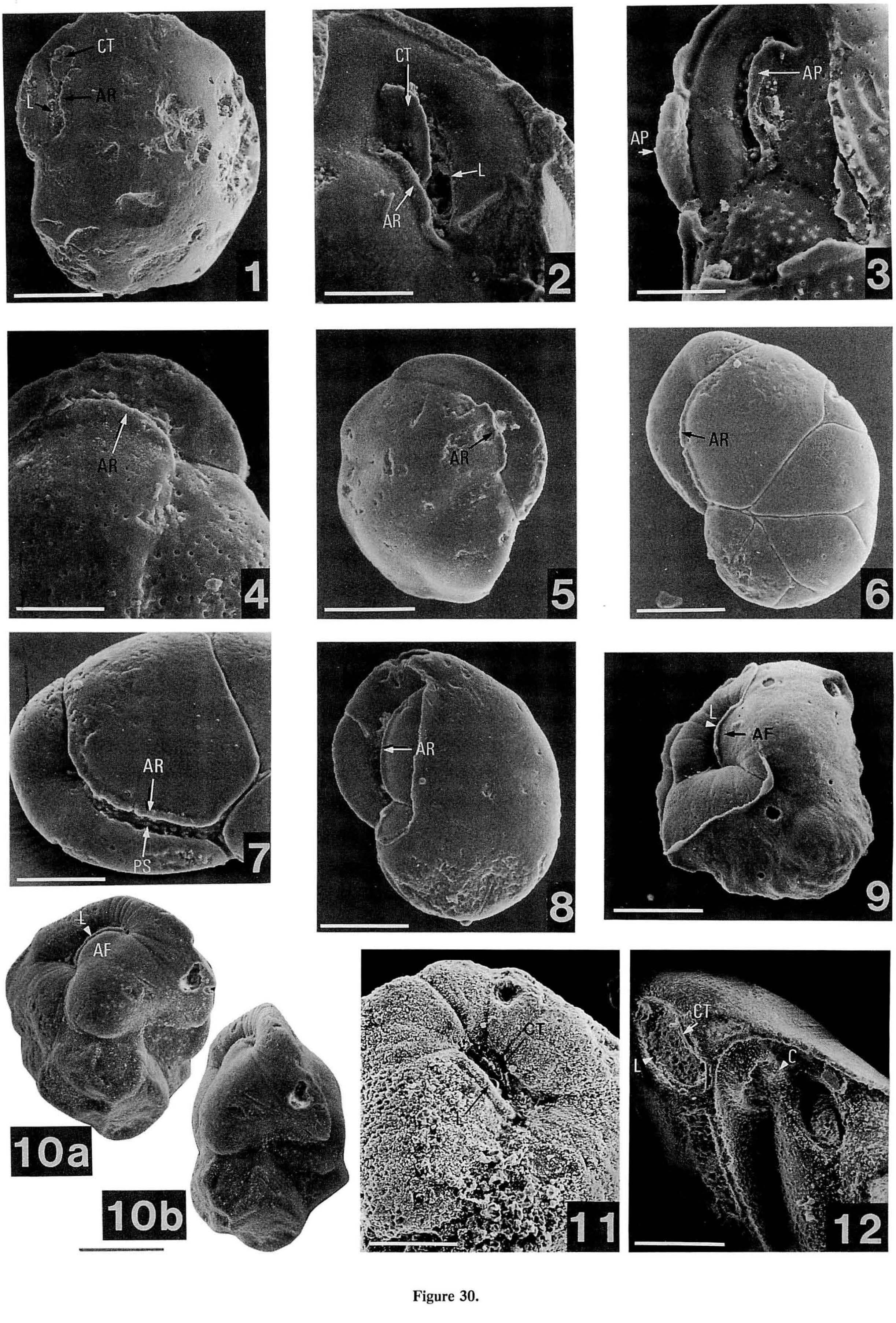
Test size:- Test width 0.24-0.30 mm, test length 0.26-0.36 mm, test thickness 0.17-0.20 mm, sample KK-117.

Occurrence:- Bihoku Group (SHO-21), Saigo Group (KK-117, -120), Nanatani Formation (NG-9), Idosawa Formation (TM-34, -39).

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone in southern Honshu; Pleistocene form found in Boso Peninsula; Recent form reported from the Pacific Ocean.

Remarks:- This species is characterized by a lenticular test with seven to eight pairs of undulated chambers in the final whorl. As described by Nomura (1983b), the aperture of this species is basically a vertical slit, but it is associated with a short basal slit and a mall cristate tooth on the posterior side, showing the tripartite feature (Figures 21-1-2). Sutures of *G. paratortuosa* are limbate but usually

Figure 29. **1a-c, 2a-c, 3a-c.** *Ehrenbergina crassitrigona* Nomura, n. sp., ISW-16. **4a-c, 5a-c.** *Reissia* sp., KITA-91. **6a-c.** *Ehrenbergina bosoensis* Takayanagi, HTTO-7. **7a-c, 8a-c.** *Ehrenbergina notoensis* Asano., NOTO-10. **9a-c, 10a, b, 11a, b, 12a-c.** *Rutherfordoides erectus* (McCulloch), NOTO-27. **13a-c.** *Paracassidulina stabilis* Nomura, n. sp., NOTO-15. **14a-c, 15a-c.** *Evolvocassidulina kuwanoi* (Matoba), KK-117. Scale bar=0.5 mm.


CT
L
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7
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8
L
AF
9
L
AF
10a
10b
CT
11
CT
L
C
12

Figure 30.

indistinct because of the thick wall.

The Miocene form is characterized by its thicker test and its globular appearance. Five specimens of *G. paratortuosa* from Sample T-39 have test thickness with maximum diameter ratios of 0.71 to 0.87 (on the average 0.79), while the holotype has a ratio of 0.55. I regard this feature as a variation of *G. paratortuosa.* Geographic distribution of Miocene species is limited to the cassidulinid I Zone of southern Honshu.

Globocassidulina pseudojaponica Nomura sp. nov.

Figures 17-1a-c, -2a-c, 23-7, -8

Diagnosis:- Large biserial subglobular test; apertural opening filled with cristate tooth and secondary tongue.

Description:- Test large, circular in side view and inflated oval in edge view; periphery rounded, not lobulate; chambers broadly elongate, not inflated, four pairs associated with triangular portions on periphery; umbilical region closed; sutures indistinct because of thick walls, somewhat limbate, slightly curved on surface; aperture elongate, parallel to the base of apertural face, showing a cristate tooth and secondary tongue protruding out of apertural opening; wall smooth, polished, matted, finely perforate.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture with the protruded cristate tooth on the posterior side of the opening and secondary tongue on the previous wall near anterior base of the opening; copula attached to the anterior part of the preceding apertural face with a primary tongue; secondary tongue developed on the preceding chamber; gap is usually formed between the primary and secondary tongues. The aperture in the immature stage is oval, oblique to the base with the rudimentary cristate tooth; secondary tongue is indistinct (Figures 23-7-8).

Holotype:- Figure 17, nos. 1a-c, NFL9522, sample IW-1, early middle Miocene, Tomesaki Formation, Iwate Prefecture; paratypes and hypotype, Figure 17, nos. 2a-c, NFL9523.

Test size:- Holotype, test width 0.47 mm, test length 0.56 mm, test thickness 0.33 mm, sample IW-1; paratype, test width 0.27-0.47 mm, test length 0.32-0.56 mm, test thickness 0.23-0.33 mm, sample IW-1.

Occurrence:- Honsubetsu Formation (HON-31), Hatatate Formation (HTTO-7, ISW-16, -19), Tomesaki Formation (IW-1), Nanao Limestone (NANA), Sekinohana Sandstone (SEKI), Wakkauenbetsu Formation (WAK-69/71).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ib Subzone in Honshu and Hokkaido.

Remarks:- This new species occurs from lower middle Miocene deposits of Noto Peninsula and Aomori Prefecture, where its occurrence is very abundant in association with *G. lenticularis.* The aperture of this new species is characterized by having a similar structure as those of *Islandiella japonica* or *I. californica* showing the elongate aperture with large cristate tooth. Nevertheless, this new species is differentiated from those in having the optically granular texture and the test size is generally smaller than those.

A globular type of islandiellid species, which is common in Pliocene to Recent deposits of the Sea of Japan and northern Japan, may be a descendant of this new species, with the evolution of crystalline structure from the granular to radial texture.

The specific name refers to homeomorphic feature between this form and *I. japonica.*

Globocassidulina tsuchidai Nomura, 1983

Figures 17-9a-c, -10a-c, -11a-c

Globocassidulina tsuchidai Nomura, 1983a, p. 70, pl. 2, figs. 4a-c; pl. 17, figs. 3-7.

Globocassidulina pseudoquadrata Nomura. Akimoto, 1990, p. 200, pl. 19, figs. 8a, b, 10a, b.

Globocassidulina ? sp. Hatta and Ujiié, 1992, p. 173, pl. 26, fig. 5.

Hypotypes:- Figure 17, nos. 9a-c, 10a-c, 11a-c, NFL 9524, sample TM-35, Idosawa Formation, Tomioka Group, Gunma Prefecture, early middle Miocene.

Test size:- Test width 0.17-0.24 mm, test length 0.22-0.30 mm, test thickness 0.16-0.18 mm, sample TM-35.

Occurrence:- Saigo Group (KK-117, -120), Nanatani Formation (NG-9), Haratajino Formation TM-3, -204, -205), Idosawa Formation (TM-35, -39).

Figure 30. **1.** *Globocassidulina lenticularis* showing well developed cristate tooth (CT). Scale bar=136μm. **2.** Details of penultimate aperture of *Globocassidulina lenticularis* showing well-developed cristate tooth (CT), apertural ridge (AR), and lip (L). Note that the apertural structure is very similar to that of *planocassidulina yabei.* Scale bar=60μm. **3.** Details of penultimate aperture of *Cassidulina reniforme* showing well developed apertural plate (AP) covering the apertural opening. Note apertural plate of the final aperture attached to the periphery of preceding apertural face. Scale bar=43μm. **4.** Details of the final aperture of *Paracassidulina stabilis* showing slit-shaped aperture with apertural ridge (AR). Scale bar=38μm. **5.** *Paracassidulina neocarinata* showing slit-shaped aperture with apertural ridge (AR). Scale bar=75μm. **6.** *Paracassidulina* cf. *miuraensis* showing slit-shaped aperture with apertural ridge (AR). Note the sutural grooves on surface. Scale bar=86μm. **7.** Details of the final aperture of *Paracassidulina* cf. *miuraensis.* Note long slit with apertural ridge (AR) and pseudolip (PL). Scale bar=60μm. **8.** *Paracassidulina izuensis* with dissected final chamber wall showing apertural ridge (AR). Scale bar=86μm. **9.** Side view of *Ehrenbergina notoensis.* Note the curved slit aperture with faint apertural grooves on the apertural face. AF=apertural flap, L=lip. Scale bar=86μm. **10.** *Ehrenbergina crassitrigona.* (a) apertural side, (b) side view. AF=apertural flap, L=lip. Scale bar=86μm. **11.** The final aperture of *Reissia* sp. showing apertural grooves on the face. Lip (L) and poorly developed cristate tooth (CT) are present. Scale bar=43μm. **12.** *Rutherfordoides erectus* showing poorly developed cristate tooth (CT) and lip (L) in the final aperture and copula (C) of penultimate aperture without free structure. Scale bar=43μm.

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone in southern Honshu; Pleistocene form found in southern Honshu.

Remarks:- This species is characterized by an elongate, almost rounded quadrangular test and the flat apertural face with distinct tripartite aperture and triangular apertural flap.

Miocene forms have less developed apertural flap relative to the test size in comparison with the holotype and paratype specimens in the Pleistocene Ofuna Formation, Kanagawa Prefecture. However, the measurements of test sizes (test length, width and thickness) indicate that Miocene forms are in the range of variation of this species.

Globocassidulina tsuchidai is rare in Miocene deposits of Japan and occurs mostly in southern Honshu.

Genus *Evolvocassidulina* Eade, 1967

Evolvocassidulina Eade, 1967, p. 431.

Type species:- *Cassidulina orientalis* Cushman, 1922, p. 129; Loeblich and Tappan, 1985, p. 106 figs. 1-5.

Remarks:- Lectotype of this genus, *C. orientalis*, was designated by Loeblich and Tappan (1985) from the sample off New Zealand, from which Cushman (1919) described it as *C. bradyi*.

Japanese Miocene *Evolvocassidulina* is quantitatively limited in both number of species and individuals, only represented by *E. kuwanoi*.

Evolvocassidulina kuwanoi (Matoba, 1967)

Figures 29-14a-c, -15a-c

Cassidulinoides kuwanoi Matoba, 1967, p. 253, pl. 29, figs. 1a, b, 2.

Evolvocassidulina kuwanoi (Matoba). Nomura, 1983b, p. 46, pl. 4, figs. 1a-c, pl. 20, figs. 4-7.

Hypotypes:- Figure 29, nos. 14a-c, 15a-c, NFL9527, sample KK-117, Saigo Group, Shizuoka Prefecture, early middle Miocene.

Test size:- Test width 0.09-0.12 mm, test length 0.15-0.17 mm, test thickness 0.08-0.11 mm, sample KK-117.

Occurrence:- Honsubetsu Formation (HON-31), Saigo Formation (KK-117), Sagara Group (KK-17, -18), Nanatani Formation (NG-27).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in southern Honshu; Pleistocene and Recent form found in southern Honshu and Kyushu.

Remarks:- This species is characterized by a small elongate test with curved early portion. Most forms collected from the Miocene have more than four pairs of chamber. Their shapes are in the range of No. 1 to No. 9 of Nomura's ontogenetic scheme (Nomura, 1983b, p. 47, fig. 40).

Test shape of No. 1 to No. 6 is also similar to younger forms of *Cassidulina howei* Cushman, but *E. kuwanoi* has more compressed test, compared with *C. howei.* Nevertheless, they can be assigned to the same phylogeny.

Genus *Cassidulina* d'Orbigny, 1826

Cassidulina d'Orbigny, 1826, p. 282.

Entrochus Ehrenberg, 1843, p. 408 (type, *Entrochus septatus* Ehrenberg, 1843).

Selenostomum Ehrenberg, 1858, p. 12 (*fide* Loeblich and Tappan, 1987, p. 504).

Lernina Saidova, 1975 (type, *Lernina micae* Saidova, 1975, p. 325).

Type species:- *Cassidulina laevigata* d'Orbigny, 1826, p. 282, pl. 15, figs. 4, 5.

Remarks:- The genus *Cassidulina* appeared from the cassidulinid III Zone in Japanese Miocene strata. The apertural plate of this genus is derived from the cristate tooth of *Globocassidulina,* suggesting that the ancestral form of *Cassidulina* is found in some species of *Globocassidulina.*

Cassidulina carinata Silvestri, 1896

Cassidulina laevigata d'Orbigny var. *carinata* Silvestri, 1896, p. 104, pl. 2, figs. 10a-c.

