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Miocene-Pliocene Foraminifera from the subsurface sections in the Yufutsu Oil and Gas Field, Hokkaido

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Abstract. Miocene-Pliocene foraminifera recovered from three subsurface sections in the Yufutsu Oil and Gas Field, southern Hokkaido, are studied in detail to infer paleoceanographic and paleobathymetric implications and to clarify the history of the basin. Foraminiferal faunas indicate a progressive increase in bathymetry from a brackish shallow marine to a bathyal condition during the Middle Miocene. The basin then came under the spell of volcanism and nearly 1000 m of basalt-basaltic andesite flows accumulated until the top of the volcano emerged out of the sea. After the cessation of volcanic activity, the basin subsided and cold bathyal conditions prevailed in which diatomaceous-siliceous sediment was accumulated during the Late Miocene. The periodic episodes of subsidence are inferred to have been related to the genesis of the Japan Sea. The basin witnessed a major hiatus during the Late Miocene-Early Pliocene. During the Late Pliocene, coarse clastic sediments accumulated in the region in a cold bathyal condition of deposition. The clastic sediment is thought to have derived from the eastern upland where the Upper Cretaceous and Paleogene sedimentary rocks were exposed. It is supposed that the hiatus in the Late Miocene-Early Pliocene is a result of an upheaval of central Hokkaido, which unstabilized the sediment and changed bottom current condition.

The Early to Middle Miocene microfauna of the region is similar to those of the Japan Sea region, whereas the Late Miocene fauna is different in abundance of agglutinated foraminifera. Such faunal differences between the study area and Japan Sea region of Honshu in the Late Miocene are mainly due to the variable distances from the proto-Tsugaru Strait that let carbonate-saturated Pacific seawater into the Japan Sea.

Key words: Foraminifera, Hokkaido, Miocene, paleoenvironment, Pliocene

Introduction

Pioneering studies of the Miocene Foraminifera from Hokkaido were carried out by Asano (1952a; 1953a) and Yoshida (1958). These studies focused chiefly on the taxonomy of benthic foraminifera and ages based on a limited number of samples. Although subsequent studies have improved our knowledge of the foraminiferal fauna in Hokkaido (Ujiié *et al.*, 1977; Tai and Kato, 1981, 1983), an inherent difficulty exists in obtaining unweathered rock samples systematically from any surface section because exposures of the Neogene strata are limited.

In the Yufutsu area, Pacific coast of central Hokkaido, a number of boreholes have been drilled to explore hydrocarbon reservoirs in the Paleogene and Cretaceous since the discovery of natural gas in the Minamiyufutsu well in 1989 by Japan Petroleum Exploration Co. Ltd. ("JAPEX" henceforth; Figure 1). Information on the subsurface geology in the Yufutsu Oil and Gas Field is contained in several reports dealing with various aspects including drilling engineering, geochemistry and tectonics (Yufutsu Research Group of JAPEX Sapporo *et al.*, 1992; Fujii and Moritani, 1998; Kurita and Yokoi, 2000; Taketomi and Nishita, 2002; Kuniyasu and Yamada, 2004). Foraminifera and other microfossils such as diatoms and calcareous nannofossils have been studied from most of the borehole sections in this field. The studied intervals are mainly below the Pliocene with the help of systematically collected ditch cuttings and core samples. These data contains invaluable information on geohistory of Hokkaido and adjoining region.

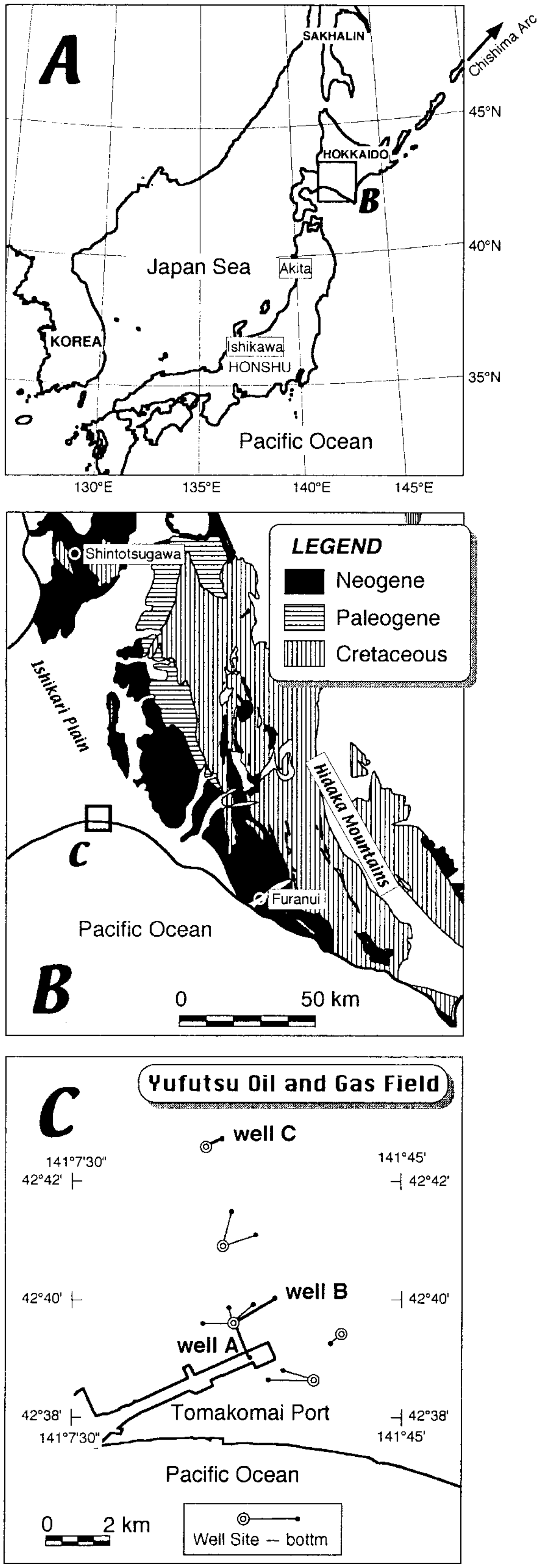
The purpose of this study is to describe the foraminiferal faunas of the Miocene-Pliocene occurring in the three subsurface sections of the Yufutsu Field and to explore their paleobathymetric and paleoceanographic implications for the consideration of the basin evolution.

Geologic setting

Hokkaido was in a complicated tectonic setting in the Miocene-Pliocene time due to such factors as the opening and rifting which originated the Japan Sea and upheaval of central Hokkaido as a consequence of the westward motion of the Chishima (Kuril) Arc, east of Hokkaido (Kimura and Kusunoki, 1997). Paleobathymetry and other paleoceanographic information on the basin deduced from benthic fossils can be a fundamental source of information for the consideration of basin evolution. However, very few such studies have been attempted in the Miocene-Pliocene of Hokkaido.

In southwestern Hokkaido, the Cretaceous, Paleogene and Neogene sedimentary rocks are generally distributed in ascending order in north-south belts to the west of the Hidaka Mountains, which forms a central axis (Figure 1B). The Neogene sequence extends further westward in the subsurface of the Ishikari Plain as revealed by many boreholes including the present ones.

In the Yufutsu area, Cretaceous granitoids forms the basement and the overlying succession in ascending order is as follows: The Ishikari Group (Eocene), Poronai Formation (Eocene), Minaminaganuma Formation (Oligocene), Takinoue Formation, "Biratori plus Karumai formations" and "Nina plus Quaternary formations" (Kurita and Yokoi, 2000). This study treats the stratigraphic interval from the Takinoue Formation to the lower part of the "Nina plus Quaternary formations". All of these formation names applied to subsurface sequence came from surface stratigraphy of the southern Hidaka region. However, surface stratigraphy applied to the subsurface is partly based on unpublished geologic information of JAPEX, and therefore mostly informal. Hiramatsu (2004) showed a correlation between the subsurface sections of Yufutsu area and the surface sections of the Hidaka coastal region based on diatom biostratigraphy. He indicated that the "Biratori plus Karumai formations" in the subsurface of the Yufutsu area is correlatable to the Nina Formation at the surface as to the geologic age, and the "Nina plus Quaternary formations" of the subsurface is younger in age than the exposed Nina Formation. It is worth mentioning



← **Figure 1.** Index map showing location of study well sections. Distribution of the Upper Cretaceous, Paleogene and Neogene formations shown in B is after compilation of Kato (1990).

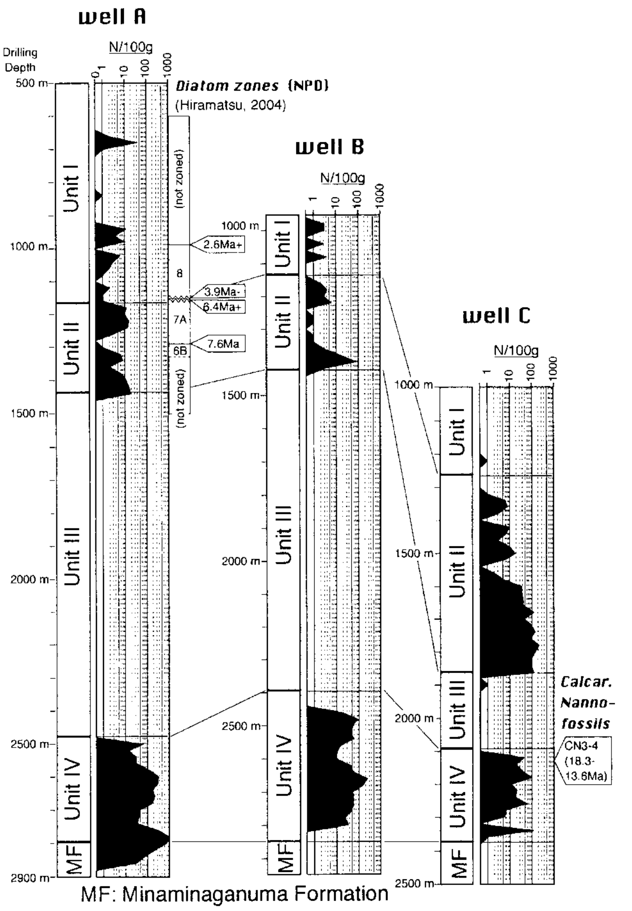


Figure 2. Stratigraphic correlation of wells studied indicating foraminiferal abundance (N/100 g) and diatoms and calcareous nannofossil zones. Scales of foraminiferal abundance (N/100 g; painted-out) graph are logarithmic, except 0–1.

here that the "Biratori Formation" has no formal definition and is not valid nomenclature, while the Karumai Formation has a formal one (Omura, 1930).

In order to overcome existing confusion on nomenclature, a simplified division of the subsurface into lithostratigraphic Units I to IV in descending order in the Neogene interval is proposed herein (Figure 2). Unit I corresponds to the lower interval of "Nina plus Quaternary formations"; Unit II to the "Biratori plus Karumai formations"; Unit III to the igneous rock interval of the Takinoue Formation; Unit IV to the siltstone-dominant interval of the Takinoue Formation of previous reports (e.g., Kurita and Yokoi, 2000).

Stratigraphy and biochronology

Three deviated hole sections, indicated as wells A, B and C, are studied (Figure 1C). Wells A and B were drilled from the same site while well C is approximately 6 km north of it. They were penetrated vertically from the surface down to approximately 1200 m, where they were kicked off with a slight deviation from the vertical (normally less than 30°) toward the target (Fujii and Moritani, 1998). Here, "depth" refers to drillers' depth measured using length of drilling assembly, while unit boundaries were taken from the wireline logs. The proposed lithostratigraphic units are briefly discussed.

Unit I is composed mainly of unconsolidated gravel and sand beds with occasional intercalation of sandy silt beds. Gravel beds consist of subrounded to rounded moderately sorted gravel, dark black to olive black shale, green rock, andesite and chert. A hiatus exists between Units I and II (Hiramatsu, 2004). An interval approximately 700 m from the base of Unit I was examined in well A, whereas lower interval of 100–200 m above Unit II were studied in the other two wells.

Unit II is characterized by olive-gray siliceous siltstone. It occasionally contains glauconite in the lower horizons. Diatoms and radiolarians were commonly found in it. Tubular fossils (about 1 mm in diameter) of *Makiyama chitanii* (Makiyama) were commonly found at 1700–1860 m depth in well C.

Unit III is composed mainly of basalt to basaltic andesite. Toward the top the unit is characterized by scoria and fine volcanic glasses indicating nonmarine conditions. This means that the volcano emerged above the sea and formed an island (Okubo, 2001). Furthermore, glauconite-bearing reworked sediments, which lie above Unit III, are considered to have formed on the volcanic mountain when it resubmerged (Hiramatsu, 2004).

Unit IV unconformably overlies the Oligocene Minaminaganuma Formation (Kurita and Yokoi, 2000). It is dominated by alternation of siltstone and claystone beds and intercalates of thin tuffs. Siltstone and silty mudstone show olive gray to medium gray color, calcareous and firm. Tuff beds are acidic, light gray and firm.

Geologic ages of these units were obtained from calcareous nannofossil and diatom biostratigraphies. Calcareous nannofossil *Sphenolithus heteromorphus* has its total range in the Early-Middle Miocene (18.2–13.6 Ma; Berggren *et al.*, 1995) and was found in a sample from 2140 m depth in well C in the upper part of Unit IV (JAPEX unpublished data, analysis by Kazue Watanabe). Therefore, this sample is correlatable to CN3–4 of Okada and Bukry (1980).

Hiramatsu (2004) reported the diatom biostratigraphy of Units I and II in well A, and recognized the following diatom zones defined by Yanagisawa and Akiba (1998).

Depth 540–980 m (Unit I): Rare-diatom-bearing interval. No zone could be defined.

Depth 1000–1140 m (Unit I): *Neodenticula koizumii–Neodenticula kamtschatica* Zone (NPD8: (3.9–3.5)–(2.7–2.6) Ma).

Depth 1160–1280 m (Unit II): *Rouxia californica* Zone (NPD7A: 7.6–6.4 Ma).

