

Post-glacial Foraminifera of the incised Yangtze paleo-valley and paleoenvironmental implications

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Abstract.—Three gravity cores (LZK1, ZKA4, and CSJA6) from the incised Yangtze paleo-valley comprise a thick sequence of the post-glacial deposit. Nineteen genera (26 species) of the benthic foraminifers are described from these cores, with detailed down-core foraminiferal variations to investigate their paleoenvironmental implications. Three foraminiferal assemblages are recognized for the lower, middle, and upper parts of the cores respectively. The lower part is dominated by *Ammonia beccarii* var. and *Florilus decorus* with lower abundance and diversity. In the middle part, the foraminifers are abundant and diverse, dominated by both *Ammonia beccarii* var. and *Elphidium advenum*. *Cavarotalia annectens*, *Pararotalia nipponica*, and porcellaneous benthic foraminiferal forms are always present, sometimes abundant. The upper part is characterized by the *Ammonia beccarii*-*Elphidium magellanicum* assemblage, except for the Core ZKA4, which is barren of foraminifers in this interval. AMS ¹⁴C dates and foraminiferal assemblages both confirm that the transgression-regression sequence in these cores belongs to the “*Ammonia* transgression” during the Holocene. In addition to documenting the post-glacial sea-level fluctuations, the benthic foraminifers also reflect a warmer climate during the early–middle Holocene. The foraminiferal differences among the three cores can be used to interpret the influence of seawater during the post-glacial sea-level fluctuations. The area in the vicinity of Core ZKA4 was affected by marine water only during the middle Holocene, which was much shorter than the areas of the other cores.

Introduction

Sediments of the coastal plains and the continental shelves record the dynamic history of the shoreline migration caused by the ~120 m sea-level changes during the Quaternary (Fleming et al., 1998). Through regional micropaleontological and stratigraphic comparisons in the sedimentary cores from East China, four major marine transgressions have been recognized during the late Pleistocene. The last one, post-glacial “*Ammonia* transgression”, is the most notable and widespread along the coastline (Wang et al., 1981). Numerous boreholes have been drilled and studied in various parts of East China over the last several decades (Lin, 1979; Wang and Min, 1979; Li et al., 1988; Zhu and Lin, 1990; Chen and Stanley, 1995; Stanley and Chen, 1996; Wang et al., 2002; Shu et al., 2010; Xiong et al., 2010; Wang et al., 2012). However, introduction of old carbon and reworking resulted in less-reliable dates, which has hampered further study on the glacial-interglacial environmental changes in East China (Stanley and Chen, 2000).

Due to the lower last glacial sea level and excavation of previous marine sediments, the deeply incised Yangtze paleo-valley received a significant amount of post-glacial deposits, up to 80 m thick in this region (Li and Wang, 1998; Li et al., 2000), which provides an excellent opportunity for reconstructing the post-glacial environmental changes in East China.

In this study, benthic foraminiferal assemblages are reported from three cores of the incised Yangtze paleo-valley. The foraminiferal fauna can be correlated with records of previous studies in the Yangtze Delta region. Based on reliable AMS ¹⁴C dates, the high-resolution foraminiferal data presented here provide new evidence for post-glacial variations in climate and depositional environments.

Geological setting

The Yangtze Delta has been developing in a sedimentary basin formed in association with the Quaternary neotectonic orogeny in East China (Guo et al., 1997; Wang et al., 2008). The Quaternary stratigraphic sequence of the Yangtze Delta is up to