Cassidulina cf. *sicula* Seguenza. Parker, 1958, p. 272, pl. 4, figs. 16, 17.

Cassidulina carinata Silvestri. Nomura, 1983b, p. 51, pl. 4, figs. 9a, b, 10a, b, 11, pl. 3, fig. 5, pl. 4, fig. 5, pl. 23, figs. 6-9; Hasegawa et al., 1990, p. 477, pl. 4, figs. 1, 2; Akimoto, 1990, p. 194, pl. 17, fig. 3; Kaiho, 1992b, pl. 3, figs. 4a, b; Loeblich and Tappan, 1994, p. 114, pl. 220, figs. 7-12.

Cassidulina cf. *C. neocarinata* Thalmann. Xu and Ujiié, 1994, fig. 8, nos. 2, 3.

Cassidulina teretis Tappan. Ujiié, 1995, p. 61, pl. 5, figs. 9a, b (part).

Not *Islandiella carinata* (Silvestri). Finger, 1990, p. 140, pl.-figs. 1-8.

For further synonymy, see Nomura (1983b).

Test size:- Maximum test diameter 0.16-0.25 mm, test thickness 0.10-0.12 mm, sample KK-16.

Occurrence:- Anno Formation (AN-74), Sagara Group (KK-16,18,19).

Stratigraphic and paleogeographic distribution:- Pliocene sequence of southern Honshu; Pleistocene and Recent form is common in the Pacific Ocean.

Remarks:- *Cassidulina carinata* is characterized by its disc-shaped test with keel and curved elongate chamber. The aperture of this species is filled by a thin apertural plate, showing an arch-shaped narrow opening somewhat oblique to the base of apertural face. The specimens figured by Parker (1958) are deposited in the U. S. National Museum, in which I found two specimens (USNM coll. 377188 and 377189) named as *C.* cf. *sicula* by her. They have *carinata*-type aperture as mentioned above and chamber arrangement. Her specimens should be identified as C. *carinata.*

Recently, Finger (1990) noted that a California specimen had walls of optically radial texture and described it under the genus *Islandiella.* However, the figured aperture of his specimen does not show the apertural plate of *carinata,* but the cristate tooth. The aperture of this type is included in the I-type aperture of this paper and it is common in the genus *Islandiella.* I believe his specimen can not be put in the range of *carinata*'s variations and should be identified to some other species of *Islandiella. Cassidulina carinata* differs from Arctic and boreal species of *C. teretis* and *C. neoteretis,* in having smaller umbilical boss area (Seidenkrantz, 1995).

This species is common in late Miocene to Recent sediments in southern Japan.

Cassidulina reniforme Nϕrvang, 1945

Figures 18-18a-c, -19a-c, 30-3

Cassidulina crassa d'Orbigny var. *reniforme* Nϕrvang, 1945, p. 41, text-figs. 6e-h.

Cassidulina islandica Nϕrvang var. *norvangi* Thalmann, 1952, p. 83, footnote 1.

Cassidulina barbara Buzas, 1965, p. 25, pl. 25, fig. 2a, b, 3; Smith, 1978, p. 156, pl. 6, figs. 4, 5.

Cassidulina reniforme Nϕrvang. Sejrup, and Guilbault, 1980, p. 79, figs. 2F-K; Rodrigues, Hooper and Jones, 1980, p. 58, pl. 2, figs. 2, 4, 6, pl. 3, figs. 3, 6, 9, 11, 12, pl. 5, figs. 10-12; Sejrup et al., 1981, p. 290, pl. 1, fig. 7; Feyling-Hanssen et al., 1983, p. 105, pl. 1, fig. 10; Feyling-Hanssen and Ulleberg, 1984, p. 99, pl. 2, figs. 15, 16; Sejrup et al., 1987, fig. 12E; Feyling-Hanssen, 1990, pl. 1, figs. 2-4; Thomas, et al., 1990, p. 227, pl. 10, fig. 10; Seidenkrantz, 1993, fig. 5-18.

Globocassidulina subglobosa (Brady). Ujiié et al., 1977, pl. 7, figs. 3a, b.

Cassidulina norvangi Thalmann. Nomura, 1983b, pl. 4, figs. 12a-c, 13, pl. 23, figs. 10-12, pl. 24, figs. 1-3; Oki, 1989, 143, pl. 19, figs. 1a-f; Ujiié, 1990, p. 38, pl. 18, figs. 4a, b, 5a, b.

Islandiella norvangi (Thalmann). Ujiié et al., 1983, p. 61, pl. 9, figs. 3-6; Inoue, 1989, pl. 23, figs. 10a, b, pl. 32, figs. 14a, b.

For further synonymy, see Nomura (1983b).

Hypotypes:- Figure 18, nos. 18a-c, 19a-c, NFL9528, FUNA-11, Funakawa Formation, Akita Prefecture, late Miocene.

Test size:- Maximum test diameter 0.14 to 0.48 mm, test thickness 0.09 to 0.16 mm, sample FUNA-11.

Occurrence:- Anno Formation (AN-67), Funakawa Formation (FUNA-11).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pliocene to Recent form found in northern Pacific Ocean and the Sea of Japan.

Remarks:- Nomura (1983b) identified this species as *Cassidulina norvangi,* following the previous worker's results given in the synonym list. Pointing out the presence of an apertural plate and its small test size, however, some workers such as Sejrup and Guilbault (1980) and Rodrigues et al. (1980) discussed the previous confusion of this species in which it has been identified as one of the following four taxa as *C. crassa, C. obtusa, C. reniforme,* and *C. norvangi.* I agree with the conclusions of Sejrup and Guilbault (1980) and Rodrigues et al. (1980), who identified the present form as *C. reniforme.* Thus this species differs from *C. crassa* in having a more smaller and compressed test, from *C. obtusa* in having the apertural plate instead of a tripartite aperture and undepressed sutures (Figure 30-3). In relation to this apertural structure, the photographic specimens of Schröder-Adams et al. (1990, pl. 7, figs. 9, 10) do not show the apertural plate. They can not be identified with *Cassidulina reniforme.*

Cassidulina norvangi, which was designated as a new name of *C. islandica* var. *minuta* by Thalmann (1952), is an original synonym of *C. reniforme* at the time the two species were recognized.

This species is very common from the late Miocene to the present. It is associated with islandiellids and planocassidulinids in northern seas of Japan. However, Ujiié (1990) reported this species from piston core samples off Miyakojima Island, the Ryukyu Islands.

Genus ***Paracassidulina*** Nomura, 1983

Paracassidulina Nomura, 1983a, p. 94

Type species:- *Cassidulina orientale* Cushman, 1925a, p. 37, pl. 7, figs. 6a-c (original designation); *Globocassidulina nipponensis* Eade, 1969, p. 65, pl. 13, figs. 1-4 (secondary designation).

Remarks:- The slit shaped aperture of this genus shows little variation and is a stable character for the systematic of the Cassidulinidae.

Paracassidulina neocarinata (Thalmann, 1950)

Figures 16-13a-c, 30-5

Cassidulina laevigata d'Orbigny var. *carinata* Cushman, 1922, p. 124, pl. 25, figs. 6, 7.

Cassidulina neocarinata Thalmann, 1950, p. 44; Kohl, 1985, p. 86, pl. 30, figs. 1a-c.

Paracassidulina neocarinata (Thalmann). Nomura, 1983b, p. 63, pl. 5, figs. 11a, b; Ujiié et al., 1983, p. 60, pl. 8, figs. 4, 5; Akimoto, 1990, p.206, pl. 17, fig. 4; Loeblich and Tappan, 1994, p. 116, pl. 227, figs. 12-15 (part); Ujiié, 1995, p. 62, pl. 6, figs. 1, b.

Cassidulina carinata Silvestri. Inoue, 1989, pl. 22, figs. 3a, b.

For further synonymy, see Nomura (1983b).

Hypotype:- Figure 16, nos. 13a-c, NFL9530, sample KK-15, Sagara Formation, Shizuoka Prefecture.

Test Size:- Maximum diameter 0.16-0.22 mm, test thickness 0.09-0.12 mm, sample KK-15.

Occurrence:- Saigo Formation (KK-117), Sagara Formation (KK-15, -17, -19, -20), Nanatani Formation (NG-27).

Stratigraphic and paleogeographic distribution:- Pliocene sequence in southern Honshu; Pleistocene to Recent form found in southern Honshu, Okinawa, and southern Pacific Ocean.

Remarks:- Cushman's hypotype (USNM 16375) is deposited in the U. S. National Museum. I confirm the specimen has a slit-shaped aperture, following the peripheral curve of the preceding apertural face and associated with very thin transparent apertural ridge in the specimen (Figure 30-5). Details of the aperture are described in Nomura (1983b).

This species is very common from the Pliocene onward, but Miocene specimens occurring in the Nanatani Formation (NG-27) are characterized by a small-sized test and less developed peripheral keel.

Paracassidulina izuensis (Aoki, 1967)

Figures 16-10a-c, 30-8

Cassidulina orientale Cushman. Asano and Nakamura, 1937, p. 147, pl. 14, figs. 6a, b.

Cassidulina izuensis Aoki, 1967, p. 381, pl. 1, figs. 16-18.

Paracassidulina nipponensis (Eade). Nomura, 1983a, p. 95, pl. 25, fig. 3, 1983b, pl. 6, figs. 13a, b, 14a-c; Hasegawa and Nomura, 1995, p. 96, figs. 3-4a-c.

Cassidulina sp. B. Kaiho, 1992b, pl. 3, figs. 6a, b.

Hypotype:- Figure 16, nos. 10a-c, NFL9531, sample ISW-19, Hatatate Formation, Miyagi Prefecture, middle middle Miocene.

Test Size:- Test width 0.21-0.23 mm, test length 0.28-0.30 mm, test thickness 0.08-0.09, sample ISW-19.

Occurrence:- Hatatate Formation (HTTO-7, ISW-19), Tomesaki Formation (IW-1), Nanatani Formation (NG-18), Niwaya Formation (TM-186), Haratajino Formation (TM-205), Idosawa Formation (TM-34, -39).

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone of Honshu; Pleistocene form found in pacific borderland of Honshu.

Remarks:- Without an examination of *Paracassidulina izuensis*, Nomura (1983a) described *Paracassidulina nipponensis* based on the topotype material from the Pleistocene Miyata Formation, Miura Peninsula, where Asano and Nakamura (1937) first reported this species. Hasegawa and Nomura (1995) also examined the hypotype of Asano and Nakamura (1937) deposited in Tohoku University. Based on these studies, Japanese *nipponensis* has been recognized as having an elongate test with a narrow slit aperture as suggested by Eade (1967). Nomura (1983a) described that the sutures are flush with surface as another diagnostic character of this species (Figure 30-8). Thus, four allied species such as *P. miuraensis, P. nabetaensis, P. oshimai,* and *P. izuensis* have been distinguished from *P. nipponensis,* mainly based on the presence or absence of sutural grooves and test size.

Paracassidulina izuensis was described by Aoki (1967) from the Nabeta cove of the Izu Peninsula, though the sutural character was not fully mentioned, only referred to the very slightly depressed sutures. I examined the holotype, which was a personal collection of the late Prof. N. Aoki, Tsukuba University. It shows flushed sutures and short downward apertural grooves. Such features are equal to the diagnoses of *Paracassidulina nipponensis* as described in Nomura (1983a). Thus the form reported by Nomura (1983a) and Hasegawa and Nomura (1995) should be a junior synonym of *P. izuensis.*

In order to compare the above mentioned species with the type species of this genus, furthermore, I have examined the holotype of Cushman's *orientale* (=*P. nipponensis*) deposited in the U. S. National Museum (USNM 20279). Cushman's holotype is well preserved and it shows clearly sutural grooves and furrows on the apertural face. The chambers are not inflated and their shapes are similar to those of *P. miuraensis.* I also compared *P. nabetaensis* with the holotype of *P. oshimai.* Although sutural grooves and apertural furrows were not noted by Aoki (1967) in the original description of *P. oshimai,* the holotype of *oshimai* has these characters. In addition, the chamber inflation of *oshimai* is not as distinct as in *P. nabetaensis,* but their characters can not be distinguished from Cushman's *orientale.* Based on the examination of these holotypes, I confirmed that *P. nipponensis* (Cushman's *orientale*) is a senior synonym of *P. oshimai.* From *P. nabetaensis,* it seems that *P. nipponensis* is slightly different in having inflated chambers. However, the inflated nature of the chambers and test thickness may not be distinct characters. These characters may represent a variation of *P. nipponensis.* These closely allied species are herein treated as a synonym of *P. nipponensis* (Cushman's *orientale*).

The species *nipponensis* was designated by Eade (1967), as a new name for *Cassidulina orientale* (Cushman, 1925), because Cushman's *orientale* and *orientalis* represent a different shape of aperture and test morphology. Loeblich and Tappan (1985) redescribed Cushman's *Cassidulina orientalis* from off Poor Knights Islands, east of New Zealand, and redefined it as a syntype of the genus *Evolvocassidulina.*

Paracassidulina cf. *miuraensis* (Higuchi, 1954)

Figures 16-8a-c, -9a-c, 30-6, -7, 31

Cf. *Cassidulina miuraensis* Higuchi, 1954, p. 58, text-figs. 1a, b, 2a, b.

Cf. *Paracassidulina miuraensis* (Higuchi). Nomura, 1983a, pl. 5, fig. 3, pl. 25, figs. 4-6; 1983b, p. 70, pl. 6, figs. 7a, b, 8, 9, 10; Akimoto, 1990, p. 206, pl. 15, fig. 4.

Cf. *Paracassidulina nipponensis* (Eade). Akimoto, 1990, p. 206, pl. 19, figs. 2a, b.

Hypotypes:- Figure 16, nos. 8a-c, 9a-c, NFL9532, sample NANA, Nanao Limestone, Noto Peninsula, Ishikawa Prefecture, early middle Miocene.

Test size:- Test width 0.23-0.32 mm, test length 0.30-0.44 mm, test thickness 0.13-0.17 mm, sample NANA.

Occurrence:- Hatatate Formation (HTTO-7, ISW-16), Tomesaki Formation (IW-1), Shitazaki Formation (IW-12), Mizunami Group (MIZU), Nakanami Formation (NAKA), Nanao Limestone (NANA), Higashi-innai Formation (NOTO-3, -8, -10, -15, -16), Hojuji Formation (NOTO-27), Sekinohana Limestone (SEKI), Niwaya Formation (TM-11), Haratajino Formation (TM- 4, -153, -159, -186), Idosawa Formation (TM-34, -39).

Stratigraphic and paleogeographic distribution:- Cassidulinid I to III Zones in Honshu.