Depth 1300–1340 m (Unit II): Upper part of the *Thalassionema schraderi* Zone (NPD6B: (7.9–7.8)–7.6 Ma).

The above results reveal that an interval represented by the *N. kamtschatica* Zone (NPD7B: 5.5–(3.9–3.5) Ma) is completely missing in this section. Hiramatsu (2004) pointed out that the absence of NPD7B is not a result of erosion but a hiatus within the geologic structure, based on his interpretation of seismic profiles.

In addition, the *Denticulopsis hyalina* Zone (NPD4B: 14.9–13.1 Ma), *D. praedimorpha* Zone (NPD5B: 12.9–11.5 Ma) and *D. dimorpha* Zone (NPD5D: 10.0–9.2 Ma) were confirmed from glauconite-bearing reworked volcanic sediment in a well adjoining the present wells (Hiramatsu, 2004). This suggests that volcanic activity ceased until the late Middle Miocene, and the top of the volcano was already again below the surface of the sea.

Samples and methods

All samples used in this study are ditch cuttings with a sample spread of 20 m. Unit III, which is mainly volcanics, was not examined. A total of 164 samples were examined. Casing points were placed above the middle part of Unit II in every well (Fujii and Moritani, 1998). Although contamination caused by caving is inevitable, it is negligible below this level. Sampling interval of the well A is from 2860 m to 660 m; that of well B is from 2800 m to 980 m; that of well C is from 2360 m to 1220 m.

All samples were oven-dried. Subsamples of about 100 g were soaked in boiled sodium sulfate supersaturated solution for about three hours. After removing excess solution, soaked samples were left for more than three days. Then they were wet sieved through a 125 μm-opening screen. All specimens in the residues were picked and identified.

Results

Sixty-three species belonging to 41 genera were identified from 121 samples from three wells. Forty-three samples were confirmed to be barren. Abundance (Number of specimens per 100 g rock sample: N/100 g, hereinafter) of specimens in each well section is shown in Figure 2. Specimens are generally moderate in preservation in comparison with fossil specimens of the same age obtained in northern Japan (e.g., Hanagata, 2003), but the ones just below the volcanic rock interval of Unit III are considerably distorted.

In addition, ostracodes were found in Unit IV of well A, at 2834 m and 2840 m. Radiolarians, diatoms and large tubular fossils *Makiyama chitanii* (Makiyama) were commonly found in the washed residues in Unit II in all the wells. Diatoms were sparse or completely barren below the horizon of the Opal A/Opal CT transformation at about 1350 m in vertical depth in all the wells (Hiramatsu, 2004).

Occurrences of foraminifers are as follows in ascending order in each borehole section. Abundances of selected species are given in Figures 3–5.

Well A

The lowermost horizon of Unit IV, samples of 2860 m and 2840 m depth, yields abundant *Hippocrepinella variabilis*. *Ammonia yubariensis, Buccella citronea, Cribroelphidium imanishii, Poropullenia excavata, Glandulina* sp. 1, and *Nonionella miocenica* increase toward the depth of 2780 m. *Haplophragmoides* sp. 1 increases its abundance from 2780 m to 2680 m and disappears at the horizon. Then those species that characterize the lower sequence decrease in abundance and *Epistominella pacifica* characteristically increases toward the depth of 2600 m. In the uppermost part of Unit IV, 2540–2500 m, *Alveolophragmium indentatus* and other distorted specimens of *Bathysiphon, Martinottiella, Bulimina, Gyroidina* and *Cibicides* replace *A. yubariensis* and the other species dominant in the lower horizon.

The lower horizon of Unit IV was barren of planktonic foraminifers. *Neogloboquadrina continuosa* and other poorly preserved planktonic foraminifers occur scarcely and sporadically in the upper horizon, 2700–2520 m. Then they appear abundantly in the uppermost part of Unit IV (at 2500 m), which yielded 43 specimens. Of these, 40 specimens were indeterminable due to bad preservation. Hence, a precise age could not be deduced from planktonic foraminifera.

Numbers of foraminiferal specimens in Unit II are small, whereas the lowermost interval of Unit II, 1440–1360 m, yields relatively abundant specimens, up to 20 specimens per 100 g rock. Agglutinated foraminifera such as *A. indentatus* and other distorted specimens of *Cribrostomoides, Martinottiella and Re-*

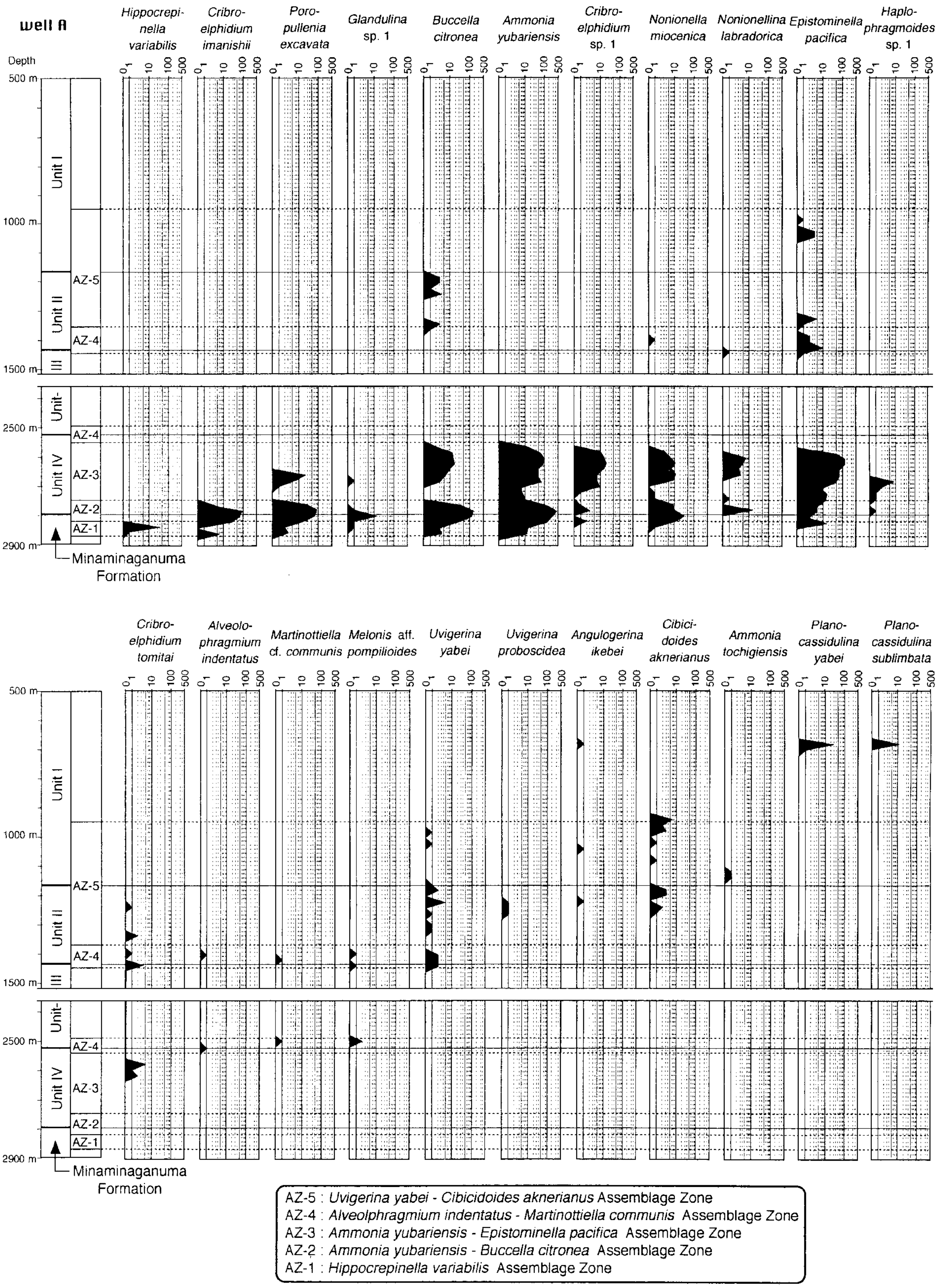


Figure 3. Occurrence of selected foraminifera in well A. Each painted-out graph shows absolute abundance in a sample (N/100 g). Scales are logarithmic, except 0–1.

curvoidella characterize this interval. It also yields various calcareous species including *Cribroelphidium tomitai, E. pacifica, Melonis affinis, Nonionella miocenica, Nonionellina labradorica, Planocassidulina praehelenae* and species of *Stilostomella*. Agglutinated foraminifera disappear between 1360 m and 1340 m, where N/100 g shows a minimum (2 specimens/100 g). From the horizon, calcareous foraminifera including *B. citronea, Bulimina striata, Angulogerina ikebei, Cibicidoides aknerianus, Uvigerina proboscidea* and *Uvigerina yabei* gradually increase upward; the number of specimens then decreases from 1180 m of Unit II; however *U. yabei, E. pacifica* and *C. aknerianus* occur continuously up to 940 m, about 200 m above the boundary of Units II and I.

Unit II was almost barren of planktonic foraminifera, but a solitary specimen of left-coiling *Neogloboquadrina pachyderma* was found at 1220 m.

Foraminifera were not found in almost all samples from the 920–700 m interval of Unit I, probably due to dilution by the coarse clastic sediment. A foraminiferal assemblage occurring at 680 m in Unit I is dominated by *Planocassidulina yabei* and *Planocassidulina sublimbata*, and *Cibicides refulgens* and *A. ikebei* accompany them.

Cretaceous and Paleogene reworked fossils are found between 1300 m and 520 m of Units II and I. Reworked specimens from Unit II are, though not abundant, probably derived from the upper horizon as cavings (fallen from the borehole wall) because they accompanied gravels of Unit I. They are distinguishable from autochthonous (*in situ*) fossils based on their degree of fossilization. Fossils derived from the upper Cretaceous such as *Silicosigmoilina futabaensis, Bathysiphon, Glomospira, Involutina* and other lituoliids occur in the lower interval, 1300–920 m, and those from the Paleogene such as *Cyclammina pacifica, Evolutinella subamakusaensis, Haplophragmoides* sp. B of Hanagata (2002) and *Poronaia poronaiensis* occur in the upper interval, 920–950 m.

Well B

Occurrence of foraminifera in well B is similar to that in well A.

The lowermost part of Unit IV, 2800–2760 m is characterized by *H. variabilis.* Above this horizon, *A. yubariensis, B. citronea, C. imanishii, N. miocenica* and *P. excavata* increase toward 2660 m; they then gradually decrease in abundance and are replaced by *E. pacifica* until 2460 m, the top of Unit IV. The assemblage dominated by *A. indentatus* and other agglutinated foraminifera which was observed in the uppermost part of Unit IV in well A was not found in well B.

The lowermost interval of Unit II, 1400–1380 m, is characterized by abundant agglutinated foraminifera such as *A. indentatus, Cribrostomoides subglobosus, Cyclammina* cf. *C. cancellata, G. miocenica* and *M. communis*. An interval of rare occurrence continues from 1340 m to 1240 m, then *U. yabei, C. aknerianus* and *C. tomitai* occurs continuously in 1220–980 m, across the boundary of Units II and I.

Planktonic foraminifera were absent in the entire sequence of well B.

Well C

Ammonia yubariensis dominates from the basal part of Unit IV, at 2360 m, to the upper part of Unit IV, at 2120 m. Other species are missing except for several specimens of *B. citronea* in the interval of 2360–2200 m. *Alveolophragmium indentatus* appears continuously in the upper part of Unit IV, 2180–2110 m. This interval also yields *M. communis, Recurvoidella spadix*, *B. citronea, Cassidulinoides porrectus, Gyroidina orbicularis, N. labradorica* and *Pullenia apertula*.

Abundance and diversity of benthic foraminifera increase from the basal part of Unit II up to around 1780 m, and decrease toward 1560 m. Diverse agglutinated species including *A. indentatus, C. subglobosus, G. miocenica, M. communis* and *Spirosigmoilinella compressa* occur in this interval. Calcareous foraminifera including *B. citronea, Bulimina marginata, B. striata, C. porrectus, C. aknerianus, E. pacifica, M. affinis, M.* aff. *M. pompilioides, P. praehelenae, Sphaeroidina bulloides* and *U. proboscidea* also occur continuously from 1860 m to 1680 m. Foraminifers are rare in the interval of 1520–1220 m, except for 1420–1340 m where *U. yabei, C. aknerianus* and comparable distorted specimens of them continuously occurred.

Poorly preserved planktonic foraminifera occur sporadically in the upper part of Unit IV, 2180 m and 2160 m, two samples of Unit II, 1840 m and 1680 m, and one sample of Unit I, 1220 m.

Biostratigraphy

This study defines the following assemblage zones of benthic foraminifera for the borehole sections based on the occurrences of dominant species, in ascending order, and correlates each zone among the three wells A, B, and C.