Remarks:- The Miocene form is comparable to the Pleistocene *miuraensis* except for the test thickness. Its thickness is about twice that of the topotype specimens of *P. miuraensis*. However, other systematic characters such as a slit-shaped aperture without apertural grooves and U-shaped sutural grooves, as well as an uncoiled nature of chamber arrangement, are the same as those of *miuraensis* (Figures 30-6 -7, 31). This form is apparently similar to *P. nipponensis* in having the grooved sutures and non-inflated chambers as remarked in *P. izuensis*. However, apertural furrows are not developed in this species.

This species is common in the cassidulinid I and II Zones of early middle Miocene.

Paracassidulina quasicarinata Nomura, 1983

Figures 16-11a-c, -12a-c

Paracassidulina quasicarinata Nomura, 1983a, p. 100, pl. 2, figs. 19a-c, pl. 25, figs. 9, 10, 11; Oki, 1989, p. 145, pl. 19, figs. 5a-f; Akimoto, 1990, p. 206, pl. 19, figs. 5a, b.

Paracassidulina neocarinata (Thalmann), Loeblich and Tappan, 1994, p. 116, pl. 227, figs. 1-11 (part).

Hypotypes:- Figure 16, nos. 11a-c, 12a-c, NFL9533, sample TM-186, Niwaya Formation, Gunma Prefecture, early middle Miocene.

Test size:- Test width 0.22–0.36 mm, test length 0.24–0.40 mm, test thickness 0.19–0.21 mm, sample TM-186.

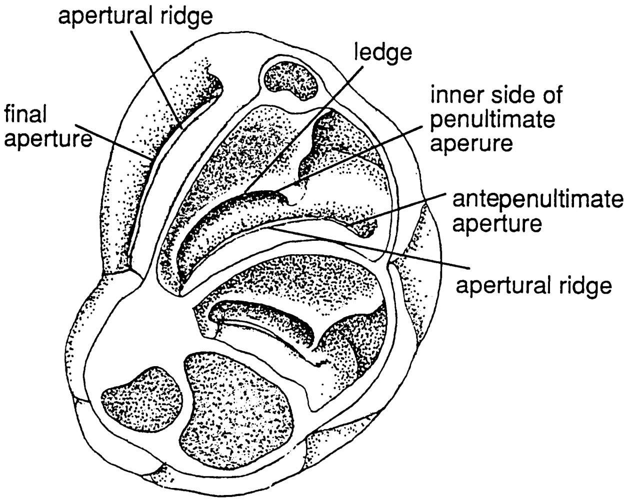

Figure 31. Internal structure of *Paracassidulina cf. miuraensis.*

Occurrence:- Niwaya Formation (TM-11, -186).

Stratigraphic and paleogeographic distribution:- Cassidulinid II Zone in southern Honshu.

Remarks:- This species is characterized by a slit aperture at the base of apertural face and the down-ward grooves from the anterior part of aperture. This species is also characterized by the tangentially arranged chambers, which is similar to that of *P. neocarinata.*

This species was described from the Pleistocene Nojima Formation of Miura Peninsula. The Miocene form from the Tomioka Group, Gunma Prefecture, has a thicker test with angled periphery and has somewhat less developed apertural grooves compared with the Pleistocene form.

Paracassidulina stabilis Nomura sp. nov.

Figures 29-13a-c, 30-4

Cassidulina minuta Cushman. Smith, 1964, p. B39, pl. 3, fig. 8; Alavi, 1988, pl. 2, fig. 11; Boltovskoy et al., 1992, p. 195, pl. 1, figs. 29, 30; Boltovskoy and Ocampo, 1993, pl. 2, fig. 8.

Paracassidulina minuta (Cushman). Nomura, 1983b, p. 66, pl. 5, figs. 16a-c; Oki, 1989, p. 114, pl. 19, figs. 4a-c; Hasegawa et al., 1990, p. 477, pl. 4, fig. 9.

Not *Cassidulina minuta* Cushman. Haller, 1980, p. 260, pl. 12, figs. 6a-c.

Not *Paracassidulina minuta* (Cushman). Loeblich and Tappan, 1994, p. 116, pl. q223, figs. 7, 8.

Diagnosis:- Small compressed test with interiomarginal slit aperture; sutures flush with surface.

Description:- "Test small, nearly circular or very slightly longer than broad in side view, compressed oval in edge view; periphery narrowly rounded, very slightly lobulate; chambers distinct, broadly rhomboid, slightly inflated, four pairs making up last-formed whorl; sutures distinct; aperture interiomarginal, an elongate narrow slit at the base of last apertural face; wall thin, polished, very finely perforated, translucent." (Nomura, 1983b)

Optical structure:- Wall jagged-granular texture.

Apertural structure:- The aperture is an interiomarginal slit; anterior portion of the aperture attached to the previously formed chamber and the posterior portion attached to the preceding chamber (Figure 30-4).

Holotype:- IGPS (Institute of Geology and Paleontology, Tohoku University, Sendai) 97402, sample NO-2, Nobori Formation, Kochi Prefecture, Pliocene; hypotype, Figure 29, nos. 13a-c, NFL9529, sample NOTO-15, Higashi-innai Formation, Noto Peninsula, Ishikawa Prefecture, early middle Miocene.

Test size:- Maximum test diameter 0.09, test thickness 0.15 to 0.17 mm, sample NOTO-15.

Occurrence:- Bihoku Group (SHO-21, FU-5, -8, SB-6), Higashibessho Formation (H-7A), Sagara Group (KK-16, -17, -18, -19), Nanatani Formation (NG-2, -9, -19, -27), Higashi-innai Formation NOTO-3, -8, -15), Hara-

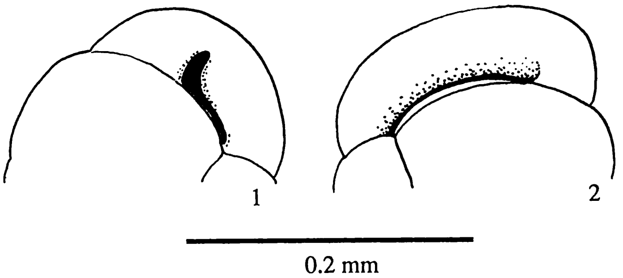

Figure 32. Different designation of *Globocassidulina minuta* (Cushman). 1. Holotype of *Cassidulina minuta* Cushman showing the aperture consisting of basal slit and its areal branch [USNM 26156]. 2. One paratype of this species showing only basal slit of aperture (paracassidulinid aperture) [USNM 25356].

tajino Formation (TM-9).

Stratigraphic and paleogeographic distribution:- Cassidulinid I Zone in southern Honshu; Pliocene to Pleistocene form found in Okinawa and southern Shikoku.

Remarks:- This species has been described as *Paracassidulina minuta* by Nomura (1983b), based on *Cassidulina minuta* Cushman. In the original description of *C. minuta,* details on the apertural structure have been limited, except for the description of an elongate aperture. I have examined the holotype (USNM 26157, 26156 in original description) and paratype (USNM 25356) and found that the aperture of the holotype is not a slit, like that of *Paracassidulina,* but tripartite, consisting of a short areal opening (Figure 32; see also Eade, 1967, fig. 5-2, 3; Loeblich and Tappan, 1994). In the paratype slide, however, three different specimens are included. One is a small test with a slit shaped aperture that is situated at the base of apertural face. This specimen should be assigned to the genus *Paracassidulina.* The other two specimens are juvenile, one of which has a more small globular test with an oblique apertural slit extending to the base of the apertural face. Thus, the holotype and two juveniles included as paratypes are assigned to the genus *Globocassidulina.*

For the forms having a small compressed test and an interiomarginal slit aperture at the base of apertural face, I herein redefine Nomura's *Paracassidulina minuta* to distinguish from Cushman's *Cassidulina minuta,* and described it as new species.

Miocene forms are more compressed and small, compared with Pliocene to Recent forms, but otherwise characters are the same, as given by Nomura (1983b).

The species name is referred to the Latin *stabilis,* meaning stable, with reference to conservative characters of the test.

Genus *Cassidulinoides* Cushman, 1927

Cassidulinoides Cushman, 1927b, p. 84.

Type species:- *Cassidulina parkeriana* Brady, 1881, p. 59; Brady, 1884, p. 432, pl. 54, figs. 11-16.

Remarks:- Miocene forms in this study are: *Cassidulinoides akitaensis* and *C. porrectus,* which occurred from the cassidulinid III Zone of the late Miocene.

Cassidulinoides akitaensis Nomura sp. nov.

Figures 33-3a-c, -4a-c, -5a-c, 34, 36-7, -8, -9

Cassidulinoides cf. *C. bradyi* (Norman). Crouch, 1952, p. 841, pl. 6, figs. 15, 16.

Diagnosis:- Curved-test with subterminal slit aperture; sutures cross at high angle to the uncoiled growth axis.

Description:-Test slender, arch-shaped, particularly in earlier portion, but tending to be rectilinear in later portion, slightly compressed in edge view; periphery rounded, not lobulate; chambers distinct, not inflated, four to five pairs in mature stages, biserially arranged throughout; sutures distinct, somewhat limbate and curved, flush with surface, cross to the axis of growth at a high angle in mature stages; aperture slit-shaped, extending to the top of apertural face, almost parallel to the axis of growth, with a small thin cristate tooth; wall translucent, polished with fine pores.

Optical structure:- Wall distinctly radial texture.

Apertural structure:- Aperture with the serrated cristate tooth on one side and serrated lip on the other side; copula without the primary tongue attached to the upper part of the previous anterior apertural face (Figures 34, 36-7, -9). Aperture in younger stages is oval opening with indistinct cristate tooth and lip.

Holotype:- Figure 33, nos. 3a-c, NFL9540, sample FUNA-11, late Miocene, Funakawa Formation, Akita Prefecture; paratypes and hypotypes, Figure 33, nos. 4a-c, 5a-c, NFL9541.

Test size:- Holotype, test length 0.44 mm, test thickness 0.16 mm, sample FUNA-11; paratype, test length 0.22-0.44 mm, test thickness 0.12-0.16 mm, sample FUNA-11.

Occurrence:- Funakawa Formation (FUNA-11).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu.

Remarks:- This new species resembles the modern Antarctic *Ehrenbergina parva* Earland, which was redescribed as *Cassidulinoides parvus* by Nomura (1984), in having a small rectilinear test. However, *C. akitaensis* differs from it by having more loosely coiled early po-

Figure 33. **1a-c, 2a-c.** *Planocassidulina helenae* (Feyling-Hanssen and Buzas), FUNA-11. **3a-c, 4a-c, 5a-c.** *Cassidulinoides akitaensis* Nomura, n. sp., FUNA-11. **6a-c, 7a-c, 8a-c, 9a-c, 10a-c.** *Cassidulinoides porrectus* Heron-Allen and Earland, IW-10. **11a-c, 12a-c.** *Planocassidulina* sp. A, WAK-69/71. Scale bar=0.5 mm.

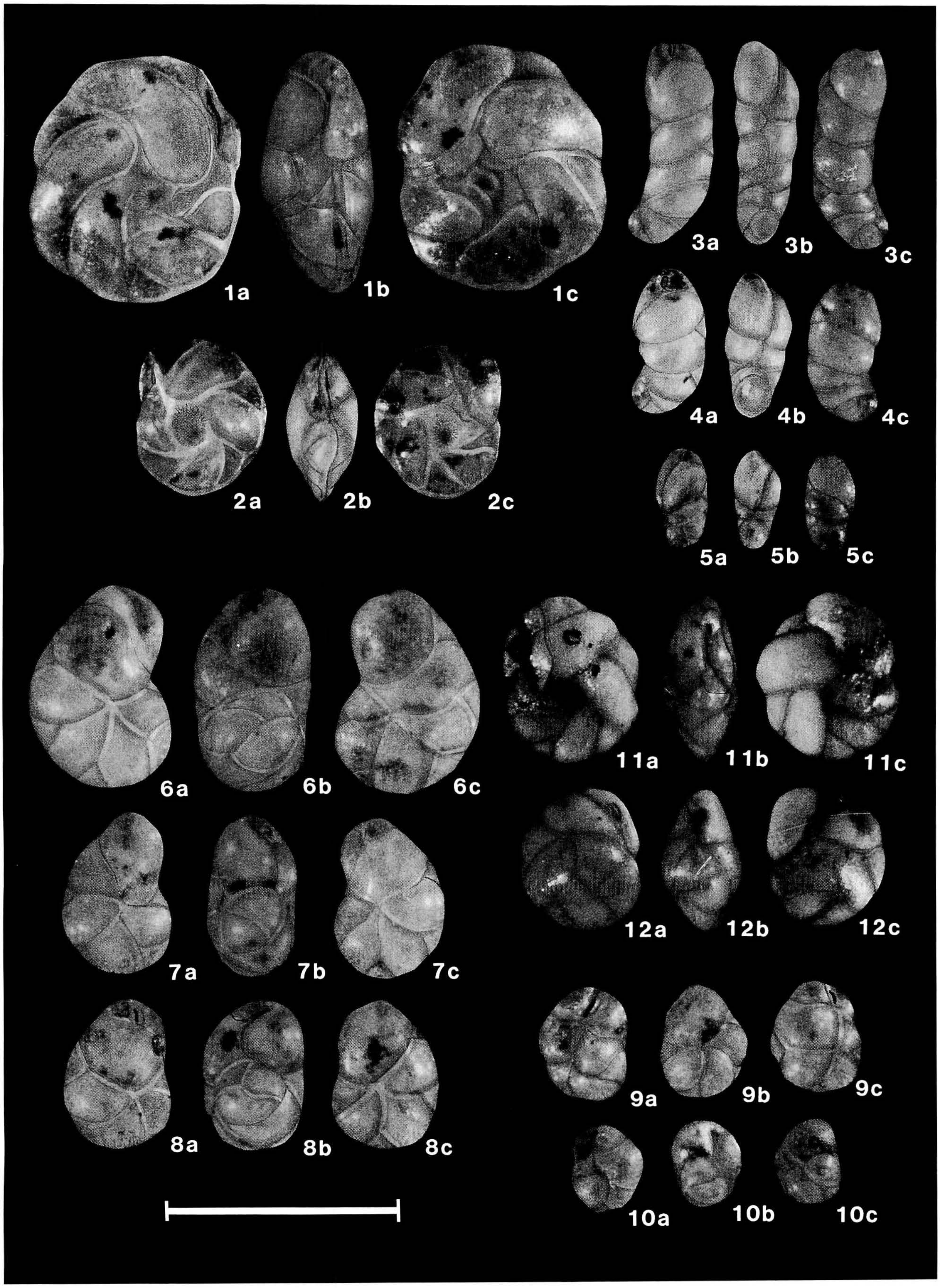
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Figure 33.

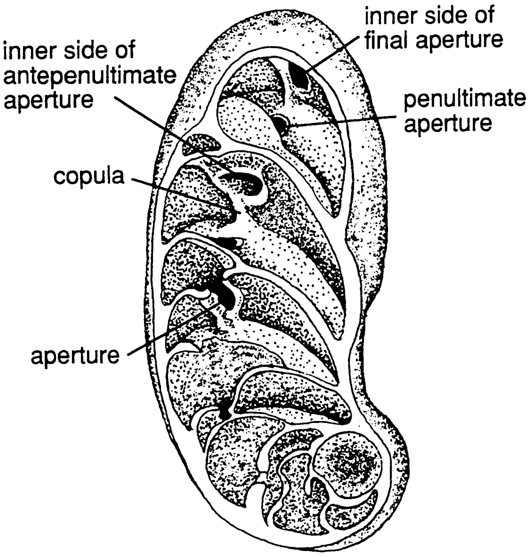

Figure 34. Internal structure of *Cassidulinoides akitaensis*, n. sp.

tion, where the proloculus can be seen. The chambers of *C. akitaensis* is less inflated than those of *C. parvus*. *Cassidulinoides akitaensis* has more oblique sutures, compared with those of *C. parvus*. However, both species are in close phylogenetic relationship.

Cassidulinoides akitaensis resembles *C. subcylindricus* Nomura from Pleistocene deposits of the Sea of Japan borderland, in having a comma-shaped test in the earlier growth stages and a simple apertural structure. Both species devoid of an internal free part of the primary tongue. Thus, *C. akitaensis* should be an ancestor of *C. subcylindricus*. In this case, the evolutionary trend from *C. akitaensis* to *C. subcylindricus* can be recognized as reducing the rectilinear growth.

This new species is morphologically similar to *Evolvocassidulina kuwanoi*, but it differs from *E. kuwanoi* in having the radial texture and the larger test.

Cassidulinoides porrectus

(Heron-Allen and Earland, 1932)

Figures 33–6a-c, -7a-c, -8a-c, -9a-c, -10a-c, 35, 36–10, -11, -12

Cassidulina crassa d'Orbigny var. *porrecta* Heron-Allen and Earland, 1932, p. 358, pl. 9, figs. 34–37.

Cassidulinoides porrectus (Heron-Allen and Earland). Parr, 1950, p. 344, pl. 12, fig. 26; Fillon, 1974, p. 139, pl. 4, figs. 1–3; Saidova, 1975, pl. 89, figs. 8, 9; Nomura, 1984, p. 495, pl. 90, figs. 4a, b,-7, pl. 92, figs. 6–9; Ward and Webb, 1986, p. 190, pl. 8, figs. 3, 7–10, pl. 11, figs. 1, 2, pl. 12, figs. 1, 3; Ishman and Webb, 1988, p. 534, pl. 6, fig. 16.

Cassidulina crassa porrecta Heron-Allen and Earland. McKnight, 1962, p. 126, pl. 21, fig. 139.

Cassidulinoides porrecta (Parr). Osterman and Kellog, 1979, p. 264, pl. 2, figs. 8, 9.

Cassidulinoides porrecta (Heron-Allen and Earland). Milam and Anderson, 1981, pl. 6, fig. 6.

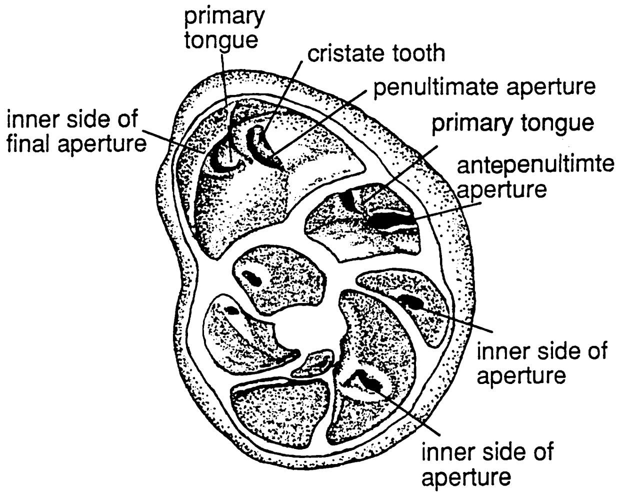

Figure 35. Internal structure of *Cassidulinoides porrectus*.

Hypotypes:- Figure 33, nos. 6a-c, 7a-c, 8a-c, 9a-c, 10a-c, NFL9542, sample IW-10, Shitazaki Formation, late Miocene, Iwate Prefecture.

Test size:- Test length 0.20–0.45 mm, test thickness 0.17–0.26 mm, sample IW-10.

Occurrence:- Atsuta Formation (AT-6, -10), Shitazaki Formation (IW-10, -12).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu and southern Hokkaido; Recent form found in the Antarctic seas.

Remarks:- This species was originally described from Recent sediments of Antarctic sea and has been reported only from the Antarctic area. This species is characterized by having a different test shape for different growth stages, such as the adult stage showing a pyriform test with the uncoiled later pair of chambers and immature stage showing the globular test. The small primary tongue that adhered to the copula developed on the preceding apertural face in mature specimens (Figures 35, 36-11-12). Nomura (1984) confirmed such an ontogenetic change in this species based on Recent Antarctic specimens. No significant morphological differences are observed between Japanese Miocene species and Recent Antarctic species, including the internal structure, except for the slightly inflated chambers of Antarctic specimens.

Fossil *Cassidulinoides porrectus* was first recognized from the late Miocene Shitazaki Formation of Northeast Honshu and the Atsunai Formation, Hokkaido. It accounts for maximum 36% of the cassidulinid assemblage in the Shitazaki Formation. Previously obtained biogeographic information suggests this species is limited in the Antarctic region. No sufficient data have been obtained to construct the time and spatial distribution of this species.

Genus *Islandiella* Nϕrvang, 1959

Islandiella Nϕrvang, 1959, p. 26.
Cassilamellina Voloshinova, 1960, p. 59 (type, *Cassidulina californica* Cushman and Hughes, 1925).

Type species:- *Cassidulina islandica* Nϕrvang, 1945, v. 2, pt. 2, p. 4 1, text-figs, 7, 8d-f. (original designation); *Islandiella islandica* (Nϕrvang), Nϕrvang, 1959, (subsequent designation); *Cassidulina algida* Cushman, 1944, p. 35, pl. 4, figs. 24a-c (secondary designation; Miller et al., 1996).

Remarks:- I have previously discussed the genus *Planocassidulina* Gudina, 1966, with the type species *C. norcrossi* Cushman, 1925, to be in synonymous with *Islandiella*, by noting the similar apertural and wall characters to those of *Islandiella*. However, the compressed and keeled periphery of the test should be a consistent character for the islandiellid/planocassidulinid systematics. A globular test (neanic stage) of lenticular forms in an immature stage has been overestimated to put both lenticular and globular forms in the synonymy of *Islandiella*. Thus, the genus *Planocassidulina* is removed from the synonymy of *Islandiella* in this study.

Islandiella algida (Cushman, 1944)

Figures 37-4a-c, -5a, b

Cassidulina algida Cushman, 1944, p. 35, pl. 4, figs. 24a-c.
Cassidulina islandica Nϕrvang, 1945, v. 2, pt. 2, p. 4 1, text-figs, 7, 8d-f.
Islandiella islandica (Nϕrvang). Ujiié et al., 1983, p. 61, pl. 8, figs. 18, 19 (part); Feyling-Hanssen et al., 1983, p. 15, pl. 1, figs. 17-19. Feyling-Hanssen and Ulleberg, 1984, p. 100, pl. 3, figs. 1, 2; Feyling-Hanssen, 1990, pl. 1, figs. 15-17.; Seidenkrantz, 1992, pl. 1, fig. 3.
Islandiella subglobosa (Brady). Ujiié et al., 1983, p. 61, pl. 9, figs. 7, 8
Islandiella algida (Cushman). Miller et al., 1996, p. 209, pl. 1, figs. 2a-c, 4, 5.
For further synonymy, see Miller et al. (1996)

Hypotypes:- Figure 37, nos. 4a-c, 5a, b, NFL9543, sample FUNA-11, Funakawa Formation, Akita Prefecture, late Miocene.

Test size:- Maximum test diameter 0.22-0.30 mm, test thickness 0.16-0.21 mm, sample FUNA-11.

Occurrence:- Funakawa Formation (FUNA-11).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pliocene to Recent form in the northern Pacific Ocean and the Sea of Japan.

Remarks:- This species was originally reported by Cushman (1944) from Recent sediments of Casco Bay, Maine. After Cushman's proposal, this species has not been examined for its systematic characters. In addition to the insufficient original description, the references of this species are also limited until now. However, recently Miller et al. (1996) pointed out the synonymy between *Islandiella islandica* and *I. algida*, based on the examination of the holotype and paratypes deposited in the U. S. National Museum.

Although Cushman proposed this species, it seems that he confused himself about the variation of this species in his later works. The specimen identified by Cushman (1948b) as *Cassidulina islandica* shows an inflated chambers and an oblique elongate-oval aperture. Its feature is put in the range of *I. algida*.

This species is characterized by four sets of inflated chambers, numerous pore tubules in the clear walls, as well as the elongate aperture associated with a small cristate tooth. Limbate sutures are another character of this species.

Islandiella algida occurs from the late Miocene (the cassidulinid III Zone) onward in association with common to abundant *Islandiella japonica* and planocassidulinids.

Islandiella compressa Nomura, 1983

Figures 37-9a-c

Islandiella compressa Nomura, 1983a, p. 49, pl. 1, figs. 1a-c.

Hypotype:- Figure 37, nos. 9a-c, NFL9544, sample IW-12, Shitazaki Formation, Iwate Prefecture, late Miocene.

Test size:- Test width 0.20-0.24 mm, test length 0.24-0.28 mm, test thickness 0.12-0.14 mm, sample IW-12.

Occurrence:- Shitazaki Formation (IW-10, -12).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pleistocene form found in northern Honshu and Hokkaido.

Remarks:- This species is characterized by having a compressed test with a flat umbilical area.

Islandiella compressa has been described from the Pleistocene Setana Formation, southern Hokkaido. The occurrence of this species from the late Miocene is rather rare and is usually associated with *I. japonica*. Such an occurrence of this species is recognized as an accessory species for islandiellid assemblage.

Islandiella japonica (Asano and Nakamura, 1937)

Figures 36-3, 37-1a-c, -2a, b, -3a-c

Cassidulina japonica Asano and Nakamura, 1937, p. 144, text-figs. 2a, b, pl. 13, figs. 1a-c, 2a-c.
Islandiella islandica (Nϕrvang). Ujiié et al., 1983, p. 61, pl. 9, figs. 1, 2.
Islandiella japonica (Asano and Nakamura). Hasegawa and Nomura, 1995, p. 91, figs. 1-1a-2d.
Islandiella californica (Cushman and Hughes). Ujiié et al., 1983, p. 60, pl. 8, figs. 10-15 (part).
Not *Islandiella japonica* (Asano and Nakamura). Loeblich and Tappan, 1994, p. 116, pl. 225, figs. 6-8.
For further synonymy, see Hasegawa and Nomura (1995).

Hypotypes:- Figure 37, nos. 1a-c, 2a-c, 3a-c, NFL9545, sample IW-12, Shitazaki Formation, Iwate Prefecture,

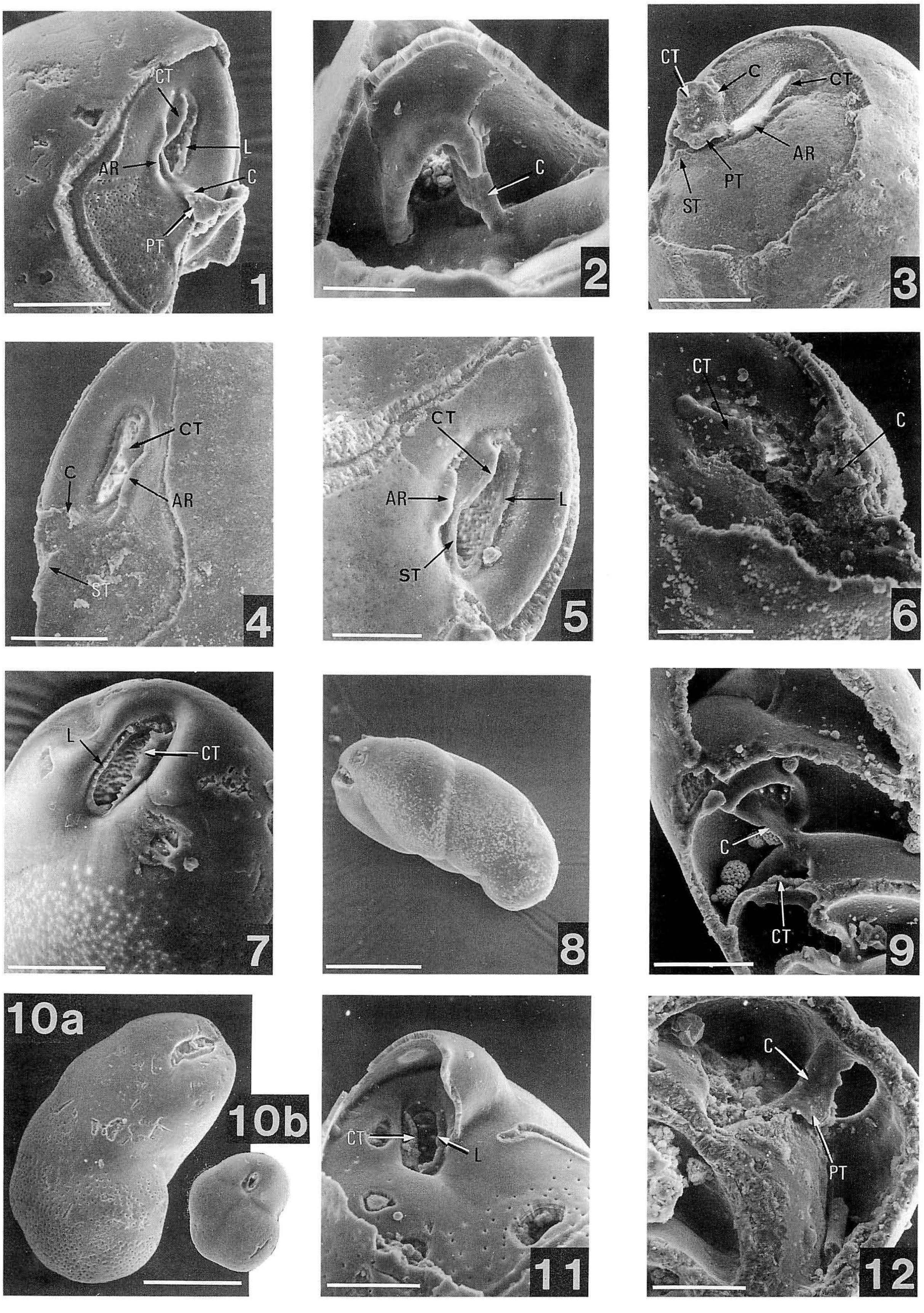
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Figure 36.

late Miocene.