Hippocrepinella variabilis Assemblage Zone

This zone is defined in the lowermost interval of Unit IV of well A, at 2860–2840 m in depth. This assemblage zone is characterized by abundant occurrence of the nominate agglutinated species. The cor-

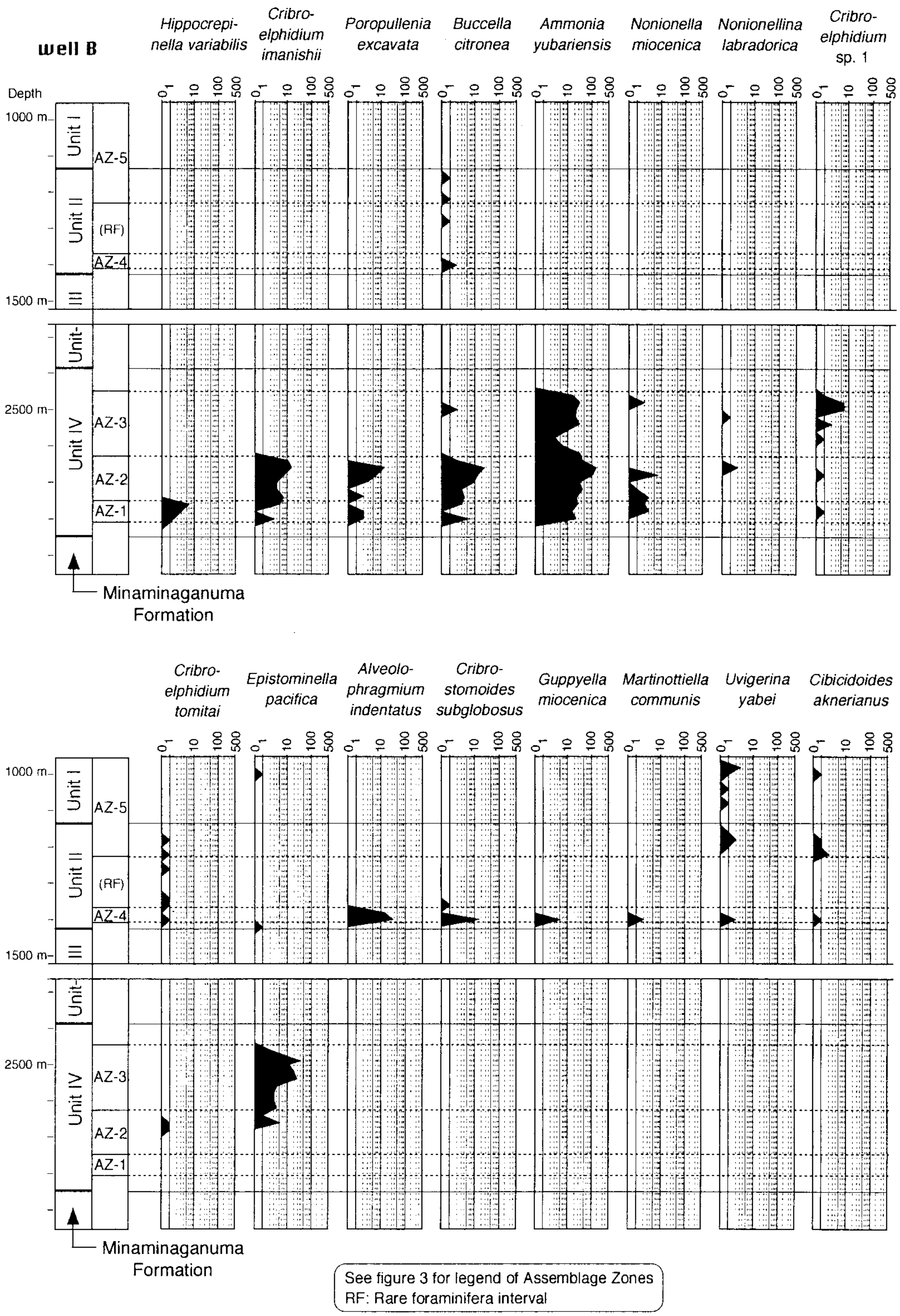


Figure 4. Occurrence of selected foraminifera in well B. See explanation of Figure 3.

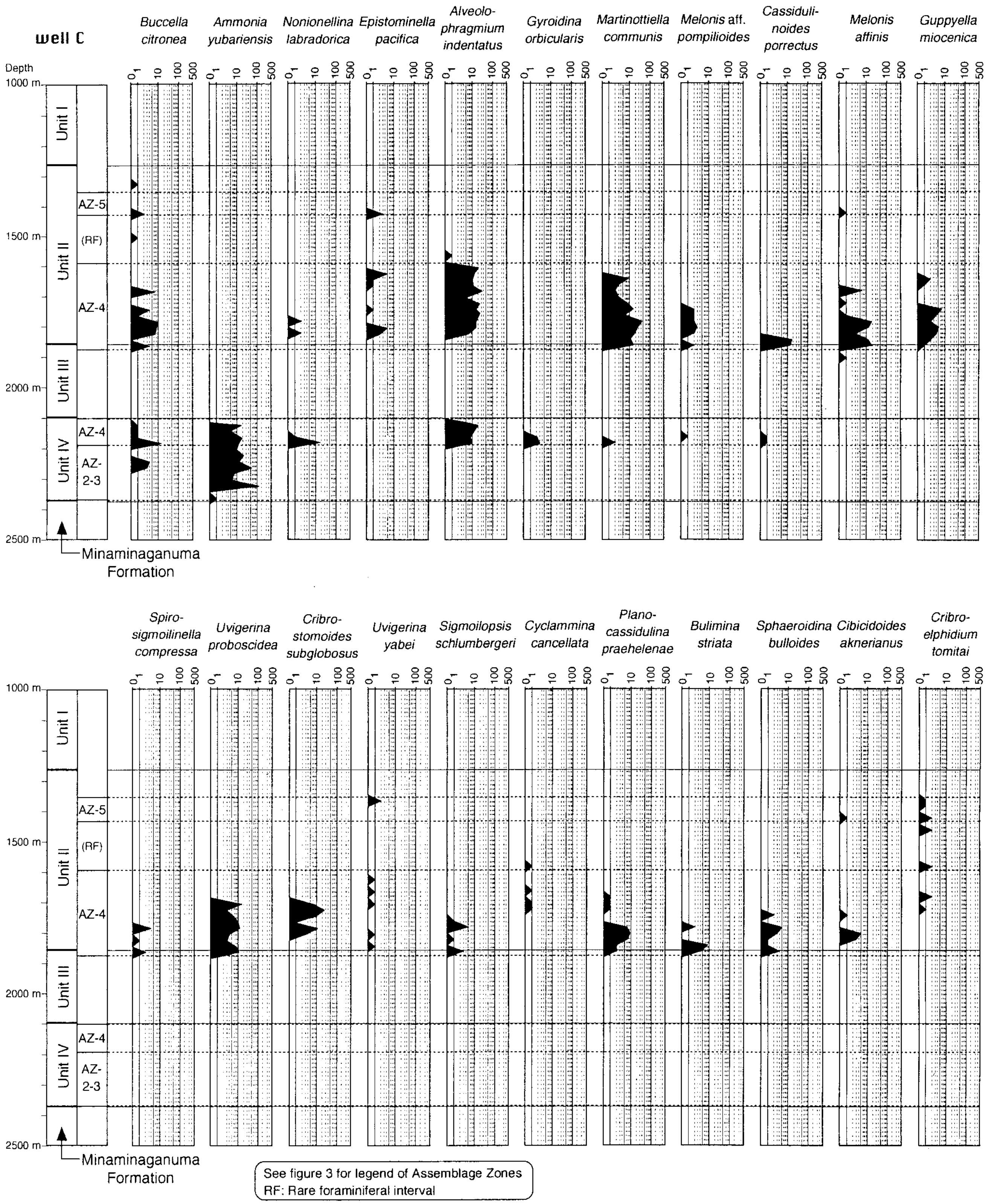


Figure 5. Occurrence of selected foraminifera in well C. See explanation of Figure 3.

relative interval exists in 2800–2760 m of well B, but the zone is not found in well C.

Ammonia yubariensis–Buccella citronea Assemblage Zone

This zone is defined in the lower interval of Unit IV in well A, at 2820–2762 m. This interval is characterized by abundant occurrences of the two nominate species with accompanying *Cribroelphidium imanishii*, *Poropullenia excavata* and *Nonionella miocenica.* The correlative interval exists at 2740–2640 m in well B. A potentially correlative interval of well C yields abundant *Ammonia yubariensis* but occurrence of *B. citronea* is rare in comparison with wells A and B.

Ammonia yubariensis–Epistominella pacifica Assemblage Zone

This zone is defined in the upper interval of Unit IV of well A, at 2740–2560 m. It is characterized by abundant occurrences of the two nominate species with rare occurrences of *Globobulimina* and *Cribroelphidium tomitai.* The correlative interval exists at 2620–2460 m of well B. *Ammonia yubariensis* occurs commonly in the potentially correlative upper horizon of Unit IV of well C; however, *E. pacifica* was absent. Therefore, accurate correlation of wells A and B with well C based on this assemblage zone cannot be achieved.

Alveolophragmium indentatus–Martinottiella communis Assemblage Zone

This zone is defined in the uppermost interval of Unit IV, 2180–2110 m and in the lower interval of Unit II, 1860–1600 m of well C. It is characterized by abundant occurrences of the two nominate species with other agglutinated species such as *Spirosigmoilinella compressa* and *Guppyella miocenica*. It also yields abundant calcareous species including *Uvigerina proboscidea* and *Melonis* aff. *M. pompilioides* in the lower horizon of Unit II. The diversities of the assemblage tends to decrease upward. Its correlative intervals are observed at 2540–2500 m and 1440–1360 m in well A and 1400–1380 m in well B.

Uvigerina yabei–Cibicidoides aknerianus Assemblage Zone

This zone is defined in the upper interval of Unit II to the lower interval of Unit I of well A, at 1340–940 m. Foraminiferal fossils are rare (less than 14 specimens/100 g), but the two nominate species continuously occur. *Bulimina striata, Cribroelphidium tomitai, Melonis affinis*, poorly preserved *Globobulimina* and *Fursenkoina* occur in this zone. Correlative intervals are observed at 1220–980 m in well B and 1420–1340 m in well C.

Paleoenvironment

Unit IV–III (?Early Miocene-Middle Miocene)

Hippocrepinella variabilis overwhelmingly dominates in the *H. variabilis* Assemblage Zone, the basal part of Unit IV. This species is an extinct species and its paleoecology is unknown. However, *Hippocrepinella* is a primitive unilocular foraminifer having a thin and finely agglutinated wall cemented by organic matter, which suggests the habitat of the taxon is likely to be under conditions of calcium carbonate undersaturation as seen in modern brackish salt marsh or estuaries. A reason for the absence of *H. variabilis* in well C is unknown at present.

The *A. yubariensis–B. citronea* Assemblage Zone yields abundant *Ammonia* and *Cribroelphidium*, which is suggestive of brackish–inner shelf conditions based on their Recent counterparts (e.g., Phleger, 1956; Matoba, 1970; Hayward and Hollins, 1994; Sen Gupta, 1999; Cann *et al.*, 2000; Kaminski *et al.*, 2002). The Early-Middle Miocene is generally considered as a warm period around the Japanese Islands (Matoba, 1984; Chinzei, 1991). The Hokkaido region was under the spell of temperate to subarctic conditions in the late Middle Miocene (Chinzei, 1986; Suzuki, 2000). These climatic interpretations were made mostly by molluscan fossils and are confirmed to microfaunal reports.

Epistominella pacifica shows an increasing trend in the *A. yubariensis–E. pacifica* Assemblage Zone, in the upper half of Unit IV. The species is found distributed in modern middle to lower bathyal cold waters of the North Pacific (1000–3800 m; Inoue, 1989) and is inferred to have lived in shallower water, probably the upper bathyal zone, in the Late Miocene-Pliocene (Hanagata and Watanabe, 2001). Other than this species no other species indicative of deeper marine conditions were recorded in the present material. The assemblages are mostly dominated by shallow sublittoral species represented by genera such as *Ammonia*, *Cribroelphidium* and *Nonionella*. Consequently, this assemblage zone is inferred to have been deposited in deeper water than that of the lower horizon based on the increase of *E. pacifica*, but accurate paleobathymetry is unknown at present due to insufficient information.

Agglutinated foraminiferal species *Alveolophragmium indentatus* and *Martinottiella communis* appear in the *A. indentatus–M. communis* Assemblage Zone, in the uppermost interval of Unit IV (Middle

Miocene). *Alveolophragmium indentatus* is an extinct species and *M. communis* prefers a water depth of 300–1200 m in the modern Northwest Pacific (Inoue, 1989). The bathymetric range which *M. communis* indicates almost corresponds to the upper-middle bathyal paleobathymetric zone (Akimoto and Hasegawa, 1989). Hence, a deeper bathyal condition of deposition is inferred for this horizon. An increase in agglutinated foraminifera suggests a decrease in calcium carbonate saturation. Occurrences of *E. pacifica* and other northwestern Pacific Recent bathyal taxa suggest cold water conditions, probably affected by the North Pacific Intermediate Water. This inference is in conformity with Chinzei's (1986) ''warm surface water with cold intermediate water'' model deduced from the molluscan fauna of Hokkaido.

In the sequence of Unit IV, diversity and abundances are generally higher in well A than in the other wells, and tend to decrease northwards. A reason for such geographical differences is presently unknown and more information is required.

Volcanic activity started close to the age of CN3–4 (18.3–13.6 Ma) and the top of the volcano eventually emerged from the surrounding waters as described previously. Thickness of Unit III, mainly volcanic, is approximately 1000 m at wells A and B, and approximately 250 m at well C.

It can be deduced that the water depth at the close of Unit IV was not deeper than 1000 m (thickness of volcanic rock interval), if no appreciable rapid subsidence occurred at the beginning of volcanic activity. A water depth of 1000 m corresponds to the middle bathyal bathymetric zone in the Recent Pacific off northeastern Japan (Akimoto and Hasegawa, 1989). Taking this into account, the depositional setting of Unit IV can be summarized as follows: assemblages in the *A. yubariensis–B. citronea* Assemblage Zone indicate sublittoral conditions; those in the *A. yubariensis–E. pacifica* Assemblage Zone indicate upper bathyal conditions; those in the *A. indentatus–M. communis* Assemblage Zone indicate upper middle bathyal conditions. However, it must be borne in mind that occurrence of an agglutinated-foraminifera-dominant fauna would be related not only to differences in paleobathymetry but also to a historical decrease of carbonate saturation caused by isolation of a basin from the outer ocean.

Occurrences of planktonic foraminifera are quite scarce in Unit IV, except at 2500 m in well A containing many specimens. This suggests that the distribution of planktonic foraminifera was primarily prevented by brackish water in the shallow marine setting while progressive inflow of open marine water enabled distribution of planktonic foraminifera in the Middle Miocene.