Test size:- Test width 0.29–0.83 mm, test length 0.37–0.96 mm, test thickness 0.28–0.59 mm, sample IW-12.

Occurrence:- Funakawa Formation (FUNA), Shitazaki Formation (IW-12).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pleistocene and Recent form found in northern Honshu, northern Pacific Ocean and the Sea of Japan.

Remarks:- This species is one of the most common species in Pliocene and Pleistocene sediments of the Sea of Japan borderland. Systematic notes of this species have been discussed by Nomura (1983b) and Hasegawa and Nomura (1995). They pointed out the dissimilarity between the holotype and paratype of *I. japonica,* which were designated from different geographic areas and stratigraphic levels. The holotype is described from Recent sediments of Urashima Bank, the southern Sea of Japan, while the paratype is from the Pleistocene Sawane Formation of Sado Island, the Sea of Japan borderland. Examination of these type specimens suggests that the different features between the holotype and paratype are found in the mature stages. Both forms in younger stages, however, cannot be distinguished, as having four to five pairs of chamber and similar apertural construction.

In relation to the similarity of this species to *Islandiella californica* (Cushman) from the Pleistocene Lomita Marl, Los Angeles, some Japanese workers recognized *I. japonica* as the variation of *I. californica* (e.g., Ishiwada, 1950; Ujiié et al., 1983). I have examined the holotype of *I. californica* and observed that *I. japonica* has more inflated chambers and a thinner test, compared with those of *I. californica.* This feature separates *I. japonica* from *I. californica.* However, another species *Islandiella setanaensis* from the Pleistocene Setana Formation of southern Hokkaido, which is characterized by the non-inflated chambers and thick test, is similar to *I. californica.* Based on the diagnostic features of both species, *Islandiella setanaensis* should be a junior synonym of *I. californica.*

Genus ***Planocassidulina*** Gudina, 1966, emended

Planocassidulina Gudina, 1966, p. 69.

Cassandra Gudina and Saidova, 1968 (in Gudina et al., 1968), p. 226. (type, *Cassidulina inflata* Gudina, 1966; not *Cassidulina inflata* LeRoy, 1944).

Discoislandiella Saidova, 1975, p. 346. (type, *Cassidulina smechovi* Voloshinova, 1952).

Type species:- *Cassidulina norcrossi* Cushman, 1933, p. 7, pl. 2, figs. 7a-c

Emended diagnosis:- Test free, lenticular, periphery carinate to subacute; chambers elongate, biserially arranged and planispirally enrolled, with a set of triangular portion on the periphery; sutures flush with surface, limbate, radially or tangentially arranged; umbilical region with usually clear shell material and pore tubules; aperture elongate, with toothplate; wall calcareous, hyaline, finely perforate, optically radial in texture; surface commonly smooth and polished.

Occurrence:- Oligocene to Recent.

Remarks:- This genus is refined for the forms having a compressed and lens-shaped test, separating it from the genus *Islandiella* which has a globular test.

Planocassidulina helenae
(Feyling-Hanssen and Buzas, 1976)

Figures 33-1a-c, -2a-c, 36-1, -2

Islandiella helenae Feyling-Hanssen and Buzas, 1976, p. 155, text-figs. 1–4; Smith, 1978, p. 142, pl. 6, figs. 1-3; Nomura, 1983b, p. 16, pl. 2, figs. 4a-c, 5a-c, pl. 7, figs. 11, 12, pl. 8, figs. 1, 2; Feyling-Hanssen and Ulleberg, 1984, p. 99, pl. 2, figs. 17, 18; Schröder-Adams et al., 1990, p. 34, pl. 7, fig. 6 (part); Seidenkrantz, 1992, pl. 1, fig. 8.

Islandiella inflata (Gudina). Feyling-Hanssen and Ulleberg, 1984, p. 100, pl. 3, fig. 6; Feyling-Hanssen, 1990, pl. 1, figs. 8–14; Seidenkrantz, 1993, pl. 1, fig. 21

Figure 36. **1.** Penultimate aperture of *Planocassidulina helenae* showing cristate tooth (CT), lip (L) and apertural ridge (AR), and copula (C) of the final aperture is also shown on the lower side of the penultimate aperture. Note the copula without primary tongue in its attached portion to the apertural face. Scale bar=60µm. **2.** Internal view of penultimate aperture of *Planocassidulina helenae* showing column like copula (C). Scale bar=25µm. **3.** Penultimate aperture showing toothplate system consisting of cristate tooth (CT), primary tongue (PT) and copula (C) of the final aperture, and also cristate tooth (CT) and apertural ridge (AR) of penultimate aperture in *Islandiella japonica.* Final secondary tongue (ST) is also shown. Note fringe-shaped primary tongue on the anterior side of the apertural face. Scale bar=100µm. **4.** Penultimate aperture of *Planocassidulina praehelenae* showing cristate tooth (CT) and apertural ridge (AR). Small secondary tongue (ST) and attached trace of copula (C) of the final aperture shown on anterior part of the penultimate aperture. Scale bar=60µm. **5.** Earlier aperture showing externally combined feature of cristate tooth (CT), secondary tongue (ST) and lip (L) in *Planocassidulina praehelenae.* Scale bar=43µm. **6.** Penultimate aperture showing cristate tooth (CT), and the trace of copula (C) in *Planocassidulina praehelenae.* Scale bar=43µm. **7.** Final aperture of *Cassidulinoides akitaensis* showing comb-like cristate tooth (CT) and lip (L) with knobs. Scale bar=38µm. **8.** Side view of *Cassidulinoides akitaensis.* Scale bar=120µm. **9.** Internal view of *Cassidulinoides akitaensis* showing simple copula (C) without free part. The copula formed in the middle portion of the preceding apertural face. Scale bar=38µm. **10.** Side view of *Cassidulinoides porrectus* showing the different features of test shape through the ontogenetic development. (a) fully matured specimen and (b) the juvenile. Note that the immature stage of this species is apparently similar to *Globocassidulina subglobosa.* Scale bar=120µm. **11.** Penultimate aperture with cristate tooth (CT) and lip (L) in *Cassidulinoides porrectus.* The proximal side of the copula adheres not to the preceding aperture, but to the preceding apertural face. The final primary tongue of this specimen is broken. Scale bar=43µm. **12.** Internal view of the final aperture showing copula (C) and primary tongue (PT) in the proximal part of copula in *Cassidulinoides porrectus.* Scale bar=50µm.

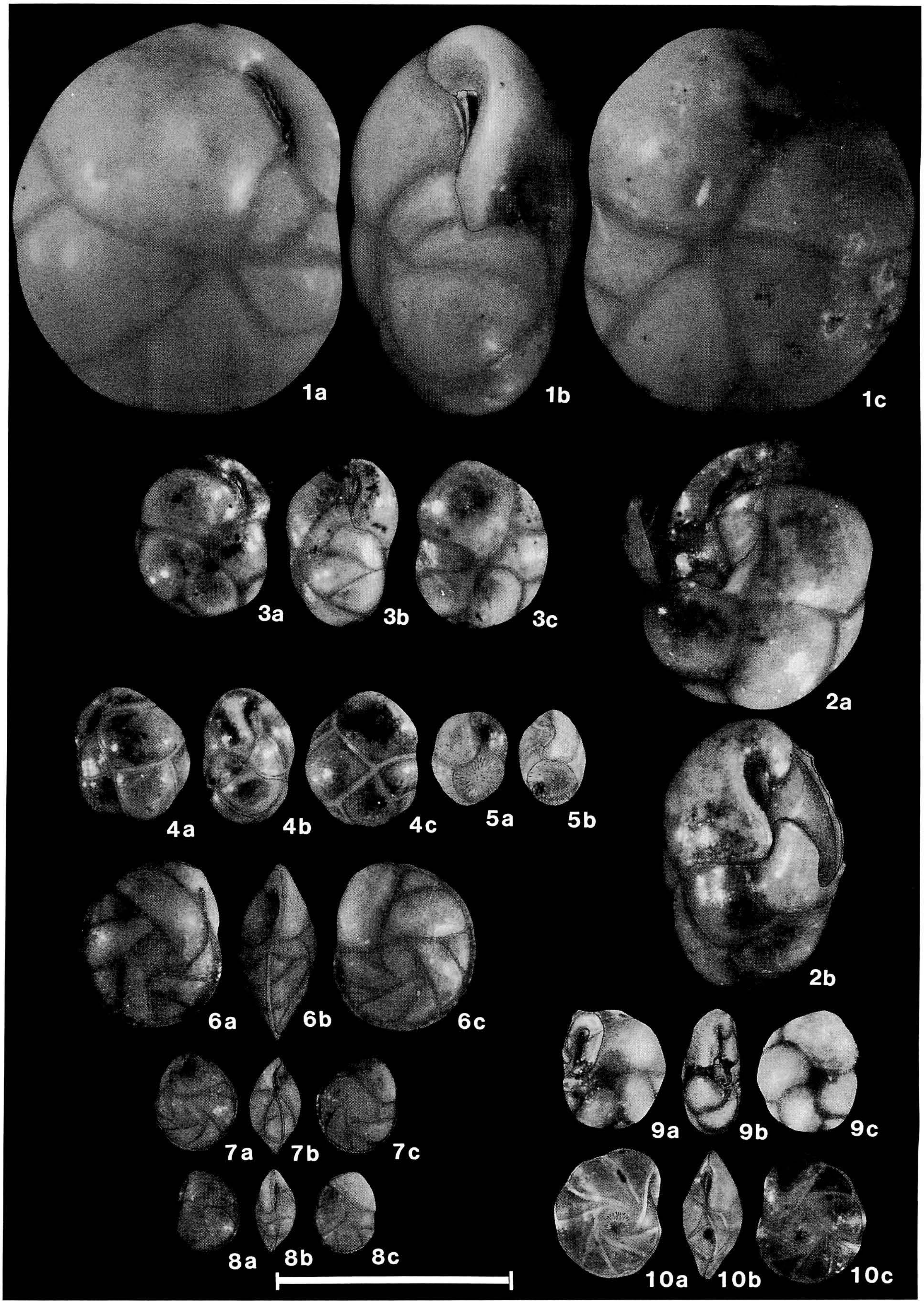
1a
1b
1c
3a
3b
3c
2a
4a
4b
4c
5a
5b
6a
6b
6c
2b
9a
9b
9c
7a
7b
7c
8a
8b
8c
10a
10b
10c

Figure 37.

For further synonymy, see Nomura (1983b)

Hypotypes:- Figure 33, nos. 1a-c, 2a-c, NFL9546, sample FUNA-11, Funakawa Formation, Akita Prefecture, late Miocene.

Test size:- Maximum test diameter 0.15–0.54 mm, test thickness 0.10–0.26 mm, sample FUNA-11.

Occurrence:- Funakawa Formation (FUNA, FUNA-11), Shitazaki Formation (IW-10, -12).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pleistocene and Recent form found in northern Honshu, Hokkaido, northern Pacific Ocean and the Sea of Japan.

Remarks:- This species was originally described by separating from *Cassidulina teretis*, described from the Arctic seas by Tappan (1951), based on that *P. helenae* has the optically radial texture and has the toothplate instead of an apertural plate. Detailed internal structure and wall structure have been given by Nomura (1983b).

An external shape of Miocene *Planocassidulina helenae* is similar to *P. yabei* in its elongate oval chamber, but *P. helenae* is smaller than *P. yabei* and has more thin walls. The cristate tooth of *P. helenae* is smaller and less developed than that of *P. yabei* (Figures 36–1–2).

Planocassidulina norcrossi (Cushman, 1933)

Figures 37–10a-c

Cassidulina norcrossi Cushman, 1933, p. 7, pl. 2, figs. 7a-c; Ujiié et al., 1983, p. 60, pl. 8, figs 6, 7.

Cassidulina kasiwazakiensis Husezima and Maruhasi, 1944, p. 399, pl. 34, figs. 13a-c.

Cassidulina nakamurai Uchio, 1951, p. 40, figs. 4a, b.

Planocassidulina norcrossi (Cushman). Gudina, 1966, p. 69, pl. 6, figs. 2a, b, 3a, b.

Islandiella norcrossi (Cushman). Beck, 1981, fig. 7-L; Nomura, 1983b, p. 13, pl. 2, figs. 2a-c, 3, pl. 3, fig. 2, pl. 4, fig. 1, pl. 5, fig. 1, pl. 8, figs. 3 - 10; Schröder-Adams et al., 1990, p. 34, pl. 7, figs. 4, 5; Seidenkrantz, 1992, pl. 1, fig. 4.

Islandiella helenae (Feyling-Hanssen and Buzas). Schröder-Adams et al., 1990, p. 34, pl. 7, fig. 7 (part).

Not *Islandiella narcissi* (Cushman). Smith, 1978, p. 143, pl. 6, fig. 7.

Not *Cassidulina norcrossi* Cushman. Xu and Ujiié, 1994, fig. 8, no. 4.

For further synonymy, see Nomura (1983b)

Hypotype:- Figure 37, nos. 10a-c, NFL9547, sample FUNA-11, Funakawa Formation, Akita Prefecture, late Miocene.

Test size:- Maximum test diameter 0.16–0.30 mm, test thickness 0.10–0.14 mm, sample FUNA-11.

Occurrence:- Funakawa Formation (FUNA, FUNA-11).

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pleistocene and Recent form found in northern Honshu, Hokkaido, northern Pacific Ocean and the Sea of Japan.

Remarks:- Because of apparently uniserial chamber arrangement of this species, several generic names have been proposed, but their diagnoses stressing the chamber arrangement are insufficient to distinguish this form from other biserial forms as a different genus. As described by Nomura (1983b) and Knudsen (1971), such a chamber arrangement should be recognized as a variation of biserial nature. A clear trend of the biserial arrangement is shown in the last pair of chambers in adult forms.

This species is common in the upper Miocene cassidulinid Zone III, particularly in the Sea of Japan borderland.

Planocassidulina praehelenae Nomura sp. nov.

Figures 36–4, -5, -6, 37–6a-c, -7a-c, -8a-c

Cassidulina laevigata carinata Cushman. Asano, 1953a, text-figs. 9a, b; Asano, 1953b, pl. 3, figs. 10a, b.

Diagnosis:- Small to medium-sized test with keeled periphery, fairly compressed; sutures distinctly limbate, flush with surface; wall transparent, showing not only previous chambers, but also the proloculus.

Description:- Test small to medium in size, nearly circular in side view, compressed lenticular in edge view; periphery not lobulate, keeled, sometimes serrated; chambers elongate trapezoidal, with small triangular chambers in marginal area, four and one-half pairs in the last whorl increasing gradually in size; sutures distinct, limbate, flush with surface, very slightly curved toward periphery; umbilical portion clear, showing large proloculus in megalospheric, and earlier chambers of previous whorls; aperture an oblique slit to the base of apertural face, with a small fragile cristate tooth on the posterior side; walls very thin, transparent, smooth and polished.

Optical structure:- Wall distinctly radial texture.