Unit II (? Middle-Late Miocene)

Alveolophragmium indentatus–Martinottiella communis Assemblage Zone, lower interval of Unit II in well C yields abundant and diverse foraminifera. Some extant species provide information on possible paleobathymetry;

Uvigerina proboscidea: 90–539 m around the Japanese Islands (Asano, 1958).

Uvigerina yabei: 200–2000 m, Northwest Pacific (Inoue, 1989, as *U. akitaensis*).

Bulimina marginata: 60–180 m, Northwest Pacific (Inoue, 1989).

Bulimina striata: 150–1200 m, Northwest Pacific (Asano, 1958; Inoue, 1989).

Cibicidoides aknerianus: 135–1000 m, Japan Sea and Northwest Pacific (Ishiwada, 1964; Inoue, 1989, as *Cibicides asanoi*).

Hanzawaia nipponica: 64–155 m, Northwest Pacific (Ishiwada, 1964).

Sphaeroidina bulloides: 42–1500, around the Japanese Islands (Asano, 1957; Inoue, 1989).

On the basis of this record, this horizon seems to have been deposited under the upper bathyal zone (approximately 170–550 m deep in Northwestern Pacific; Akimoto and Hasegawa, 1989) or deeper, under the effect of cold intermediate water.

No shallow marine faunal evidence is seen from the basal part of Unit II. Hence, it is inferred that the basin underwent subsidence of nearly 1000 m after the deposition of volcanic rock, or continued to subside after the deposition of Unit IV. Accumulation of very little sediment on the volcanic mountain is due to a very slow sedimentation rate evidenced by deposition of glauconite-bearing sediment at the basal part of Unit II as discussed by Hiramatsu (2004).

Diversity and abundances of foraminiferal assemblages decrease upward in Unit II up to the top of the *A. indentatus–M. communis* Assemblage Zone (around 1360 m in well A; 1360 m in well B; 1560 m in well C). Most of the agglutinated foraminifera including *A. indentatus* and *M. communis* disappear around this level. Then onwards diversity and abundance show an upward-increasing trend. It is surmised that the site of deposition witnessed a shallowing condition from middle bathyal to upper bathyal if we accept the supposition that such a faunal difference mirrors differences in paleobathymetry.

There is no appreciable change in the composition of fauna, though diversity and abundance fluctuates, in the upper part of Unit II, the *U. yabei–C. akneria-*

nus Assemblage Zone (Late Miocene). The fluctuation may be ascribed to changes in paleoceanographic conditions such as primary productivity, dissolved oxygen level or calcium carbonate saturation inferred from biogenic siliceous sediment of Unit II. Stable occurrences of *U. yabei* and *E. pacifica* suggest a higher tolerance of these species to such environmental changes.

Planktonic foraminifera are too rare to discuss their paleoenvironment. Occurrence of a single specimen of left-coiling *Neogloboquadrina pachyderma* at 1220 m (Unit II) of well A suggests the influence of cold water because it is found distributed in the Oyashio water region of the modern Pacific Ocean (Bé, 1977; Thompson and Shackleton, 1980).

Unit I (Pliocene-)

The lower part of Unit I below 940 m in well A and the same horizon in wells B and C yielded species similar to those of the upper part of Unit II such as *Uvigerina yabei*, *Cibicidoides aknerianus* and *Epistominella pacifica* and we regarded this interval as part of the *U. yabei–C. aknerianus* Assemblage Zone, though a hiatus exists between Units II and I. This assemblage indicates deeper bathymetric conditions than the sublittoral zone and also the effects of cold intermediate water. It is difficult to surmise that the discontinuity between Units II and I was formed on land, and it is evident that the discontinuity existed seaward without conspicuous change in the water depth.

The foraminiferal assemblage found at 680 m in well A is characterized by dominance of *Planocassidulina sublimbata* and *P. yabei* (88% in total). *Planocassidulina yabei* is reported from 80–800 m around the Japanese Islands and is a cold-water species (Inoue, 1989). A modern cassidulinids-dominant fauna is reported from a water depth of 600–900 m on the Erimo Bank, south of Hokkaido, where cold subarctic waters exist (Ishiwada, 1964). Consequently, an upper or middle bathyal condition is inferred for this assemblage. Associated *Cibicides refulgens* and *Lobatula* cf. *L. lobatula* are characterized by their attaching habitats (Kitazato, 1988), suggesting the existence of objects for attachment.

Abundant reworked fossils occurred in Unit I of well A (Figure 6). These are obviously derived from Upper Cretaceous and Paleogene sediments. This evidences that the Hidaka Mountains rose and the Upper Cretaceous and Paleogene strata were subjected to erosion in the Late Pliocene, after NPD8 ((3.9–3.5)–(2.7–2.6) Ma). Then, the basin was filled in by sediments to the present level.

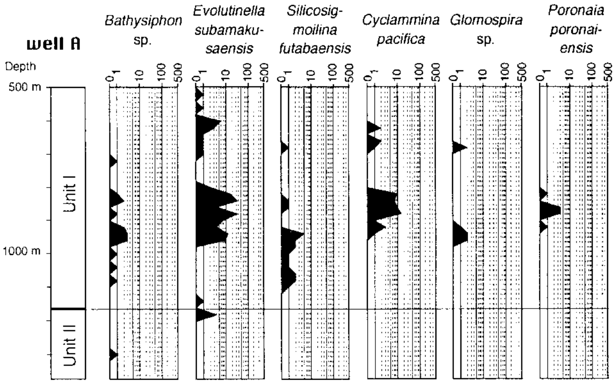


Figure 6. Occurrence of reworked Cretaceous and Paleogene foraminifera from Unit I of well A. See explanation of Figure 3.

Comparison with other areas

In this section, the Miocene foraminiferal fauna of the Yufutsu area are compared with those of other regions of northern Japan, further to infer the paleoenvironmental setting.

Surface sections of Hokkaido

Asano (1953a) reported foraminifera from the Miocene Nishitoppu Group and overlying Shintotsugawa Group in the Shintotsugawa area, Kabato region, Japan Sea side of Hokkaido. The Wakkauenbetsu Formation, upper part of the Nishitoppu Group, yielded *Nonionella hanzawai, Plectofrondicularia japonica, Plectofrondicularia miocenica, Bolivina marginata, Ammonia tochigiensis, Ammonia yubariensis* and *Valvulineria nipponica.* The Shintotsugawa Group is characterized by *Cribroelphidium imanishii, Nonionella miocenica, Epistominella japonica* and *Virgulina miocenica*, which show deepening of the basin. Foraminiferal faunas in the region are similar to the Yufutsu area in the occurrence of species like *Ammonia yubariensis* and *Cribroelphidium imanishii.* However, comparison of faunas between these two areas is presently difficult because the geologic age of the Nishitoppu and Shintotsugawa Groups is not well understood. The unconformity between the Nishitoppu and Shintotsugawa Groups is an erosional surface on land. Such shoaling of the basin, however, is not observed in the Yufutsu area. This suggests that the tectonics of the basin in the Miocene was different between these two regions at the time the basal part of the Shintotsugawa Group was deposited.

Tai and Kato (1981) restudied foraminifera of the Wakkauenbetsu Formation. They distinguished two types of assemblages. Their ''lower assemblage'' is characterized by abundant *Ammonia* species similar to the foraminiferal fauna of Unit IV in this study. In addition, their data indicate an upward-deepening trend as evidenced by the decrease of *Ammonia* and increase of *Uvigerina, Epistominella* and agglutinated foraminifera, which is closely similar to our present study in the Yufutsu area. Their ''upper assemblage'' which is characterized by abundant *Plectina* and other agglutinated taxa is not observed in the Yufutsu area. This is probably because such deep marine conditions did not occur or were concealed in the volcanic rock interval of Unit III in the Yufutsu area. They pointed out the similarity of the foraminiferal fauna with Miocene faunas of the Japan Sea region in Honshu such as those of the Nishikurosawa Formation in the Oga Peninsula, Akita Prefecture, Sugota Formation in Akita Prefecture and Higashi-innai and Najimi Formations in the Noto Peninsula, Ishikawa Prefecture.

Tai and Kato (1983) examined the Miocene foraminiferal fauna of the Furanui Formation in southern Hokkaido, east of the Yufutsu area. They reported dominant calcareous foraminifera from the lower horizon and dominant agglutinated foraminifera from the upper horizon of the Furanui Formation, but there were not enough samples to analyze any stratigraphic change in the assemblages. The *Ammonia*-dominant fauna in the lower horizon and an upward increase of agglutinated foraminifera are similar to what was observed in Unit IV of the Yufutsu area.

The similarity of the faunal change that occurred in Unit IV of the Yufutsu area to that reported by Tai and Kato (1981, 1983) is important in that the transgression seen in these areas is thought to have been related to the tectonic activity which generated the Japan Sea in the Early Miocene (Otofuji *et al*., 1985). The Miocene transgression revealed in this study, in turn, suggests that the eastern shoreline of the proto-Japan Sea was located east of Yufutsu and also in the areas of the Takinoue and Furanui Formations. In addition, the Japan Sea at the time of its initiation was brackish, probably due to a strong input of fresh terrestrial water.

Japan Sea region of Honshu

The Early-Middle Miocene foraminiferal fauna of the Yufutsu area is generally similar to that of the Japan Sea regions of Honshu in the abundance of *Ammonia* and other calcareous shallow marine species (Matsunaga, 1963; Nomura, 1992a). However, the Yufutsu fauna lacks subtropical taxa such as *Miogypsina* and *Operculina*, indicating colder conditions than Honshu (Tai, 1959). Absence of globorotaliid planktonic foraminifera from Hokkaido also supports colder surface water conditions than Honshu, where diverse globorotaliid foraminifers were reported (e.g., Saito and Maiya, 1973; Maiya, Saito and Sato, 1976). Such a longitudinal difference in paleoclimatic conditions is in conformity with studies of molluscan fossils (Chinzei, 1986, 1991; Suzuki, 2000).

On the contrary, the Late Miocene fauna of the Yufutsu area shows a distinct contrast with that of the Japan Sea region. Late Miocene to Early Pliocene foraminiferal faunas of the Japan Sea region have been studied by many workers (e.g., Asano, 1950a; Matsunaga, 1963; Hanagata, 2003). They are characterized by abundant agglutinated foraminifers such as *Spirosigmoilinella compressa*, *Miliammina echigoensis*, *Martinottiella communis*, *Alveolophragmium indentatus*, *Cyclammina japonica* and diverse lituolids suggesting a calcium carbonate-undersaturated condition. The Japan Sea fauna is partly similar to the bathyal assemblages recognized in the *A. indentatus–M. communis* Assemblage Zone, uppermost part of Unit IV and lowermost part of Unit II of the Yufutsu area. However, the Upper Miocene fauna in the *Uvigerina yabei-Cibicidoides aknerianus* Assemblage Zone is dominated by calcareous foraminifera such as *Epistominella pacifica* and *Uvigerina* spp. and thus different from those of the Japan Sea region.

Such regional differences of Upper Miocene faunas could be attributed to the geographic distance from the proto-Tsugaru Strait which introduced outer ocean water saturated by calcium carbonate into the Japan Sea. The Japan Sea formed a large embayment due to closure of its southern connection during the Middle to Late Miocene (Figure 7) with waters undersaturated in calcium carbonate due to terrestrial water input and also to widespread silica-rich seawater around the Tsugaru region (Hanagata, 2003).

Summary

The history of the Miocene to Pliocene sequence in the Yufutsu Oil and Gas Field region has been summarized based on the stratigraphic occurrence of foraminiferal assemblages (Figure 8).

Onset of submergence relating to the Japan Sea generation in this region is marked by the occurrence of *Hippocrepinella variabilis* in the *H. variabilis* Assemblage Zone, suggesting brackish-water conditions with strong influence of fresh water influx. Brackish conditions continued as inferred by the *Ammonia-Cribroelphidium* dominant assemblages in the *Ammonia yubariensis-Buccella citronea* Assemblage Zone. Further upwell in this sequences, deeper and cold-

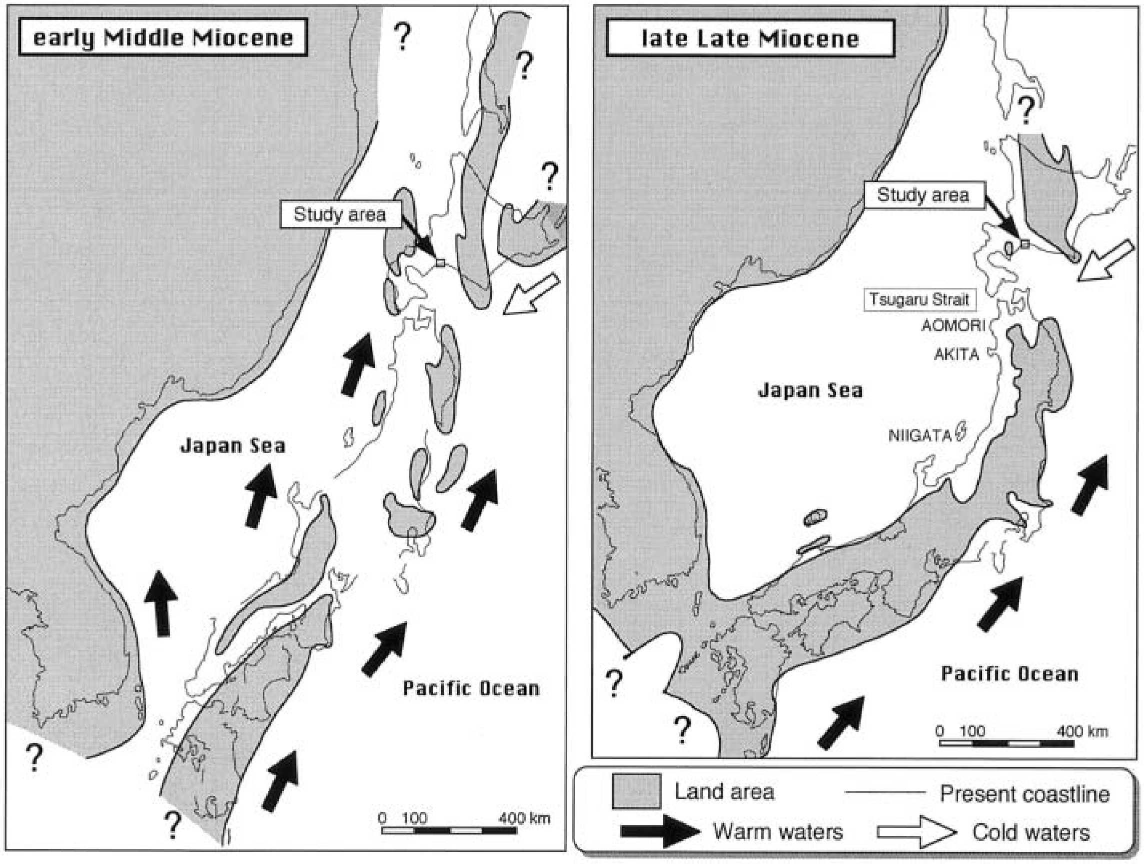
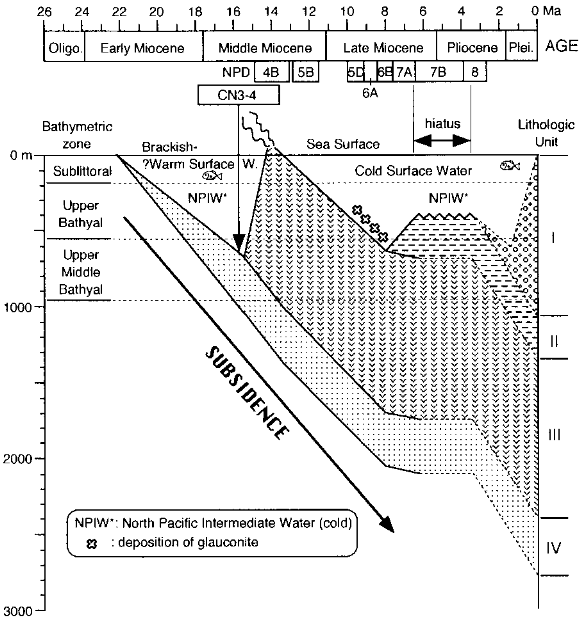


Figure 7. Paleogeography and distribution of seawaters in early Middle Miocene (left) and late Late Miocene (right). Paleogeographic maps are after Iijima and Tada (1990) and distribution of seawaters are after Chinzei (1986; 1991), both with slight modification.



← **Figure 8.** Schematic geohistory diagram showing paleobathymetric change and subsidence history in the location of wells A and B. Vertical axis shows water depth and tectonic movement (subsidence), and horizontal axis shows geologic age from left to right. Compaction of sediment is not taken into consideration. Thickness of each lithologic unit is after Fujii and Moritani (1998). Water depth during the hiatus in the Late Miocene-Early Pliocene is unknown, therefore tectonic motion in that time interval is uncertain. Note that the volcano which deposited Unit III emerged above the sea between or in the ages of the CN3–4 and NPD5D.

water conditions are implied by the record of species like *Epistominella pacifica* in the *A. yubariensis–E. pacifica* Assemblage Zone and agglutinated foraminifera in the *Alveolophragmium indentatus–Martinottiella communis* Assemblage Zone. The above faunal change is similar to that of the Japan Sea region.

During the Middle Miocene, close to the time of

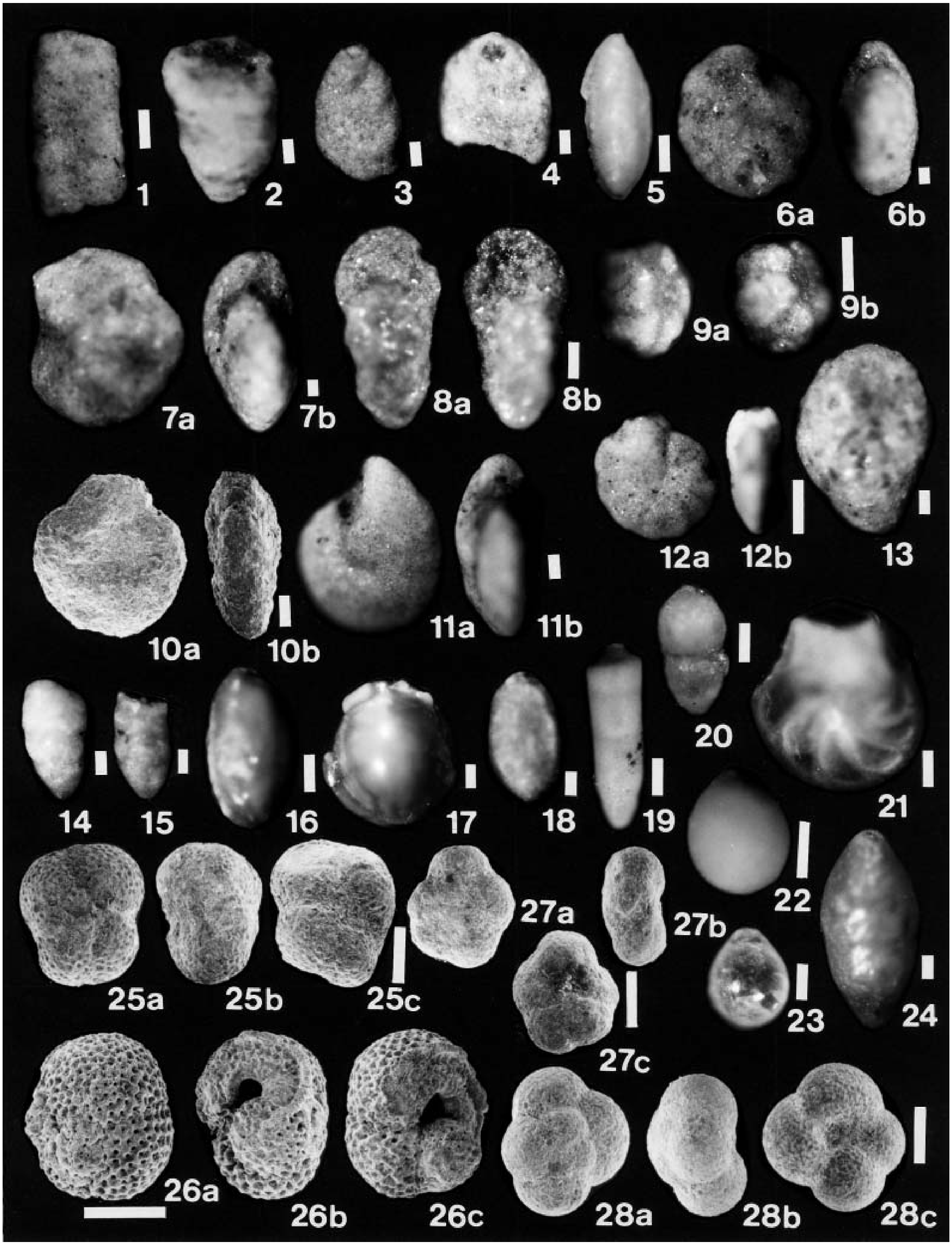

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Figure 9

CN3–4 (18.2–13.6 Ma), volcanic activity started and basalt-basaltic andesite was accumulated. The volcanic mountain eventually grew above the surface of the sea.

The volcanic island was again submerged under the sea in the Middle Miocene and then siliceous sediment was accumulated. Paleobathymetry reached bathyal depths and assemblages of the *A. indentatus–M. communis* Assemblage Zone appeared again. Agglutinated foraminifers disappear in or before the time of NPD6B (8.5–7.6 Ma) and are replaced by low-diversity calcareous foraminiferal assemblages of the *Uvigerina yabei–Cibicidoides aknerianus* Assemblage Zone that continued until NPD7A (7.6–6.4 Ma). Late Miocene foraminiferal faunas are dominated by calcareous taxa such as *Epistominella pacifica* and *Uvigerina proboscidea* and *U. yabei.* Here the faunal record differs from that of the Japan Sea region, where agglutinated foraminifera are dominant. This is probably attributable to the distance from the proto-Tsugaru Strait that let seawater from the Pacific Ocean into the Japan Sea (embayment) to the Yufutsu area, which was affected mainly by outer ocean water.

⬅ **Figure 9.** Foraminifera from the Yufutsu Oil and Gas Field. All scale bars = 0.1 mm.
1. *Bathysiphon* sp. Well C, 1740 m, Unit II, side view. **2–4.** *Hippocrepinella variabilis* Voloshinova. 2: Well B, 2800 m, Unit IV, side view; 3, 4: Well A, 2840 m, Unit IV, side views of distorted specimens. **5.** *Spirosigmoilinella compressa* Matsunaga. Well C, 1860 m, Unit II, side view. **6a–7b.** *Cribrostomoides subglobosus* (Cushman). 6: Well C, 720 m, Unit II, 6a, side view, 6b, apertural view; 7: Well B, 1360 m, Unit II, 7a, side view, 7b, apertural view. **8a, b.** "*Haplophragmoides*" sp. 1. Well A, 2680 m, Unit IV, 8b, apertural view of distorted specimen, 8a, opposite of 8b. **9a, b.** *Recurvoidella spadix* (Kuznetsova). Well A, 1380 m, Unit II, 9a and 9b, opposite sides. **10a, b.** *Alveolophragmium indentatus* (Voloshinova). Well C, 1560 m, Unit II, 10a, side view, 10b, apertural view. **11a, b.** *Cyclammina cancellata* Brady. Well C, 1580 m, Unit II, 11a, side view, 11b, apertural view. **12a, b.** *Cyclammina pseudopusilla* Hanagata. Well A, 1420 m, Unit II, 12a side view, 12b, apertural view. **13.** *Guppyella miocenica* (Cushman). Well C, 1640 m, Unit II, side view. **14, 15.** *Martinottiella communis* (d'Orbigny). Well C, 1760 m, Unit II, side views. **16.** *Quinqueloculina* sp. Well A, 1400 m, Unit II, side view. **17.** *Pyrgo* sp. Well A, 1420 m, Unit II, frontal view. **18.** *Sigmoilopsis schlumbergeri* (Silvestri). Well C, 1780 m, Unit II, side view. **19.** "*Nodosaria*" sp. 1. Well A, 2800 m, Unit IV, side view. **20.** *Nodosaria* sp. Well A, 2800 m, Unit IV, side view. **21.** ?*Lenticulina* sp. Well C, 1340 m, Unit II, side view. **22.** *Lagena* sp. Well A, 1340 m, Unit II, side view. **23.** *Fissurina* sp. Well C, 1800 m, Unit II, side view. **24.** *Glandulina* sp. 1. Well A, 2800 m, Unit IV, side view. **25a–c.** *Neogloboquadrina continuosa* (Blow). Well A, 2660 m, Unit IV, 25a, dorsal view, 25b, peripheral view, 25c, umbilical view. **26a–c.** *Neogloboquadrina pachyderma* (Ehrenberg). Well A, 1220 m, Unit II, 26a, dorsal view, 26b, peripheral view, 26c, umbilical view. **27a–c.** *Globigerina* cf. *G. ciperoensis angustiumbilicata* Bolli. Well A, 2500 m, Unit IV, 27a, dorsal view, 27b, peripheral view, 27c, umbilical view. **28a–c.** *Globigerina* cf. *G. falconensis* Blow. Well C, 1220 m, Unit I, 28a, dorsal view, 28b, peripheral view, 28c, umbilical view.

➡ **Figure 10.** Foraminifera from the Yufutsu Oil and Gas Field. All scale bars = 0.1 mm.
1a–c. *Globigerina* cf. *G. praebulloides* Blow. Well A, 2660 m, Unit IV, 1a, dorsal view, 1b, peripheral view, 1c, umbilical view. **2a, b.** *Globoturborotalia* cf. *G. woodi connecta* (Jenkins). Well A, 2660 m, Unit IV, 2a, dorsal view, 2b, umbilical view. **3a–c.** *Bolivina* sp. Well A, 2820 m, Unit IV, 3a, b, side view, 3c, apertural view. **4–6b.** *Cassidulinoides porrectus* (Heron-Allen and Earland). 4, 5: well C, 1860 m, Unit II, frontal view; 6a, b: well C, 1840 m, Unit II, 6a, frontal view, 6b, peripheral view. **7.** *Globocassidulina* cf. *G. subglobosa* (Brady). Well A, 1040 m, Unit I, frontal view. **8a, b.** *Planocassidulina praehelenae* Nomura. Well C, 1780 m, Unit II, 8a, frontal view, 8b, edge view. **9a, b.** *Planocassidulina sublimbata* (Asano and Nakamura). Well A, 680 m, Unit I, 9a, frontal view, 9b, edge view. **10a, b.** *Planocassidulina yabei* (Asano and Nakamura). Well A, 680 m, Unit I, 10a, frontal view, 10b, edge view. **11.** *Bulimina marginata* d'Orbigny. Well C, 1780 m, Unit II, side view. **12.** *Bulimina striata* d'Orbigny. Well C, 1840 m, Unit II, side view. **13, 14.** *Uvigerina proboscidea* Schwager. 13 and 14: Well C, 1740 m, side views. **15.** *Uvigerina yabei* Asano. Well C, 1700 m, Unit II, side view. **16a, b.** *Angulogerina ikebei* Husezima and Maruhasi. Well A, 680 m, Unit II, 16a, side view, 16b, apertural view. **17a, b.** *Angulogerina* sp. Well C, 2180 m, Unit IV, 17a, side view, 17b, apertural view. **18.** *Stilostomella* cf. *S. lepidula* (Schwager). Well A, 1420 m, Unit II, side view of broken specimens. **19a–c.** *Gavelinopsis* sp. Well A, 1420 m, Unit II, 19a, dorsal view, 19b, peripheral view, 19c, umbilical view. **20a–c.** *Cibicidoides aknerianus* (d'Orbigny). Well A, 940 m, Unit I, 20a, dorsal view, 20b, peripheral view, 20c, umbilical view. **21a–22c.** *Epistominella pacifica* (Cushman). 21: Well A, 1420 m, Unit II, 21a, dorsal view, 21b, peripheral view, 21c, umbilical view; 22: Well A, 2680 m, Unit IV, 22a, dorsal view, 22b, peripheral view, 22c, umbilical view. **23a–c.** *Cibicides refulgens* de Montfort. Well A, 680 m, Unit I, 23a, dorsal view, 23b, peripheral view, 23c, umbilical view. **24a–c.** *Lobatula* cf. *L. lobatula* (Walker and Jacob). Well A, 2720 m, Unit IV, 24a, dorsal view, 24b, peripheral view, 24c, umbilical view. **25.** *Sphaeroidina bulloides* Deshayes. Well C, 1780 m, Unit II, side view.