Apertural structure:- Aperture with the protruded cristate tooth and lip; cristate tooth sometimes externally fused with the secondary tongue (Figures 36–4–6) in mature specimens; copula attached to the preceding anterior part of the apertural face; primary tongue is undeveloped; secondary tongue formed on the previously formed chamber wall; aperture a small slit with indistinct cristate tooth in immature growth stages.

Holotype:- Figure 37, nos. 6a-c, NFL9548, sample H-5, early middle Miocene, Higashibessho Formation, Toyama Prefecture; paratypes and hypotypes, Figure 37, nos. 7a-c, 8a-c, NFL9549.

Test size:- Holotype, maximum test length 0.40 mm, test thickness 0.18 mm, sample H-5; paratype, maximum test length 0.18–0.38 mm, test thickness 0.10–0.18 mm,

Figure 37. **1a-c, 2a, b, 3a-c.** *Islandiella japonica* (Asano and Nakamura), IW-12. **4a-c, 5a, b.** *Islandiella algida* (Cushman), FUNA-11. **6a-c, 7a-c, 8a-c.** *Planocassidulina praehelenae* Nomura, n. sp., H-5. **9a-c.** *Islandiella compressa* Nomura, IW-12. **10a-c.** *Planocassidulina norcrossi* (Cushman), FUNA-11. Scale bar=0.5 mm.

sample H-5.

Occurrence:- Masuda Group (MA-10), Josoji Formation (JS-1), Bihoku Group (SHO-23, FU-5, -8, SB-6), Onnagawa Formation (AK-3), Atsuta Formation (AT-6, -9, -10, -22), Higashibessho Formation (H-3A, -4A, -5, -6A, -7A, -9B, -10B), Honsubetsu Formation (HON-31, -32), Hatatate Formation (HTTO-7, ISW-16, -19), Mizunami Group (MIZU), Nanatani Formation (NG-2, -4, -6, -27), Higashi-innai Formation (NOTO-3, -8, -15, -16), Hojuji Formation (NOTO-27), Sekinohana Limestone (SEKI), Niwaya Formation (TM-11, -186), Haratajino Formation (TM-3, -9), Idosawa Formation (TM-39), Wakkauenbetsu Formation (WAK-65, WAK-69/71), Mashike Formation (MAS-60/63/64).

Stratigraphic and paleogeographic distribution:- Cassidulinid I to III Zones in Honshu and Hokkaido.

Remarks:- Voloshinova (1952) designated four subspecies (*smechovi, carinata, umbonata,* and *sulcata*) in the species *smechovi,* from the Miocene of Sakhalin. The subspecies are discriminated from one another based on the test size, peripheral condition, umbilical inflation, and the magnitude of sutural depression. Of four subspecies, *smechovi smechovi* has a small test (0.2–0.35 mm diameter and 0.12–0.20 m thickness), and is comparable to the present species. She noted that this species is the most primitive form of the subspecies, reporting the occurrence from the lower Miocene. However, the periphery of *smechovi smechovi* is described as acute, without keel. Japanese Miocene specimens are consistently associated with narrow to distinct keel, which is another character of this species. In addition, a more compressed test and almost straight sutures of this species are here recognizable as another characteristic to distinguish it from Voloshinova's four subspecies.

Many diversified upper Miocene to Recent *Planocassidulina* always have the cristate tooth, primary tongue, and secondary tongue. The Miocene specimens of *P. praehelenae* have similar apertural structure to that of *P. helenae* as can be seen in Figure 36–1.

The specific name is referred to the close relation to *Planocassidulina helenae,* assuming the ancestor of the latter species.

Planocassidulina yabei
(Asano and Nakamura, 1937)

Cassidulina yabei Asano and Nakamura, 1937, p. 145, pl. 14, figs. 1a, b.
Islandiella yabei (Asano and Nakamura). Hasegawa and Nomura, 1995, p. 96, figs. 2–3a-4d.
For further synonymy, see Hasegawa and Nomura (1995).

Test size:- Maximum test diameter 0.19–0.64 mm, test thickness 0.14–0.30 mm, sample Shitazaki Formation.

Occurrence:- Shitazaki Formation.

Stratigraphic and paleogeographic distribution:- Cassidulinid III Zone in northern Honshu; Pleistocene and Recent forms found in northern Honshu, Hokkaido, northern Pacific Ocean and the Sea of Japan.

Remarks:- *Planocassidulina yabei* was found in the Shitazaki Formation, which assigned to the late Miocene (Oda et al., 1983, 1984). The fan-shaped cristate tooth of Miocene forms is the same as those of the type specimen in the Pleistocene Setana Formation.

Planocassidulina sp. A

Figures 33–11a-c, -12a-c

Hypotypes:- Figure 33, nos. 11a-c, 12a-c, NFL9551, sample WAK-69/71, Wakkauenbetsu Formation, Hokkaido, early middle Miocene.

Test size:- Maximum test diameter 0.32–0.38 mm, test thickness 0.18–0.20 mm, sample WAK-69/71.

Occurrence:- Wakkauenbetsu Formation (WAK-73, WAK-69/71).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in Hokkaido.

Remarks:- There are rare and badly preserved specimens found in the Wakkauenbetsu Formation of Hokkaido. The apertural structure is not defined because of fillings of secondary materials. However, this form is distinguished from *Planocassidulina praehelenae* by the angled periphery without keel. In appearance, this form is similar to *G. lenticularis,* but differs in having a smaller test and an optically radial texture. This form is also similar to *Cassidulina smechovi smechovi* Voloshinova, but differs from it in having the larger test.

Genus *Takayanagia* Nomura, 1983

Takayanagia Nomura, 1983a, p. 52.

Type species:- *Cassidulina delicata* Cushman, 1927, p. 168, pl. 6, fig. 5, Recent, off Panama, Pacific Ocean (original designation); *Cassidulina cushmani* R. E. and K. C. Stewart, 1930, p. 71, pl. 9, figs. 5a, b, Pliocene, Ventura County, California (secondary designation).

Remarks:- The type species of this genus has been designated as *Cassidulina delicata* Cushman by Nomura (1983a). An examination of the holotypes of *C. delicata* and *C. cushmani* indicates that the Japanese specimens used in the designation of this genus morphologically resemble *C. cushmani* rather than *C. delicata.*

This genus is morphologically similar to the species of *Paracassidulina* in having the interiomarginal slit aperture without toothplate. However, this genus differs from *Paracassidulina* by the optically radial texture. The hyaline appearance of well preserved walls in reflected light suggests such an optical character of walls. This genus consists of two species, *delicata* and *cushmani.*

The species of this genus occurred from the cassidulinid III Zone of the late Miocene in Japan.

Takayanagia cushmani (Stewart and Stewart, 1930)

Figures 16–14a-c, -15a-c

Cassidulina cushmani R. E. and K. C. Stewart, 1930, p. 71, pl. 9, figs. 5a, b; Smith, 1964, p. B39, pl. 3, fig. 5; Douglas, 1973, p. 632, pl. 6, fig. 6; Resig, 1981, p. 652, pl. 4, fig. 10.

Cassidulina delicata Cushman. Cushman, 1930, p. 61, pl. 8, fig. 16 (Cushman Coll. 13994); Crouch, 1952, pl. 6, fig. 7 (USNM 548355); Todd, 1965, p. 98, pl. 9, fig. 17 (USNM 626823); Ishiwada, 1964, p. 42, pl. 7, fig. 95; Matoba, 1967, p. 252, pl. 28, figs. 7a, b; Whittaker, 1988, p. 105, pl. 14, figs. 4, 5; Inoue, 1989, pl. 33, figs. 12a, b.

Cassidulina asanoi Uchio, 1950, p. 190, fig. 13; Uchio, 1951, p. 39, pl. 3, figs. 2a, b.

Takayanagia delicata (Cushman). Nomura, 1983a, p. 53, pl. 1, figs. 3a-c, pl. 7, figs. 1–5.

For further synonymy, see Nomura (1983a)

Hypotypes:- Figure 16, nos. 14a-c, 15a-c, NFL9552, sample AN-76, Anno Formation, Boso Peninsula, Chiba Prefecture, late Miocene.

Test size:- Maximum test diameter 0.29 to 0.50 mm, test thickness 0.16 to 0.18 mm, sample AN-76.

Occurrence:- Anno Formation (AN-76), Atsuta Formation (AT-9, -10, -22).

Stratigraphic and paleogeographic distribution:- Cassidulinid III and lower Pliocene sequence in Honshu and Hokkaido.

Remarks:- The specimens occurred in Pleistocene to Recent sediments of Japan, and are characterized by an interiomarginal slit aperture, highly curved sutures and transparent walls. They have been mistakenly identified as *delicata* or *asanoi*. Nomura (1983a) followed these previous worker's results and named it as *delicata* without the examination of holotype which was described from the Pacific Ocean (428 fathoms), off Panama.

In addition to above noted diagnoses, all the examined Japanese specimens have a keel on the periphery, although its development is dependent on the test thickness. Based on the holotype (USNM 20304) and paratypes (Cushman Coll. 7219) of *Cassidulina delicata*, however, no such a keel is detected. The periphery of *delicata* is consistently subacute or compressed rounded. Furthermore, *Cassidulina delicata* has a longer slit than that of *cushmani*. I regard these systematic criteria significant enough to distinguish *delicata* from the other Pliocene species *cushmani*. In one specimen slide (USNM 688789), Natland arranged the specimens of both *delicata* and *cushmani* and he wrote "grade into one another... I would prefer to lump them," on the margin of this slide. However, the species on this slide are not of the same origin. He also wrote "these specimens range in age from Recent to lower Pliocene. "As far as my observation of these specimens, the periphery does not show a gradual change between *delicata* and *cushmani*. It is difficult to recognize that the two species fall into the same species concept. I support R. E and K. C. Stewart 's (1930) original notes recognizing that *cushmani* has a sharp periphery, greater extension of chambers around the opposite sides of the test, and more angled sutures, which distinguishes it from *delicata*. Thus, *cushmani* assigned to the synonymy of *delicata* by Nomura (1983a) is invalid. Finger (1990) pointed out this morphological difference between the Japanese specimens and *delicata*. He also observed that the wall of *delicata* is optically granular, and he assigned *delicata* to the genus *Paracassidulina*. However, his observation was not agreed with Feyling-Hanssen and Buzas (1976) by the observation on the holotype. They reported the walls optically radial.

Many specimens of *delicata* that are deposited in the U. S. National Museum are confused with morphologically similar species *Paracassidulina sulcata* (Belford). Recent specimens from off Bikini Atoll, the Marshall Islands, reported by Todd are identified as *Paracassidulina sulcata* in showing numerous grooves out of the aperture and distinct sutural grooves. A similar confused identification is shown in the figured specimens from off southeast coast of New Guinea by Haig (1993, p. 171, pl. 7, figs. 8–10) and from a lagoon between Ishigaki and Iriomote Islands, the Ryukyu Islands, by Ujiié and Hatta (1994, p. 13, pl. 2, fig. 6).

Takayanagia cushmani was described from early Pliocene sediments of Ventura County, California. Small sized specimens of this species occur rarely from the late Miocene of the Sea of Japan borderland, Hokkaido. In Pliocene to Pleistocene sediments, this species is common in the Pacific borderland.

Genus **Rutherfordoides** McCulloch, 1981

Rutherfordia McCulloch, 1977 (type, *Rutherfordia rotundiformis* McCulloch, 1977)

Rutherfordoides McCulloch, 1981 (type, *Rutherfordia rotundiformis* McCulloch, 1977)

Hastilina Nomura, 1983a (type, *Virgulina mexicana* Cushman, 1922, p. 120)

Type species:- *Rutherfordia rotundiformis* McCulloch, 1977, p. 249, pl. 105, figs. 6–10.

Remarks:- The elongate and subfusiform test with uncoiled biserial chamber has been recognized under the genus *Hastilina* by Nomura (1983a). At the time of the proposal of this genus, no information about optical wall character of the genus *Rutherfordoides* had been obtained. Kohl (1985) stressed the morphological similarity between *Hastilina* and *Rutherfordoides*, and put *Hastilina* in the synonymy of *Rutherfordoides*. Loeblich and Tappan (1987) also recognized *Rutherfordoides* and described the optical character of this genus as a granular texture. Thus, I follow their results and put *Hastilina* in the Genus *Rutherfordoides*.

Genus *Rutherfordoides* was originally proposed as *Rutherfordia* by McCulloch (1977), with the type species *R. rotundiformis* from Recent sediments of Japan. Later she gave the present name because the genus *Rutherfordia* was preoccupied (McCulloch, 1981).

Rutherfordoides erectus (Cushman and Renz, 1941)

Figures 29–9a-c, -10a, b, -11a, b, -12a-c, 30–12, 38, 39

Cassidulinoides erecta Cushman and Renz, 1941, p. 25, pl. 4, figs. 6a, b, 7; Renz, 1948, p. 126, pl. 9, figs. 15a-c; Cassell and Sen Gupta, 1989, p. 61, pl. 7, fig. 5; Bolli et al., 1994, p. 345, fig. 80, 33a, b.

Fursenkoina mexicana (Cushman). Konda, 1980, p. 38, pl. 1, figs. 12, 13.

Rutherfordoides erecta (Cushman and Renz). Kohl, 1985, p. 89, pl. 18, figs. 2a-d.

Optical structure:- Wall mosaic-granular texture.

Apertural structure:- Aperture of this species is oval with small cristate tooth and lip; toothplate is very simple, without primary tongue and secondary tongue; copula attached to the upper part of the preceding aperture near the opening (Figures 30–12, 38).

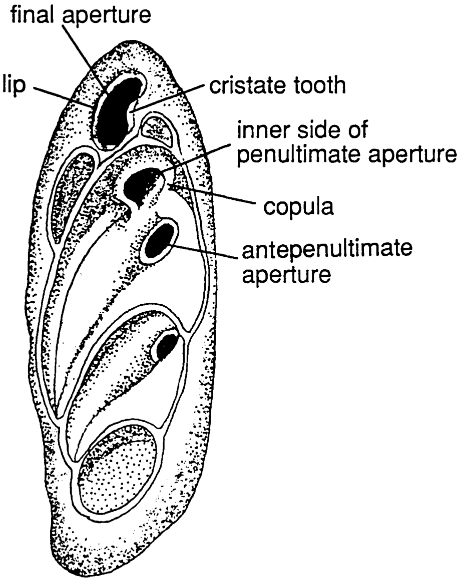

Figure 38. Internal structure of *Rutherfordoides erectus*.

Hypotypes:- Figure 29, nos. 9a-c, 10a, b, 11a, b, 12a-c, NFL9538, sample NOTO-27, Hojuji Formation, Noto Peninsula, Ishikawa Prefecture, early middle Miocene.

Test size:- Test length 0.18–0.32 mm, test thickness 0.13–0.20 mm, sample WAK-74; test length 0.28–0.48 mm, test thickness 0.16–0.20 mm, sample NOTO-27.