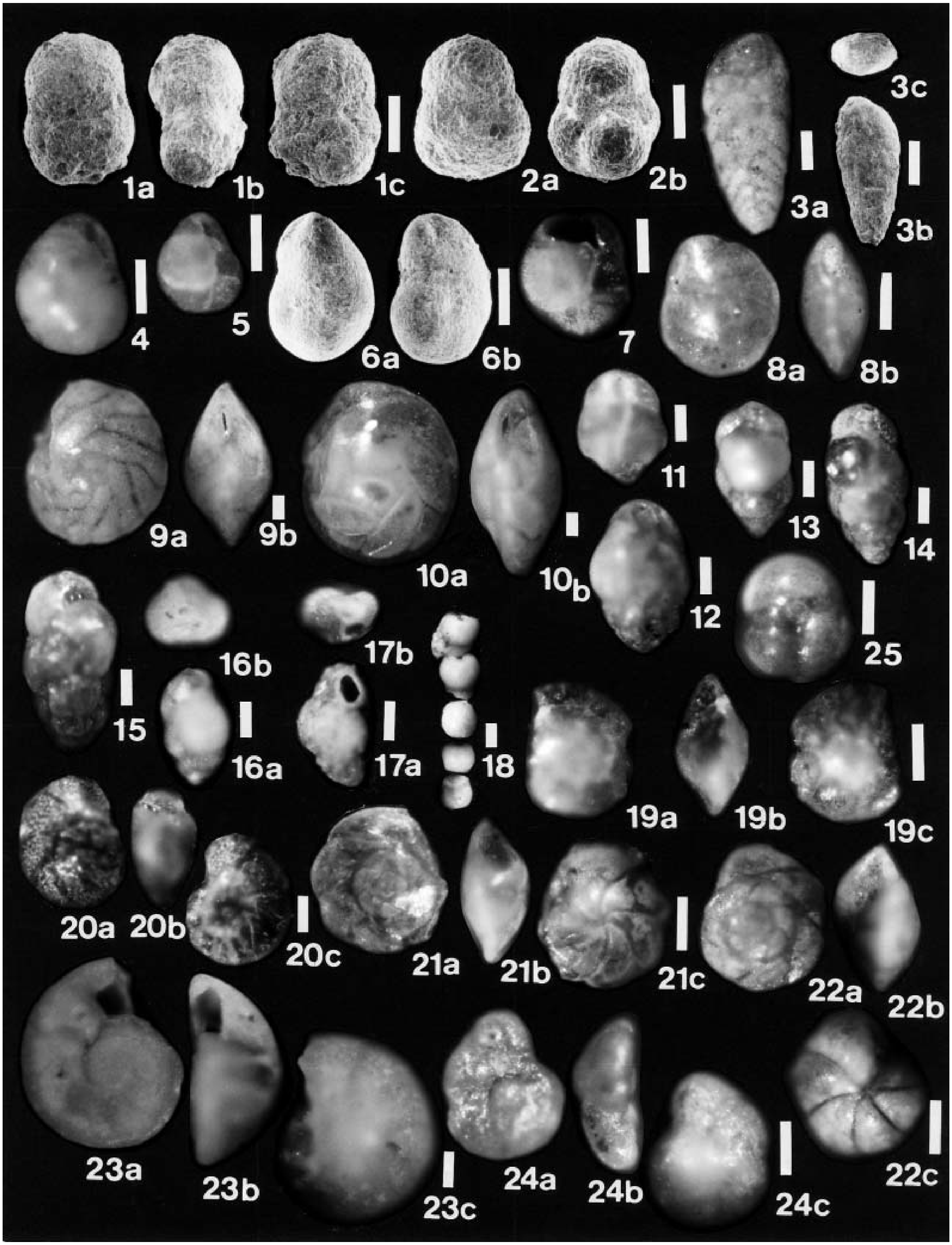
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Figure 10

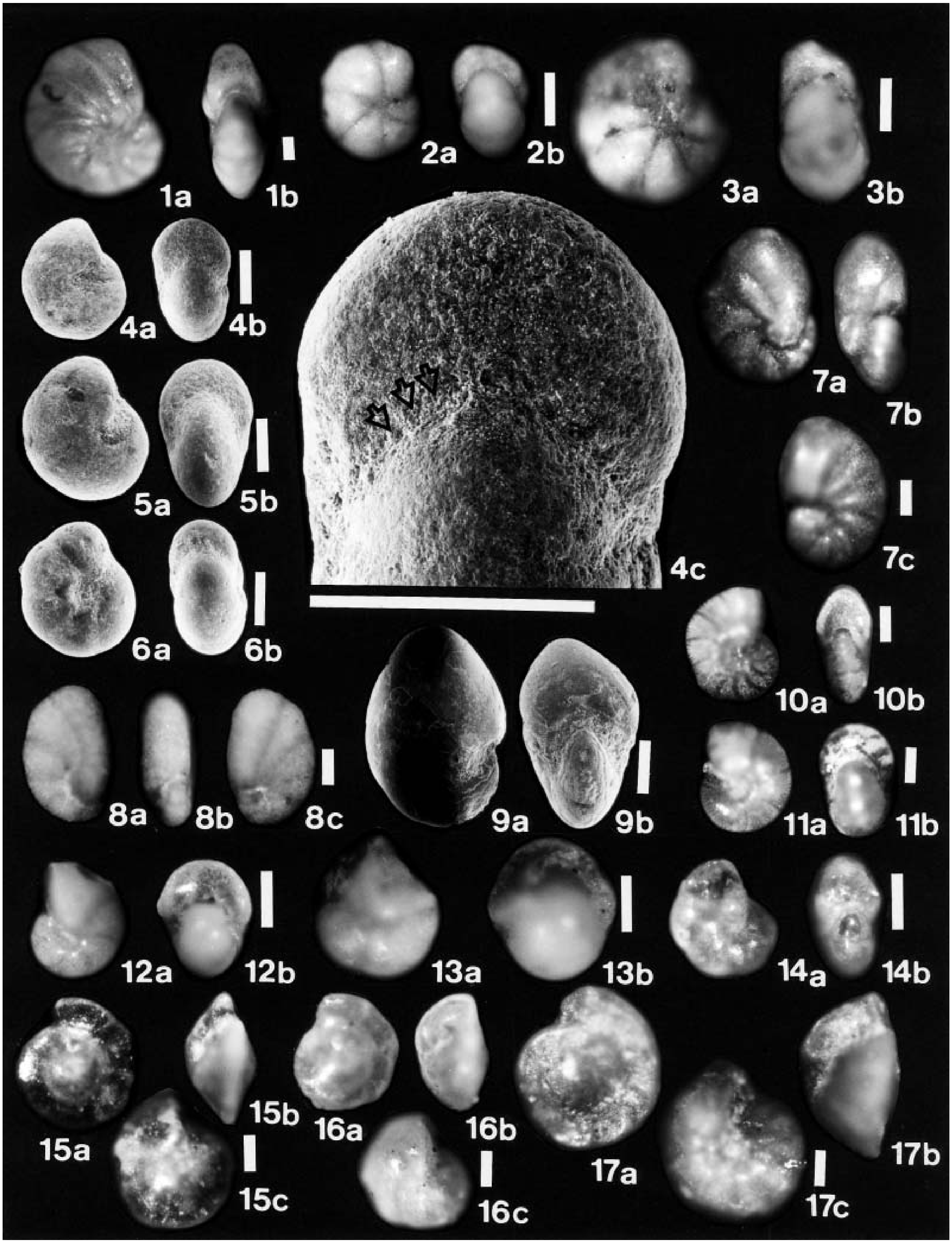
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Figure 11

Late Miocene to Early Pliocene strata are missing in the region. In the Late Pliocene during NPD8 ((3.9–3.5)–(2.7–2.6) Ma), the coarse-grained sediment of *U. yabei–C. aknerianus* Assemblage Zone started to accumulate under cold bathyal conditions. The Late Pliocene sediment was derived from the Upper Cretaceous and Paleogene rocks exposed in the eastern upland.

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⬅ **Figure 11.** Foraminifera from the Yufutsu Oil and Gas Field. All scale bars = 0.1 mm.
1a, b. *Nonion nakosoense* Asano. Well B, 1040 m, Unit I, 1a, side view, 1b, apertural view. **2a–6b**. *Poropullenia excavata* Voloshinova. 2, 3: Well A, 2660 m, Unit IV, 2a, 3a, side views, 2b, 3b, apertural views; 4–6, Well A, 2780 m, Unit IV, 4a, 5a, 6a, side views, 4b, 5b, 6b, apertural views, 4c, enlarged apertural face. Note that small pores are arranged on the base of the apertural face. **7a–c.** *Nonionella miocenica* Cushman. Well A, 2780 m, Unit IV, 7a and 7c, opposite side views, 7b, apertural view. **8a–c.** *Nonionella* cf. *N. turgida* (Williamson). Well B, 1220 m, Unit II, 8a and 8c, opposite side views, 8b, apertural view. **9a, b.** *Nonionellina labradorica* (Dawson). Well A, 1440 m, Unit II, 9a, side view, 9b, apertural view. **10a, b.** *Melonis affinis* (Reuss). Well A, 1200 m, Unit II, 10a, side view, 10b, apertural view. **11a, b.** *Melonis* aff. *M. pompilioides* (Fichtel and Moll). Well C, 1760 m, Unit II, 11a, side view, 11b, apertural view. **12a, b.** *Pullenia apertula* Cushman. Well A, 980 m, Unit I, 12a, side view, 12b, apertural view. **13a, b.** *Pullenia* cf. *P. bulloides* (d'Orbigny). Well C, 2180 m, Unit IV, 13a, side view, 13b, apertural view. **14a, b.** *Pullenia* cf. *P. salisburyi* K.C. and R.E. Stewart. Well C, 1820 m, Unit II, 14a, side view, 14b, apertural view. **15a–c.** *Oridorsalis* cf. *O. umbonatus* (Reuss). Well C, 1820 m, Unit II, 15a, dorsal view, 15b, peripheral view, 15c, umbilical view. **16a–c.** *Gyroidina komatsui* Aoki. Well C, 1820 m, Unit II, 16a, dorsal view, 16b, peripheral view, 16c, umbilical view. **17a–c.** *Gyroidina orbicularis* (Parker, Jones and Brady). Well C, 2180 m, Unit II, 17a, dorsal view, 17b, peripheral view, 17c, umbilical view.

➡ **Figure 12.** Foraminifera from the Yufutsu Oil and Gas Field. All scale bars = 0.1 mm.
1a–c. *Hanzawaia nipponica* Asano. Well C, 1860 m, Unit II, 1a, dorsal view, 1b, peripheral view, 1c, umbilical view. **2a–3c.** *Buccella citronea* Leonenko. 2: Well A, 2780 m, Unit IV, 2a, dorsal view, 3b, peripheral view, 2c, umbilical view; 3: Well C, 1780 m, Unit II, 3a, dorsal view, 3b, peripheral view, 3c, umbilical view. **4a–c.** *Buccella inusitata* Andersen. Well A, 840 m, Unit I, 4a, dorsal view, 4b, peripheral view, 4c, umbilical view. **5a–9c, 11a–c.** *Ammonia yubariensis* Asano. 5: Well C, 2220 m, Unit IV, 5a, dorsal view, 5b, peripheral view, 5c, umbilical view; 6, 7: Well A, 2780 m, Unit IV, 6a, 7a, dorsal views, 6b, 7b, peripheral views; 7c, 8c, umbilical views; 8, 9: Well B, 2680 m, Unit IV, 8a, 9a, dorsal views, 8b, 9b, peripheral views, 8c, 9c, umbilical views; 11: Well A, 2820 m, Unit IV, 11a, dorsal view, 11b, peripheral view, 11c, umbilical view. Note that specimen of 11 has strongly curved sutures and lower spiral. **10a–c.** *Ammonia tochigiensis* (Uchio). Well A, 1140 m, Unit I, 10a, dorsal view, 10b, peripheral view, 10c, umbilical view. **12a–13c.** *Cribroelphidium imanishii* Asano. Well A, 2780 m, Unit IV, 12a, 13a, side views, 12b, 13b, apertural views. **14a, b.** *Cribroelphidium tomitai* Tai. Well A, 1440 m, Unit II, 14a, side view, 14b, apertural view. **15a, b.** *Cribroelphidium yabei* (Asano). Well C, 1760 m, Unit II, 15a, side view, 15b, apertural view, **16a, b.** *Cribroelphidium* sp. 1. Well A, 2640 m, Unit IV, 16a, side view, 16b, apertural view. **17a, b.** *Cribrononion perforatum* (Nomura). Well A, 1420 m, Unit II, 17a, side view, 17b, apertural view.

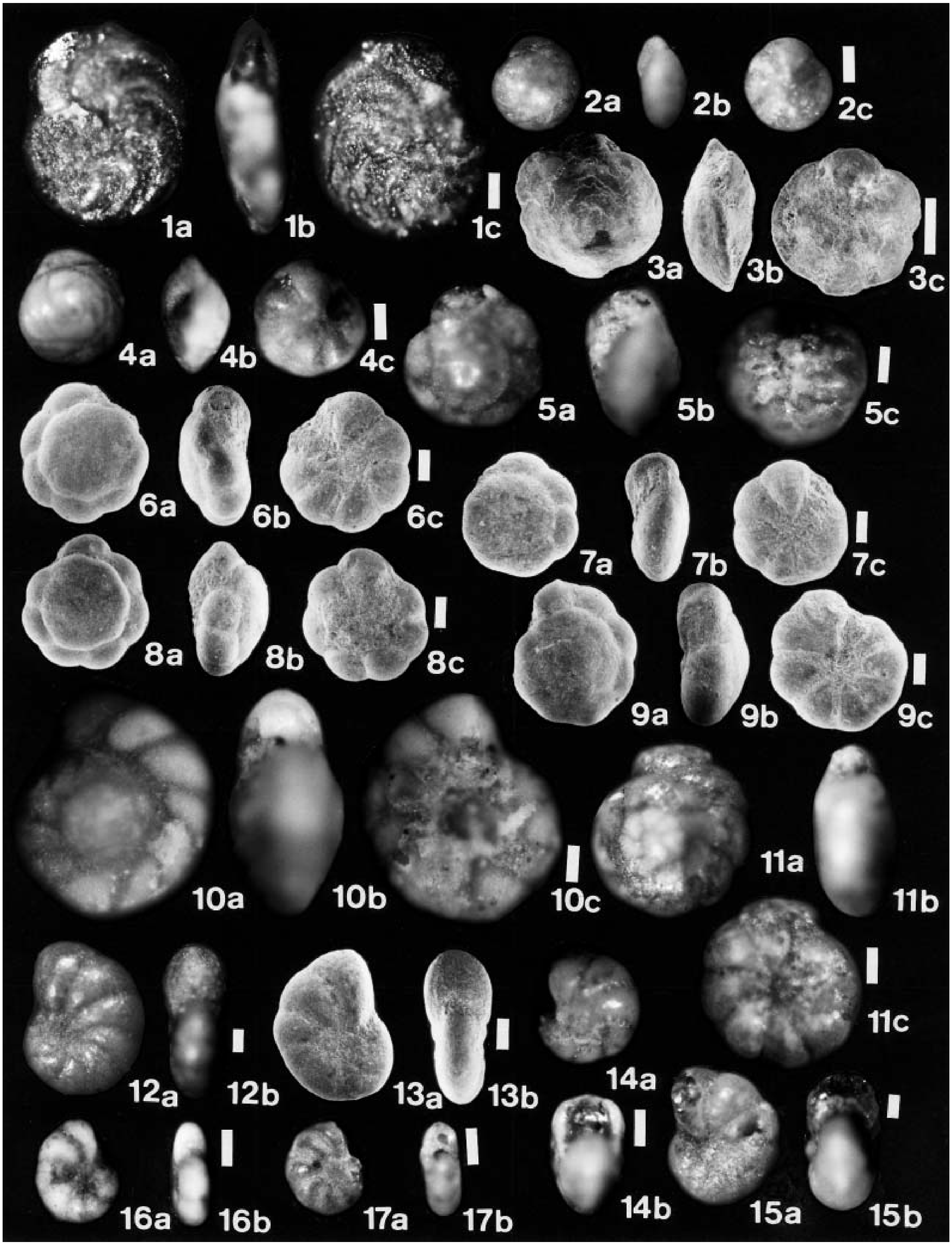
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Figure 12

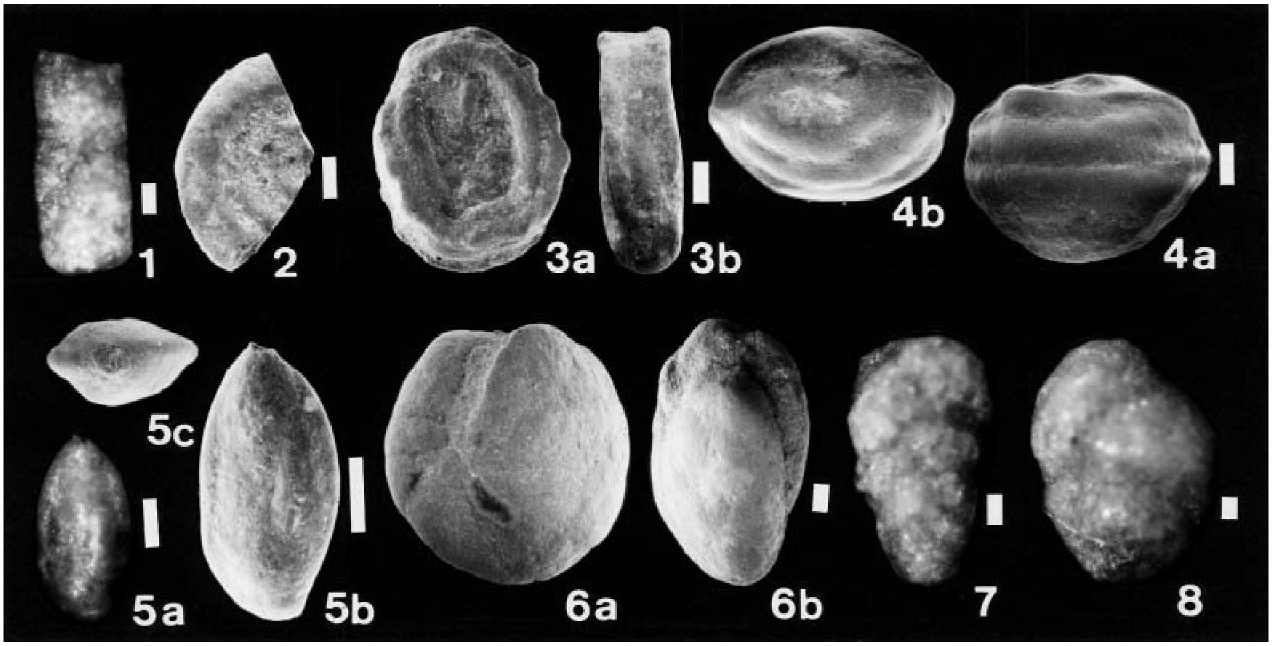

Figure 13. Reworked Cretaceous and Paleogene specimens of foraminifera from the Yufutsu Oil and Gas Field. All specimens from Unit I of well A. All scale bars = 0.1 mm.

1. *Bathysiphon* sp. 720 m, side view. **2.** *Ammodiscus* sp. 920 m, spiral view. **3a, b.** *Involutina* sp. 1140 m, 3a, spiral view, 3b, peripheral view. **4a, b.** *Glomospira* sp. 680 m, 4a, spiral view, 4b, side view. **5a, b.** *Silicosigmoilina futabaensis* Asano. 940 m, 5a, side view, 5b, apertural view. **6a, b.** *Cyclammina pacifica* Beck. 660 m, 6a, side view, 6b, apertural view. **7.** *Karreriella* sp. 820 m, side view. **8.** *Poronaia poronaiensis* (Asano). 820 m, side view.

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Appendix. Taxonomic notes. Foraminiferal species reported in this study are listed below in the taxonomic order of Loeblich and Tappan (1987, 1992). All reported specimens are deposited in the collections of JAPEX Research Center, Chiba-shi Mihama-ku Hamada 1-2-1, Chiba, Japan.

Hippocrepinella variabilis Voloshinova (Figures 9.2–9.4)

Hippocrepinella variabilis Voloshinova *in* Voloshinova *et al*., 1970, p. 46, pl. 2, figs. 1–6.

Remarks.—This species shows considerable distortion perhaps due to the thin and fragile wall cemented by organic matter.

Spirosigmoilinella compressa Matsunaga (Figure 9.5)

Spirosigmoilinella compressa Matsunaga, 1955, p. 49–50, tfs. 1, 2.

Cribrostomoides subglobosus (Cushman) (Figure 9.6, 9.7)

Haplophragmoides subglobosum Cushman, 1910, p. 105–106, tfs. 162–164.

Haplophragmoides renzi Asano, 1950a, p. 77, pl. 12, fig. 3.

Cribrostomoides subglobosus (Cushman).—Jones *et al*., 1993, pl. 1, figs. 1–3.

"*Haplophragmoides*" sp. 1 (Figure 9.8)

Diagnosis.—Test free, moderate to small for the genus, all specimens are flattened by compaction, planispiral, biumbilicate, periphery broadly rounded, chambers probably inflated before distortion, about 10 in final whorl, increasing slowly in size as added, sutures depressed, wall finely agglutinated, aperture filled by sediment and invisible, diameter about 0.5 mm, breadth about 0.25 mm in adult.

Remarks.—Specimens are considerably depressed by compaction suggesting a thin organic-cemented wall. Critical generic position is indeterminable because aperture is invisible.

Recurvoidella spadix (Kuznetsova) (Figure 9.9)

Haplophragmoides cf. *trullissatum* (Brady).—Asano, 1950a, p. 77, pl. 12, fig. 4.—Matsunaga, 1963, pl. 24, fig. 12.

Haplophragmoides spadix Kuznetsova *in* Voloshinova *et al*., 1970, p. 54, pl. 12, figs. 1a–2b.

Thalmannammina cf. *parkerae* (Uchio).—Nomura, 1992b, pl. 1, fig. 28.

Recurvoidella spadix (Kuznetsova).—Hanagata and Watanabe, 2001, pl. 2, fig. 17.—Hanagata, 2003, p. 308, pl. 2, figs. 8, 9.

Alveolophragmium indentatus (Voloshinova) (Figure 9.10)

Haplophragmoides cf. *emaciatum* (Brady).—Asano, 1950a, p. 76–77, pl. 12, fig. 5.

Haplophragmoides indentatus Voloshinova *in* Voloshinova and Budasheva, 1961, p. 190, pl. 4, figs. 5, pl. 5, figs. 1, 2.

Alveolophragmium indentatus (Voloshinova).—Hanagata, 2003, p. 310, 311, pl. 3, figs. 2–9.

Cyclammina cancellata Brady (Figure 9.11)

Cyclammina cancellata Brady, 1879, p. 63 (type figures in Brady, 1884, pl. 37, figs. 8–16).

Cyclammina pseudopusilla Hanagata (Figure 9.12)

Cyclammina pusilla Brady—Asano, 1950a, p. 78, pl. 12, figs. 6a, b.

Cyclammina pseudopusilla Hanagata, 2003, p. 312, pl. 4, figs. 2–5.

Guppyella miocenica (Cushman) (Figure 9.13)

Goesella miocenica Cushman, 1936, p. 33, pl. 5, fig. 9.

Goesella schencki Asano, 1950c, p. 2, tfs. 11–13.

Guppyella miocenica (Cushman).—Brönnimann, 1951, p. 99, pl. 11, fig. 6, p. 98, tfs. 1–4.—Hanagata, 2003, p. 320, pl. 5, figs. 8, 9.

Liebusella laevigata Voloshinova *et al*., 1970, p. 284, pl. 11, figs. 1–7.

Remarks.—This species had been assigned to *Goesella schencki* by many Japanese workers.

Martinottiella communis (d'Orbigny) (Figures 9.14, 9.15)

Clavulina communis d'Orbigny, 1846, p. 196, pl. 12, figs. 1–2.

Sigmoilopsis schlumbergeri (Silvestri) (Figure 9.18)

Sigmoilina schlumbergeri Silvestri, 1904, p. 267, 269.

"*Nodosaria*" sp. 1 (Figure 9.19)

Nodosaria sp. 1.—Hanagata and Watanabe, 2001, pl. 2, fig. 9.

"*Nodosaria*" sp. 1.—Hanagata, 2003, p. 322, pl. 5, fig. 13.

Glandulina sp. 1 (Figure 9.24)

Diagnosis.—Test free, moderate size for the genus, elongate, suture depressed, wall finely perforated, aperture terminal, length up to 0.8 mm, diameter up to 0.4 mm.

Neogloboquadrina continuosa (Blow) (Figure 9.25)

Globorotalia opima continuosa Blow, 1959, p. 218, pl. 19, figs. 125a–c.

Neogloboquadrina pachyderma (Ehrenberg) (Figure 9.26)

Aristerospira pachyderma Ehrenberg, 1861, p. 276, 277, 303.—Ehrenberg, 1873, pl. 1, fig. 4.

Globigerina* cf. *G. ciperoensis angustiumbilicata Bolli (Figure 9.27)

Compared with *Globigerina ciperoensis angustiumbilicata* Bolli, 1957, p. 109, pl. 22, figs. 12a–13c.

Globigerina* cf. *G. falconensis Blow (Figure 9.28)

Compared with *Globigerina falconensis* Blow, 1959, p. 177, pl. 9, fig. 40a–c.

Globigerina* cf. *G. praebulloides Blow (Figure 10.1)

Compared with *Globigerina praebulloides* Blow, 1959, p. 180, pl. 8, fig. 47a–c, pl. 9, fig. 48.

Globoturborotalia* cf. *G. woodi connecta (Jenkins) (Figure 10.2)

Compared with *Globigerina woodi connecta* Jenkins, 1964, p. 72, tf. 1a–c.

Cassidulinoides porrectus (Heron-Allen and Earland) (Figures 10.4–10.6)

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

Cassidulinoides porrectus (Heron-Allen and Earland).—Nomura, 1999, figs. 33.6a–33.10c, 35, 36.10–36.12.

Globocassidulina* cf. *G. subglobosa (Brady) (Figure 10.7)

Compared with *Cassidulina subglobosa* Brady, 1881, p. 60.

Planocassidulina praehelenae Nomura (Figure 10.8)

Planocassidulina praehelenae Nomura, 1999, p. 53, 54, figs. 36.4–37.8.

Planocassidulina sublimbata (Asano and Nakamura) (Figure 10.9)

Cassidulina sublimbata Asano and Nakamura, 1937, p. 146, pl. 14, figs. 3–4.

Planocassidulina yabei (Asano and Nakamura) (Figure 10.10)

Cassidulina yabei Asano and Nakamura, 1937, p. 145, pl. 14, fig. 1.