Occurrence:- Uyashinai Formation (AK-6), Higashibessho Formation (H-5, -6A, -7A), Mizunami Group (MIZU), Nanatani Formation (NG-2, -12, -14, -18, -19, -23, -25), Higashi-innai Formation (NOTO-15, -16), Hojuji Formation (NOTO-27), Niwaya Formation (TM-11), Haratajino Formation (TM-9), Wakkauenbetsu Formation (WAK-73, WAK-69/71).

Stratigraphic and paleogeographic distribution:- Cassidulinid I and II Zones in Honshu and Hokkaido.

Remarks:- This species was originally reported from upper Oligocene sediments of Venezuela by Cushman and Renz (1941). Kohl (1985) reported this species from the early Pliocene of southern Mexico. The holotype of this species is depicted as curved test with a pointed appearance in the earlier portion. However, paratypes deposited in the U. S. National Museum (USNM 45984) show quite variable shape of this earlier portion of the test. I have sketched some representatives of variations among the paratypes (Figure 39). As can be seen, some are characterized by a rounded earlier portion (Figure 39, nos. 1, 2) and some are very slightly curved (Figure 39, nos. 3, 4). These shapes may represent ontogenetic variation. Younger specimens with fewer chambers are characterized by a blunter early portion, and matured specimens with more abundant chambers tend to have a pointed initial portion. These features are also related to the microspheric and megalospheric

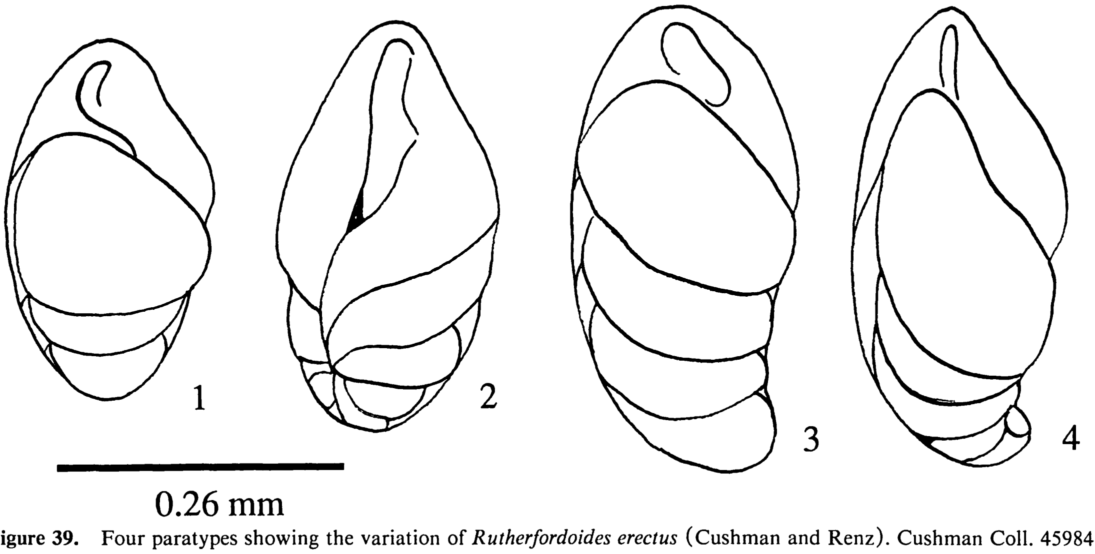

Figure 39. Four paratypes showing the variation of *Rutherfordoides erectus* (Cushman and Renz). Cushman Coll. 45984.

generations. Microspeheric forms have more pointed initial portion.

This species is common in Miocene muddy sediments of Japan, and I have recognized the same variation as the Cushman and Renz's original designation with respect to earlier portion of test. Japanese specimens are also characterized by less depressed sutures and not so inflated chambers, compared with the Cushman and Renz's specimens. However, these features should be recognized as a variation of this species.

Pleistocene to Recent *Virgulina cornuta* Cushman, 1913 (as *Hastilina cornuta* described by Nomura, 1983b) is a descendant of *R. erectus.* Through this lineage, the shortening of test length and the inflation of final chamber can be observed in *Rutherfordoides cornutus.*

Subfamily Ehrenbergininae Cushman, 1927

Genus *Ehrenbergina* Reuss, 1850

Ehrenbergina Reuss, 1850, p. 377.

Type species:- *Ehrenbergina serrata* Reuss, 1850, p. 377, pl. 48, figs. 7a-c.

Remarks:- Only one species of *Ehrenbergina* (i.e., E. notoensis) has been recorded in Miocene strata of Japan. However, three species were recognized in this study, and one of which is proposed as new species.

Ehrenbergina bosoensis Takayanagi, 1951

Figures 29-6a-c

Ehrenbergina bosoensis Takayanagi, 1951, p. 87, text-figs. 8a-c; Nomura, 1983b, p. 61, pl. 4, figs. 18a-c, pl. 5, figs. 7, 9, pl. 22, fig. 7; Kohl, 1985, p. 86, pl. 31, figs. 1a-c.

For further synonymy, see Nomura (1983b).

Hypotype:- Figure 29, nos. 6a-c, NFL9534, sample HTTO-7, Hatatate Formation, Miyagi Prefecture, middle Miocene.

Test size:- Test width 0.35-0.36 mm, test length 0.33-0.37 mm, test thickness 0.19-0.20 mm, HTTO-7.

Occurrence:- Anno Formation (AN-67, -76), Hatatate Formation (HTTO-7), Kiyosumi Formation (KI-54), SEKI (Sekinohana Limestone).

Stratigraphic and paleogeographic distribution:- Cassidulinid I to III Zones in Honshu; Pleistocene form found in southern Honshu and Okinawa Island.

Remarks:- Detailed systematic analysis has been given by Nomura (1983b). Small specimens of this species are rarely found in the Sekinohana Calcareous Sandstone of the early middle Miocene. Miocene occurrence of this species is generally rare and occupies a small portion of the cassidulinid assemblage.

Ehrenbergina crassitrigona Nomura sp. nov.

Figures 29-1a-c, -2a-c, -3a-c, 30-10

Diagnosis:- Rounded-triangular and thick test, with short spines; early portion of test with reticulate costae; median furrow broadly inflated.

Description:- Test medium in size, thick, rounded rhomboid in apertural view; early portion of dorsal and ventral side decorated with roughly reticulate costae, but not in later portion; median furrow is not steep, broadly inflated; apical end rounded, not spinose; periphery serrated in later portion, with short spines on each side; chambers low and broad, coiled in earliest portion, at least six pairs visible externally; sutures indistinct on ventral side, not depressed and limbate on dorsal side; aperture a curved-slit, parallel to the dorsal margin.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Apertural opening concealed with the fan-shaped apertural flap, showing a curved slit of opening; apertural grooves formed out of aperture, but not formed on the apertural flap; free part of toothplate unrecognizable.

Holotype:- Figure 29, nos. 1a-c, NFL9535, sample ISW-16, middle middle Miocene, Hatatate Formation, Miyagi Prefecture; paratypes and hypotypes, Figure 29, nos. 2a-c, 3a-c, NFL9536.

Test size:- Holotype, test width 0.44 mm, test length 0.48 mm, test thickness 0.32 mm, sample ISW-16; paratype, test width 0.20-0.44 mm, test length 0.21-0.48 mm, test thickness 0.16-0.32 mm, sample ISW-16.

Occurrence:- Uyashinai Formation (AK-3, -6), Hatatate Formation (ISW-16), Mizunami Group (MIZU), Nanatani Formation (NG-6, -13, -14, -18, -20), Higashiinnai Formation (NOTO-16), Niwaya Formation (TM-11, -186), Haratajino Formation (TM-153, -204).

Stratigraphic and paleogeographic distribution:- Cassidulinid I and II Zones in Honshu.

Remarks:- This species shows the intermediate shape between *E. bosoensis* and *E. notoensis.* The test of this species is more rounded and the peripheral spines are less developed than those of *E. bosoensis.* The gently inflated median furrow of this species is similar to that of *E. notoensis,* but not so compressed as in the test of *E. notoensis. Ehrenbergina crassitrigona* is similar to *E. cubensis* Cushman and Bermudez subspecies *pollentiana* from the Miocene of Spain, in showing the reticulate ornamentation in the early portion of the test. But this new species differs in having the thicker test and less developed peripheral spines.

This species is sporadically found in early to middle middle Miocene deposits of southern Japan.

The specific name is referred to the Latin *crassus,* meaning thick, and trigonum, meaning three cornered, which is the diagnosis of this species.

Ehrenbergina notoensis Asano, 1951

Figures 29–7a-c, -8a-c, 30–9

Ehrenbergina notoensis Asano, 1951, p. 6, text-figs. 29, 30; Takayanagi, 1951, p. 87, text-figs. 2a, b.

Not *Ehrenbergina notoensis* Asano. Ujiié, 1990, p. 40, pl. 20, figs, 3a-c, 4a-c, 5a-c; Loeblich and Tappan, 1994, p. 117, pl. 226, figs. 13–15.

Description:- Test medium in size, subtriangular, compressed in later portion, curved-cuneat in side view, arcuate in apertural view; dorsal side smooth and ventral side gently raised, without a raised median furrow; apical end bluntly rounded; periphery serrated in later portion without lateral spines; chambers low and broad, indistinct, slightly coiled in earliest portion, about five to six pairs of chambers overlapped; sutures on both dorsal and ventral sides not depressed, limbate and slightly raised in earliest portion on dorsal side; aperture a curved-slit, parallel to dorsal margin, associated with numerous apertural grooves, except for apertural flap.

Optical structure:- Wall jagged-granular texture.

Apertural structure:- Aperture gently curved slit, concealed by the semi-circular apertural flap; apertural grooves formed out of the aperture, excepting the area of apertural flap; proximal end of the apertural flap adheres to the preceding apertural flap (Figure 30–9); free structure of toothplate can not be recognized.

Hypotypes:- Figure 29, nos. 7a-c, 8a-c, NFL9537, sample NOTO-10, Higashi-innai Formation, Noto Peninsula, Ishikawa Prefecture, early middle Miocene.

Test size:- Test width 0.25–0.36 mm, test length 0.25–0.38 mm, test thickness 0.16–0.19 mm, sample NOTO-10.

Occurrence:- Higashibessho Formation (H-3A, -4B, -9B), Saigo Group (KK-117), Mizunami Group (MIZU), Nakanami Formation (NAKA), Higashi-innai Formation (NOTO-10), Hojuji Formation (NO TO-27).

Stratigraphic and paleogeographic distribution:- Cassidulinid Ia Subzone in southern Honshu.

Remarks:- Original description of this species was insufficient to understand the species concept. Based on the materials from near topotype, I understand this species is characterized by the compressed test and poorly developed median furrow. The apertural structure is closely allied to that of *E. bosoensis,* with numerous apertural grooves.

Ehrenbergina notoensis (USNM 470890) reported by Loeblich and Tappan (1994) from the Timor Sea has a highly developed median furrow. Ujiié's specimen from Recent sediments off Miyakojima Island, Ryukyu Islands, also has a raised median furrow and lateral spines. Those features are not the diagnostic of *E. notoensis.*

This species was described from lower middle Miocene deposits of the Noto Peninsula. There have been limited reports of this species, but it occurs in the lower middle Miocene Kurami Formation and the Mizunami Group of southern Japan.

Genus *Reissia* Loeblich and Tappan, 1964

Reissia Loeblich and Tappan, 1964a, p. 28.

Type species:- *Ehrenbergina hystrix* Brady, 1881, p. 60; Brady, 1884, p. 55, figs. 8–11.

Remarks:- This genus has been differentiated from the genus *Ehrenbergina* by having a radial texture (Loeblich and Tappan, 1964a). Internal structures as well as apertural modifications of this genus can be seen in some ehrenberginid species, suggesting morphologically very close phylogenetic relation to the genus *Ehrenbergina.*

The type species of this genus, *Reissia hystrix,* has been known from the North and South Pacific deep sea (3,000–4,500 m in depth; Brady, 1884; Loeblich and Tappan, 1987).

The first occurrence of the genus *Reissia* is recognized in Japan from the early middle Miocene.

Reissia sp. A

Figures 29–4a-c, -5a-c, 30–11

Hypotypes:- Figure 29, nos. 4a-c, 5a-c, NFL9539, sample KITA-91, Takinosawa Formation, Jozankei, South of Sapporo, Hokkaido, middle middle Miocene.

Test size:- Test width 0.24–0.36 mm, test length 0.21–0.36 mm, test thickness 0.18–0.26 mm, KITA-91.

Occurrence:- KITA-91.

Stratigraphic and paleogeographic distribution:- Cassidulinid II Zone in Hokkaido.

Remarks:- A few well preserved specimens from the middle Miocene Takinosawa Formation, Hokkaido, show an optically radial texture of the walls; thus they are identified as the species in the genus *Reissia.*

The external shape of this species is similar to Recent *Reissia hystrix* in having the apertural grooves (Figure 30–11), several knobs in the early portion of the test, and also the raised sutures on the dorsal side. However, the peripheral spines of this species are less developed and the sutures on the dorsal side do not form rows of spines or a fringe-like projection like those of *R. hystrix.*

This species may be a new for this genus. However, there are not enough specimens to understand the ontogeny and the morphological variation of this species. Until now, the genus *Reissia* is represented by the monotype of Recent *hystrix.* By the discovery of this form, the first appearance of this genus extends back to the middle middle Miocene.

Conclusions

1. Significant evolutionary changes of benthic foraminiferal cassidulinids occurred through the middle to late Miocene, and the environmental factors for the evolution responded to global paleoceanographic changes. Many middle Miocene species became extinct during the time of the global cooling event, and in turn the modern cassidulinid assemblage was formed from the late Miocene onward.

2. Miocene cassidulinids are stratigraphically divided into three interval zones: cassidulinid I, II, III Zones, and the cassidulinid I Zone is further subdivided into the Ia and Ib Subzones. The cassidulinid I Zone ranges from the early middle Miocene to middle middle Miocene (~17-14 Ma), the II Zone is from the middle middle Miocene to late Miocene (~14-10 Ma), and the III Zone is recognized from the late Miocene (~10-5 Ma). The cassidulinid I Zone is characterized by diversified globocassidulinids and the cassidulinid III Zone consists of mainly islandiellids and planocassidulinids. A less developed cassidulinid assemblage is recognized in the II Zone.

3. Systematic features of Miocene cassidulinids were examined and further observations refined the description of Nomura (1983a, b). The optical wall texture of the granular type is quantitatively analyzed by measuring the area and perimeter of crystal units using an image analysis with optically positive and negative conditions of polarizing light. The mosaic granular texture has higher area/perimeter ratios, while the jagged-granular one has lower ratios.