Bulimina marginata d'Orbigny (Figure 10.11)

Bulimina marginata d'Orbigny, 1826, p. 269, pl. 12, figs. 10–12.

Bulimina striata d'Orbigny (Figure 10.12)

Bulimina striata d'Orbigny, 1826, p. 269, no. 2.

Uvigerina proboscidea Schwager (Figures 10.13, 10.14)

Uvigerina proboscidea Schwager, 1866, p. 250, pl. 7, fig. 96.

Uvigerina yabei Asano (Figure 10.15)

Uvigerina yabei Asano, 1938b, p. 613, pl. 17, figs. 1, 2.—Hanagata, 2003, p. 328, pl. 6, figs. 7–10.

Uvigerina akitaensis Asano, 1950b, p. 14, tfs. 60–62.

Angulogerina ikebei Husezima and Maruhasi (Figures 10.16, 10.17)

Angulogerina ikebei Husezima and Maruhasi, 1944, p. 396, pl. 34, figs. 8a–c.—Hanagata, 2003, p. 332, pl. 6, figs. 11–14.

Angulogerina kokozuraensis Asano, 1949, p. 428, tf. 1.

Angulogerina kawabeensis Matsunaga, 1963, p. 112, pl. 42, fig. 1.

Stilostomella* cf. *S. lepidula (Schwager) (Figure 10.18)

Compared with *Nodosaria lepidula* Schwager, 1866, p. 210, pl. 5, figs. 27, 28.

Sphaeroidina bulloides Deshayes (Figure 10.25)

Sphaeroidina bulloides Deshayes.—Jones, 1994, p. 91, pl. 84, figs. 1–5.

Remarks.—According to Jones (1994), the first validation of this species was by Dashayes and not by d'Orbigny.

Cibicidoides aknerianus (d'Orbigny) (Figure 10.20)

Rotalina akneriana d'Orbigny, 1846, p. 156, pl. 8, figs. 13–15.

Cibicides asanoi Matsunaga, 1963, p. 116, pl. 51, fig. 4.—Inoue, 1989, p. 155, 156, pl. 24, figs. 9a, b.

Cibicidoides aknerianus (d'Orbigny).—Hanagata, 2003, p. 332, pl. 7, figs. 9, 10.

Epistominella pacifica (Cushman) (Figures 10.21, 10.22)

Pulvinulinella pacifica Cushman, 1927, p. 165, pl. 5, figs. 14–15.

Pulvinulinella parva Cushman and Laiming, 1931, p. 115, pl. 13, figs. 5a–c.

Epistominella pulchella Husezima and Maruhasi, 1944, p. 398, pl. 34, figs. 10a–c.

Epistominella carinata Voloshinova, 1960b, p. 163, 164, pl. 29, figs. 6a–c.

Epistominella troptunensis Voloshinova, 1960b, p. 164, 165, pl. 29, figs. 7a–c.

Epistominella pacifica (Cushman).—Voloshinova *et al.*, 1970, p. 131–132, pl. 32, figs. 1–5.—Hanagata, 2003, p. 332, pl. 7, fig. 8.

Remarks.—This is the type species of the genus *Epistominella* because the original type *E. pulchella* is a junior synonym of *E. pacifica*, as pointed out by many workers (e.g., Voloshinova *et al.*, 1970; Ujiié *et al.*, 1983). Previous studies separated Miocene specimens of *E. pacifica* as distinct species such as *E. parva*, *E. carinata* and *E. troptunens.* This is probably due to their smaller test size than Pliocene-Recent specimens. I follow the view of Voloshinova *et al.* (1970), regarding them as morphovariants.

Cibicides refulgens de Montfort (Figure 10.23)

Cibicides refulgens de Montfort, 1808, p. 123, p. 122.

Lobatula* cf. *L. lobatula (Walker and Jacob) (Figure 10.24)

Compared with *Nautilus lobatulus* Walker and Jacob *in* Kanmacher, 1798, p. 642, pl. 14, fig. 36.

Nonion nakosoense Asano (Figure 11.1)

Nonion nakosoense Asano, 1949, p. 428, tfs. 2.14–2.17.

Poropullenia excavata Voloshinova (Figures 11.2–11.6)

Poropullenia excavata Voloshinova *in* Voloshinova *et al.*, 1970, p. 86, pl. 16, figs. 12, 13.

Remarks.—This species was originally described from Sakhalin and is common in the lower horizon of Unit IV (Miocene) in the Yufutsu Field, though this is a first record from Hokkaido. Loeblich and Tappan (1987) included genus *Poropullenia* (Voloshinova *in* Voloshinova *et al.*, 1970) in *Bermudezinella* (Sellier de Civrieux, 1969). However, *Poropullenia* differs from the latter in not having rows of sutural pores. Further, the aperture is in the form of pores regularly arranged at the base of the apertural face and hence not slitlike. Therefore, *Poropullenia* is a distinct genus and not a synonym of *Bermudezinella*.

Nonionella miocenica Cushman (Figure 11.7)

Nonionella miocenica Cushman, 1926, p. 64.—Asano, 1949, tfs. 2.18–2.20.

Nonionella* cf. *N. turgida (Williamson) (Figure 11.8)

Compared with *Rotalia turgida* Williamson, 1858, p. 50, pl. 4, figs. 95–97.

Nonionellina labradorica (Dawson) (Figure 11.9)

Nonionina labradorica Dawson, 1860, p. 191, tf. 4.

Melonis affinis (Reuss) (Figure 11.10)

Nonion affinis Reuss, 1851, p. 72, pl. 5, fig. 32.

Melonis* aff. *M. pompilioides (Fichtel and Moll) (Figure 11.11)

Compared with *Nautilus pompilioides* Fichtel and Moll, 1798, p. 31, pl. 2, figs. a–c.

Remarks.—This species differs from typical *M. pompilioides* in having a more compressed test. This species is similar to *Melonis quadalpae* (sic) Parker in Konda (1980, pl. 4, figs. 6–7) but typical *M. guadarpae* Parker (1964, p. 633, pl. 100, figs. 13, 14) seems to have less limbate and more depressed sutures.

Pullenia apertura Cushman (Figure 11.12)

Pullenia apertura Cushman, 1927, p. 171, pl. 6, fig. 10.

Pullenia* cf. *P. bulloides (d'Orbigny) (Figure 11.13)

Compared with *Nonionina bulloides* d'Orbigny, 1846, p. 107, pl. 5, figs. 9–10.

Pullenia* cf. *P. salisburyi K.C. and R.E. Stewart (Figure 11.14)

Compared with *Pullenia salisburyi* K.C. and R.E. Stewart, 1930, p. 72, pl. 8, fig. 2.

Oridorsalis* cf. *O. umbonatus (Reuss) (Figure 11.15)

Compared with *Rotalina umbonata* Reuss, 1851, p. 75, pl. 5, fig. 35.

Gyroidina komatsui Aoki (Figure 11.16)

Gyroidina komatsui Aoki, 1964, p. 167, pl. 25, figs. 16a–c.—Hanagata, 2003, p. 334, pl. 8, figs. 7, 8.

Gyroidinoides shinjiensis Nomura, 1986, p. 473–474, fig. 11.

Gyroidina orbicularis (Parker, Jones and Brady) (Figure 11.17)

Gyroidina orbicularis (Parker, Jones and Brady).—Jones, 1994, p. 114, pl. 115, fig. 6.

Hanzawaia nipponica Asano (Figure 12.1)

Hanzawaia nipponica Asano, 1944, p. 98–99, pl. 4, figs. 1–2.

Buccella citronea Leonenko (Figures 12.2, 12.3)

Buccella citronea Leonenko *in* Voloshinova, 1960a, p. 275, 276, pl. 3, figs. 3a–5c.

Buccella complanata Voloshinova, 1960a, p. 276, figs. 1a–2c.

Buccella sulcata Kuznetsova *in* Voloshinova, 1960a, p. 278, 279, pl. 3, fig. 6a–c.

Remarks.—Voloshinova *et al.* (1970) regarded *B. complanata* and *B. sulcata* as junior synonyms of *B. citronea.* Other species of

Buccella, described by Voloshinova (1960a) from the Neogene of Sakhalin, Russia, need further investigation because this genus exhibits a wide range of variation in morphology, such as in test convexity and size. This species is distinguished from *Buccella oregonensis* reported from the Miocene of California (Finger, 1992) by its smaller test size and slightly rounded periphery.

Buccella inusitata Andersen (Figure 12.4)

Buccella inusitata Andersen, 1952, p. 147, tfs. 10–11.

Ammonia yubariensis Asano (Figures 12.5–12.9, 12.11)

Rotalia yubariensis Asano, 1952a, p. 49, pl. 6, figs. 1–2.

Rotalia beccarii hatatatensis Takayanagi, 1952, p. 62, tf. 5.

Rotalia beccarii honyaensis Asano, 1953b, p. 57, tf. 11a–c.

Remarks.—In this study, this species of *Ammonia* shows a wide range of variations in its morphology, especially in height of the spire (i.e., convexity), curvature of sutures and number of chambers. Specimens of the high-spired variety clearly show the features of *R. beccarii honyaensis* and those with fewer chambers resemble *R. beccarii hatatatensis.* The first author regards these morphotypes as indistinct species falling within the range of variation of *A. yubariensis*, which has priority.

Many species of *Ammonia* have been described from the Miocene of Japan and adjacent regions such as Sakhalin (Voloshinova *et al*., 1970). All those species requires further in-depth taxonomic study.

Ammonia tochigiensis (Uchio) (Figure 12.10)

Rotalia tochigiensis Uchio, 1951, p. 374, tfs. a–c.

Remarks.—This species is characterized by a large umbilical plug and low trochospire with numerous chambers about 11 to 14 in the final whorl. The relationship between *A. tochigiensis* and *A. tanosawaensis* [= *Rotalia tanosawaensis* Iwasa and Kikuchi, 1954, p. 192, tf. 7a–c] is not clear. *Ammonia tanosawaensis* generally shows closely similar morphology with *A. tochigiensis*, but *A. tanosawaensis* has a less developed umbilical plug and a smaller number of chambers, about eight to nine in the final whorl. *Ammonia tanosawaensis* of Shirai (1969) and *A. tochigiensis* of Asano (1953a, figs. 17a–b), Konda (1980, figs. 20a–c) and Nomura (1986, figs. 19a, b) apparently are intermediate forms between these two species. Further study on the variation of this species is required.

Cribroelphidium imanishii Asano (Figures 12.12, 12.13)

Cribroelphidium imanishii Asano, 1953a, p. 52, tf. 11a–b.

Cribroelphidium tomitai Tai (Figure 12.14)

Cribroelphidium tomitai Tai, 1955, p. 419, tf. 2a, b.

Remarks.—This species is characterized by thick and inflated six to eight chambers in the final whorl, curved sutures and a solitary pore in the apertural face.

Cribroelphidium yabei (Asano) (Figure 12.15)

Elphidium yabei Asano, 1938a, p. 589, pl. 14, figs. 9a–10b.

Cribroelphidium sp. 1 (Figure 12.16)

Diagnosis.—Test free, small for the genus, compressed, planispiral but coiling axis is occasionally inclined, biumbilicate, umbilical regions filled with tiny particles, periphery subacute, chambers slightly inflated, about seven in the final whorl, increasing slowly in size as added, suture slightly depressed with small pores, wall finely perforate, aperture interiomarginal, diameter up to 0.3 mm in adult specimens.

Cribrononion perforatum (Nomura) (Figure 12.17)

Elphidium perforatum Nomura, 1990, figs. 9.9a, b, 12a, b, 13, 11.1–11.4.

Cribrononion sp. A of Ujiié *et al*., 1983, p. 60, pl. 7, figs. 9, 10.

Reworked Specimens. Following species are reworked taxa found in Unit I of well A.

Silicosigmoilina futabaensis Asano (Figure 13.5)

Silicosigmoilina futabaensis Asano 1950d, p. 159, pl. 1, figs. 6, 7.

Remarks.—This is a common species in the Upper Cretaceous, Santonian to Campanian of northern Japan (Maiya and Takayanagi, 1977).

Evolutinella subamakusaensis (Fukuta)

Haplophragmoides subamakusaensis Fukuta, 1962, p. 9, fig. 2, pl. 1, figs. 6–10.

Haplophragmoides subevolutus Kaiho, 1984, p. 114, pl. 7, figs. 7a, b.

Evolutinella subamakusaensis (Fukuta).—Hanagata, 2002, p. 159, 161, figs. 8.10–8.12.

Remarks.—This species ranges from Late Cretaceous to Oligocene and is commonly seen in the Eocene of Hokkaido.

Haplophragmoides sp. B

Haplophragmoides sp. B of Hanagata, 2002, figs. 8.7, 8.8.

Remarks.—This species was reported from the Eocene Poronai Formation of the Yufutsu Field.

Cyclammina pacifica Beck (Figure 13.6)

Cyclammina pacifica Beck, 1943, pl. 98, figs. 2–3.—Hanagata, 2002, p. 165, figs. 9.4, 9.5.

Remarks.—This species is commonly found in the Eocene of Hokkaido.

Poronaia poronaiensis (Asano) (Figure 13.8)

Plectina poronaiensis Asano, 1952b, p. 33, 34, pl. 4, figs. 12, 13.

Poronaia poronaiensis (Asano).—Ujiié and Watanabe, 1960, p. 133, 134, pl. 2, figs. 1–8.—Hanagata, 2002, p. 165, figs. 9.12, 9.13.

Remarks.—This species is commonly found from the Eocene of Hokkaido.

Melonis cf. ***M. pompilioides*** (Fichtel and Moll)

Compared with *Nautilus pompilioides* Fichtel and Moll, 1798, p. 31, pl. 2, figs. a–c.

Remarks.—*Melonis pompilioides* is an extant species though Paleogene specimens are distinguishable from Neogene ones by their larger test size and degree of fossilization. This species is commonly found in the Eocene of Hokkaido (for example, Hanagata, 2002).