During the middle Miocene, walls of most cassidulinid species show optically granular texture, while the species with optically radial texture became common from the late Miocene on. The evolution of wall structure from optically granular to radial texture occurred during the middle to late Miocene (interval from II to III Zone). I propose that the middle Miocene *Globocassidulina lenticularis* and *G. pseudojaponica,* with granular texture, evolved to upper Miocene *Islandiella yabei* and *I. japonica* with radial texture.

4. A heterochronic evolutionary process was constructed in two lineages: one includes the *Globocassidulina hatatatensis, G. exigua* and *Cassidulina reniforme* phylogeny and the other includes the *Globocassidulina notoensis, G. imamurai, G. kakegawaensis* and *G. obtusa* phylogeny. Their diagnostic features are typically found in the apertural form, as recognized in **G1**-, **G2**- and **G3**-type apertures (also Nomura, 1983a). The apertural plate formed in the genus *Cassidulina* and developed from the cristate tooth of *Globocassidulina exigua.* The suggestion that an L-shaped aperture (E type of Nomura, 1983a) developed from rounded and slit type apertures (C and D types of Nomura, 1983b), is confirmed in the Miocene to Pliocene by the *Globocassidulina notoensis, G. imamurai, G. kakegawaensis* and *G. obtusa* phylogeny.

5. Explosive evolution of islandiellid/planocassidulinid foraminifera was due to the increased input of organic matter onto the sea floor, which was introduced by an increase of primary productivity in the marginal seas of the Pacific Ocean and an input from land area caused by global decrease of sea level. Adaptive radiation of islandiellids and other cassidulinids from the late Miocene on is intimately related to the increased food resources on the sea floor.

6. Forty species are described in detail and the generic classification is discussed. Of these, 12 species and one subspecies are first described from the Miocene of Japan. Two new species are given for the species described by Nomura (1983a, b)

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Appendix

The prefixed number in each stratigraphic unit refers to the locality number indicated in Figure 1.

1. Masuda Formation, early middle Miocene, Shimane Prefecture.

MS-10: mudstone, 34°39.9′ N, 131°50.4′ E, outcrop near Yoshida Minami primary school, Masuda City.

2. Kuri Formation, early middle Miocene, Shimane Prefecture.

OT-48: mudstone, 35°7.8′ N, 132°31′ E, river floor of the Ushibara-gawa River, Kawai-cho, Oda City.

2. Furue Formation, middle middle Miocene, Shimane Prefecture.

JS-1: mudstone, 35°27.5′ N, 132°48.8′ E, road-side outcrop, Kutami-cho, Hirata City.

2. Fujina Formation, middle middle Miocene, Shimane Prefecture.

Fujina: Siltstone, 35°27.5′ N, 133°2.0′ E, lake-side cliff of Shinjiko Lake, Fujina, Tamayu-cho, Yatsuka-gun.

3. Bihoku Group, early middle Miocene, Hiroshima Prefecture.

SHO-21: mudstone, 34°51.7′ N, 133°0.78′ E, river floor of the Saijo-gawa River, Shobara City.

SHO-23: mudstone, 34°51.7′ N, 133°0.8′ E, *ditto.*

FU-5: mudstone, 34°53.0′ N, 132°47.0′ E, Kamifuno, Funo-son.

FU-8: mudstone, 34°53.1′ N, 132°47.1E, Kamifuno, Funo-son.

SB-6: siltstone, 34°51.6′ N, 133°2.6E, Miyauchi-cho, Shobara City.

4. Kurosedani Formation, early middle Miocene, Toyama Prefecture.

KURO: fine-grained sandstone, 36°32.4′ N, 137°9.8′ E, river-side cliff of the Kubusu-gawa River, Yatsuo-machi, Nei-gun.

4. Higashibessho Formation, early middle Miocene, Toyama Prefecture.

H-3A: mudstone, 36°36.6′ E, 137°2.7′ E, river-side cliff of the Wada-gawa River, Higashibessho, Tonami City.

H-4A: mudstone, *ditto.*

H-5: mudstone, 36°36.7′ N, 137°2.7′ E, *ditto.*

H-6A: mudstone, 26°36.3′ N, 137°2.8′ E, *ditto.*

H-7A: mudstone, 36°36.1′ N, 137°2.8′ E, *ditto.*

H-9B: mudstone, 36°36.2′ N, 137°0.9′ E, tributary of the Shou-gawa River, 1.5 km northwest of Iguridani, Tonami City.

H-10B: mudstone, 36°36.2′ N, 137°1.0′ E, *ditto.*

5. Higashi-innai Formation, early middle Miocene, Noto Peninsula, Ishikawa Prefecture.

NOTO-10: fossiliferous siltstone, 37°24.5′ N, 137°3.1′ E, outcrop in Higashi-innai-machi, Wajima City.

NOTO-15: calcareous sandstone, 37°22.3′ N, 137°5.3′ E, river-side cliff of the Machino-gawa River, Noda, Wajima City.

NOTO-16: *ditto.*

NOTO-27: mudstone, 37°23.7′ N, 137°13.1′ E, river-side cliff of the Ukai-gawa River, 2.5 km southwest of Ukai, Houryo-machi, Suzu City.

NOTO-3: calcareous sandstone, 37°24.5′ N, 136°54.0′ E, sea-side cliff, Kamogaura, Wajima, Wajima City.

NOTO-8: calcareous sandstone, 37°24.5′ N, 136°58.2′ E, road-side outcrop in Fukami-machi, Wajima City.

5. Sekinohana Sandstone, early middle Miocene, Noto Peninsula, Ishikawa Prefecture.

SEKI: calcareous sandstone, 37°12.6′ N, 137°4.1′ E, sea-side cliff in Sekinohana, Togi-machi, Hakui-gun.

5. Nakanami Formation, early middle Miocene, Noto Peninsula, Ishikawa Prefecture.

NAKA: mudstone, 36°57.0′ N, 137°2.6′ E, road-side outcrop, west of Nakanami, Himi City.

5. Nanao Limestone, early middle Miocene, Noto Peninsula, Ishikawa Prefecture.

NANA: calcareous sandstone, 37°2.3′ N, 136°57.3′ E, road-side outcrop, 1 km southwest of Nanao, Nanao City.

6. Nanatani Formation, early middle Miocene, Niigata Prefecture.

NG-2: mudstone, 37° 32.4′ N, 139° 8.5′ E, tributary of the Igarashi-gawa River, Kitaimogawa, Shitada-mura, Minami-kanbara-gun.

NG-4: mudstone, stratigraphically 17 m below NG-2.

NG-6: mudstone, stratigraphically 17 m below NG-4.

NG-9: mudstone, stratigraphically 40 m below NG-6.

NG-12: mudstone, stratigraphically 27 m below NG-9.

NG-13: mudstone, stratigraphically 17 m below NG-12.

NG-14: mudstone, stratigraphically 15 m below NG-13.

NG-18: mudstone, stratigraphically 48 m below NG-14.

NG-19: mudstone, stratigraphically 10 m below NG-18.

NG-20: mudstone, stratigraphically 10 m below NG-19.

NG-23: mudstone, 37° 32.6′ N, 139° 8.9′ E, stratigraphically 45 m below NG-20.

NG-25: mudstone, 37° 37.0′ N, 139° 8.2′ E, outcrop in Kami-ohtani, Kamo City.

NG-27: mudstone, 37° 37.0′ N, 139° 8.1′ E, *ditto.*

6. Teradomari Formation, middle middle Miocene, Niigata Prefecture.

TERA: Samples of the "blue zone" from core samples at Asahibara and Maki; Teikoku Oil Company collection.

7. Nishikurosawa Formation, early middle Miocene, Oga Peninsula, Akita Prefecture.

OGA: fossiliferous mudstone, 39° 51.9′ N, 139° 48.1′ E, sea coast of Daijima, Oga City.

8. Uyashinai Formation, early middle Miocene, Akita Prefecture.

AK-3: fine-grained sandstone, 39° 43.1′ N, 140° 21.6′ E, tributary of Oide-sawa, about 2 km north of Uyashinai, Kawabe-machi, Kawabe-gun.

AK-6: fine-grained sandstone, 39° 43.2′ N, 140° 21.8′ E, *ditto.*

8. Onnagawa Formation, middle middle Miocene, Akita Prefecture.

AK-3′: hard shale, 39° 43.1′ N, 140° 21.6′ E, stratigraphically about 1 m above of AK-3.

8. Funakawa Formation, middle to late Miocene, Akita Prefecture.

FUNA: fossiliferous fine-grained sandstone, 39° 42.7′ N, 140° 18.8′ E, river-side cliff of the Iwami-gawa River, about 1.3 km west of Sannai, Kawabe-machi, Kawabe-gun.

FUNA-11: fossiliferous siltstone, 39° 42.8′ N, 140° 17.8′ E, river side cliff of the Sannai-gawa River, Sannai, Kawabe-machi, Kawabe-gun.

9. Mizunami Group, early middle Miocene, Gifu Prefecture.

MIZU: mudstone, sample information (as Hy-63-03) is given in Seto (1993).

10. Saigo Siltstone (Saigo Group), early middle Miocene, Shizuoka Prefecture.

KK-117: mudstone, 34° 48.8′ N, 138° 0.4′ E, road-side outcrop, Sakugi, Kakegawa City.

KK-120: mudstone, 34° 48.2′ N, 138° 0.2′ E, road-side outcrop, Kamitaruki, Kakegawa City.

10. Tamari Siltstone (Sagara Group), Pliocene, Shizuoka Prefecture.

KK-16: mudstone, 34° 46.0′ N, 138° 2.1′ E, road-side outcrop, Sakagawa, Kakegawa City.

KK-17: mudstone, 34° 45.9′ N, 138° 3.0′ E, road-side outcrop, 500 m south of Tamari, Kakegawa City.

KK-18: mudstone, 34° 45.8′ N, 138° 4.2′ E, road-side outcrop, Shimakawa, Kakegawa City.

KK-19: mudstone, 34° 46.2′ N, 138° 4.6′ E, road-side outcrop, 500 m east of Sawada, Kakegawa City.

KK-20: mudstone, 34° 46.3′ N, 138° 4.8′ E, road-side outcrop, 700 m east of Sawada, Kakegawa City.

11. Idosawa Formation (Tomioka Group), early middle Miocene, Gunma Prefecture.

TM-34: mudstone, sample information is given in Konda (1980).

TM-35: *ditto.*

TM-39: *ditto.*

11. Haratajino Formation (Tomioka Group), middle to late middle Miocene, Gunma Prefecture.

TM-3: mudstone, sample information is given in Konda (1980).

TM-4: *ditto.*

TM-9: *ditto.*

TM-153: *ditto.*

TM-159: *ditto.*

TM-204: *ditto.*

TM-205: *ditto.*

11. Niwaya Formation (Tomioka Group), middle middle Miocene, Gunma Prefecture.

TM-11: mudstone, sample information is given in Konda (1980).

TM-186: mudstone, *ditto.*

11. Yoshii Formation (Tomioka Group), late middle Miocene, Gunma Prefecture.

TM-83: mudstone, sample information is given in Konda (1980).

12. Kiyosumi Formation, late Miocene to Pliocene, Boso Peninsula, Chiba Prefecture.

KI-54: mudstone, 35° 11.1′ N, 140° 4.5′ E, river floor of the Sasa-gawa River, about 5 km southwest of Kazusakameyama, Kimitsu City.

12. Anno Formation, Pliocene, Boso Peninsula, Chiba Prefecture.

AN-67: mudstone, 35° 12.9′ N, 140° 3.7′ E, tributary of the Obitsu-gawa River, 2.5 km south of Hosono, Ohtomi, Kimitsu City.

AN-74: mudstone, 35° 12.2′ N, 140° 6.4′ E, tributary of the Obitsu-gawa River, 3.5 km southeast of Kazusakameyama, Kimitsu City.

AN-76: mudstone, 35° 12.1′ N, 140° 6.5′ E, *ditto.*

13. Hatatate Formation, early to middle middle Miocene, Miyagi Prefecture.

HTTO-7: middle part of the Hatatate Formation, sample information is given in Oda and Sakai (1977).

ISW-16: lower part of the Hatatate Formation, *ditto.*

ISW-19: *ditto.*

14. Kadonosawa Formation, early middle Miocene, Aomori Prefecture.

IW-29: mudstone, 40° 16.0′ N, 141° 18.6′ E, river floor of the Shimouma-gawa River, Kawamata, Fukuoka, Ninohe City.

IW-30: mudstone, *ditto.*

14. Tomezaki Formation, early middle Miocene, Iwate Prefecture.

IW-1: calcareous sandstone, 40° 20.5′ N, 141° 16.7′ E, river floor of the Mabechi-gawa River, Uwano, Kindaiichi, Ninohe City.

14. Shitazaki Formation, late Miocene, Iwate Prefecture.

IW-10: fossiliferous siltstone, 40° 20.3′ N, 141° 15.5′ E, about 1 km west of Kamazawa, Kindaiichi, Ninohe City.

IW-12: fossiliferous siltstone, *ditto.*

15. Takinosawa Formation, middle middle Miocene, Hokkaido.

KITA-91, 42° 56.0′ N, 141° 15.3′ E, the Misumai-gawa River, tributary of the Toyohira-gawa River, about 8 km southwest of Jozankei, South of Sapporo.

16. Honsubetsu Formation, early middle Miocene, Hokkaido.

HON-31: 43° 25.3′ N, 141° 40.2′ E, tributary of the Subetsu-gawa River, 5 km northeast of Nakano, Tsukigata-machi, Kabato-gun.

HON-32: 43° 25.4′ N, 141° 40.5′ E, *ditto.*

HON-41/45: 43° 24.6′ N, 141° 39.9′ E, *ditto.*

17. Wakkauenbetsu Formation, early middle Miocene, Hokkaido.

WAK-65: 43° 35.6′ N, 141° 43.5′ E, river floor of the Wakkauenbetsu-gawa River, 750 m west of Nishitoppu, Shintotsugawa-cho, Kabato-gun.

WAK-73: 43° 36.0′ N, 141° 42.8′ E, river floor, near Wakka, Shintotsugawa-cho, Kabato-gun.

WAKJ-69/71: 43° 36.0′ N, 141° 42.9′ E, *ditto.*

17. Mashike Formation, late Miocene, Hokkaido.

MAS-60/63/64: 43° 35.6′ N, 141° 44.7′ E, river floor of the Toppu-gawa River, 1 km east of Nishitoppu, Shintotsugawa-cho, Kabato-gun.

18. Atsuta Formation, late middle to late Miocene, Hokkaido.

AT-6: mudstone, 43° 21.6′ N, 141° 25.9′ E, sea cliff, 1 km north of Kotan, Atsuta-mura, Atsuta-gun.

AT-9: mudstone, 43° 21.7′ N, 141° 25.8′ E, *ditto.*

AT-10: mudstone, 43° 21.7′ N, 141° 25.8′ E, *ditto.*

AT-22: mudstone, 43° 23.3′ N, 141° 26.2′ E, 500 m south of Bekkari, Atsuta-mura, Atsuta-gun.

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