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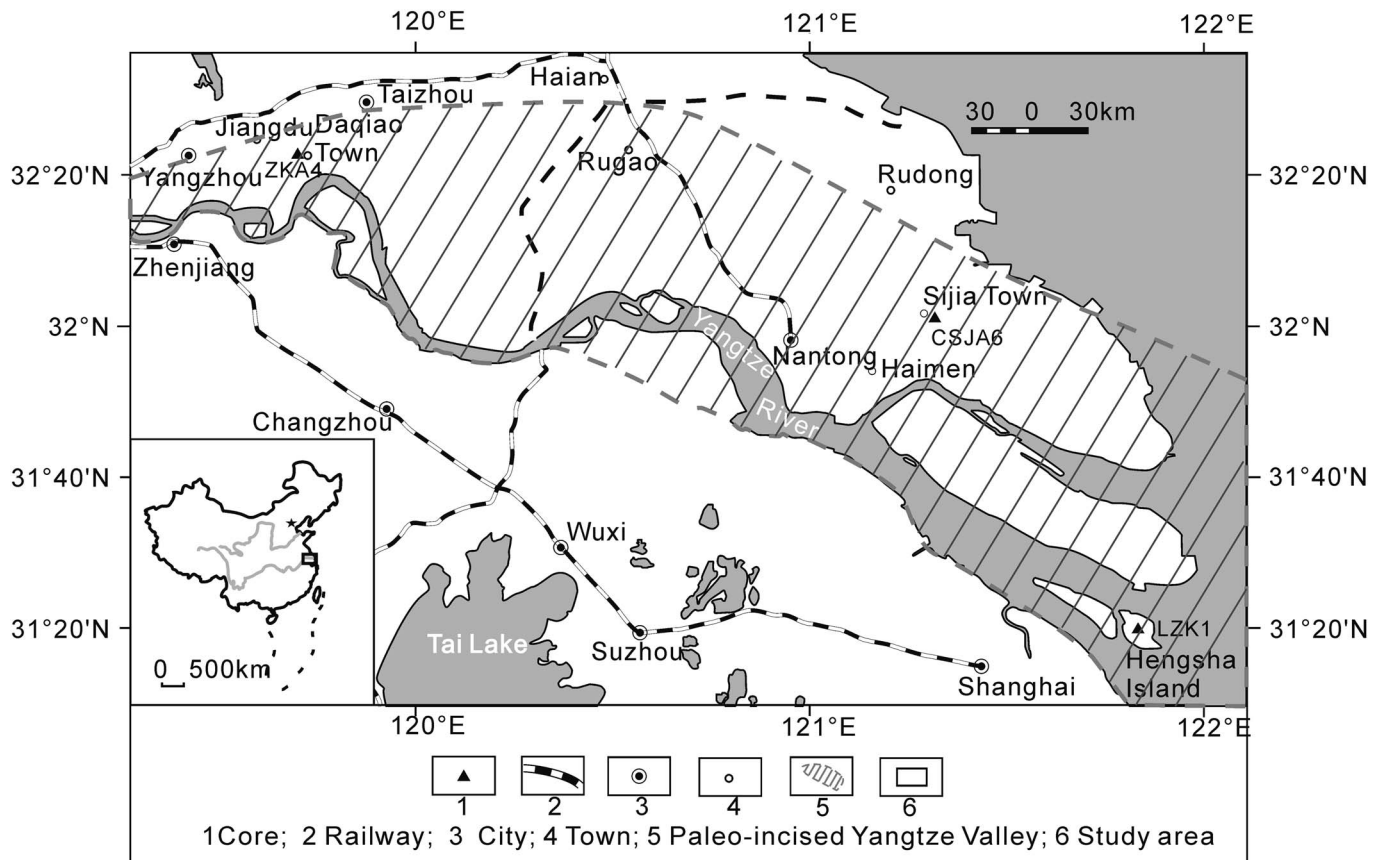


Figure 1. Location map showing the cores studied in the paleo-incised Yangtze Valley (range of paleo-incised Yangtze Valley after Li et al., 2000).

300 m thick, consisting of the Haimen Formation (lower Pleistocene), Qidong Formation (Middle Pleistocene), Kunshan Formation (MIS 5), Gehu Formation (MIS 3), and Rudong Formation (Holocene) (Wu and Li, 1987). The Rudong Formation is represented by fluvial, estuary, shallow marine, and deltaic facies, and can be divided into three members: the lower member is composed of gray silt and grayish black slit clay; the middle is composed of gray or grayish black silt, fine-grained sand, and slit clay; and the upper member is composed of grayish yellow clay, clayey silt, and gray silt (Wu and Li, 1987).

The Yangtze Delta can be subdivided into three units: the incised paleo-valley and the northern and southern flanks (Fig. 1; Li et al., 2000). The incised paleo-valley is an area where the estuary migrated, which contains several subdeltas and estuary bars. With rising sea level, the post-glacial marine transgression resulted in filling the incised valley and formation of the river channel, floodplain-estuary, estuarine-shallow marine, and deltaic sedimentary facies (Li et al., 2000). Since the middle Holocene, the delta has been developing mainly in the incised valley, prograding to the east and southeast (Li et al., 2002; Wang et al., 2013).

Materials and methods

The upper 42.2 m, 86 m, and 67 m of deposits in cores ZKA4, LZK1, and CSJA6, respectively, comprise the Rudong Formation. The sedimentary sequence varies from gravelly sand, coarse-grained sand in the basal part, fining-upward to the main

part of gray, grayish yellow, brown, or slate gray silt, silty clay, and clayey silt. Planar bedding, lenticular bedding, and micro-erosional surfaces are locally present (Fig. 2).

We analyzed 455 samples that were collected from the three cores at 10–50 cm intervals. All samples were air-dried and weighed, and soaked in water for one week. Diluted H_2O_2 (5%) was added to help disaggregate the indurated samples when needed. After the samples were washed through a 74 μm sieve, the coarse fraction was oven dried at 60°C and stored for foraminiferal studies. All the foraminiferal specimens were picked, identified, and counted. The Shannon index (H_s) was calculated to evaluate the variation of benthic foraminiferal complex diversity (Shannon, 1948).

AMS ^{14}C dating of Core ZKA4 and Core CSJA6 was performed on the plant debris, charcoal, or the whole sediments either at Beta Analytic Inc. or Peking University (Yu et al., 2014; Ma et al., 2015; Table 1).

Repositories and institutional abbreviations.—All cores examined in this study are from the paleo-valley of the Yangtze Delta, including one core from Shanghai (LZK1) and the other two from Jiangsu Province (ZKA4 and CSJA6; Fig. 1). Core LZK1 (31°20'N, 121°50'E) is just 0.25 m above the China National Vertical Datum (CNVD, 1985); cores ZKA4 (32°22'N, 119°37'E) and CSJA6 (32°05'N, 121°17'E) are 6 m and 4 m above the CNVD, respectively. All described specimens are housed at the Nanjing Institute of Geology and Palaeontology (NIGP), Chinese Academy of Science. Referred type specimens are

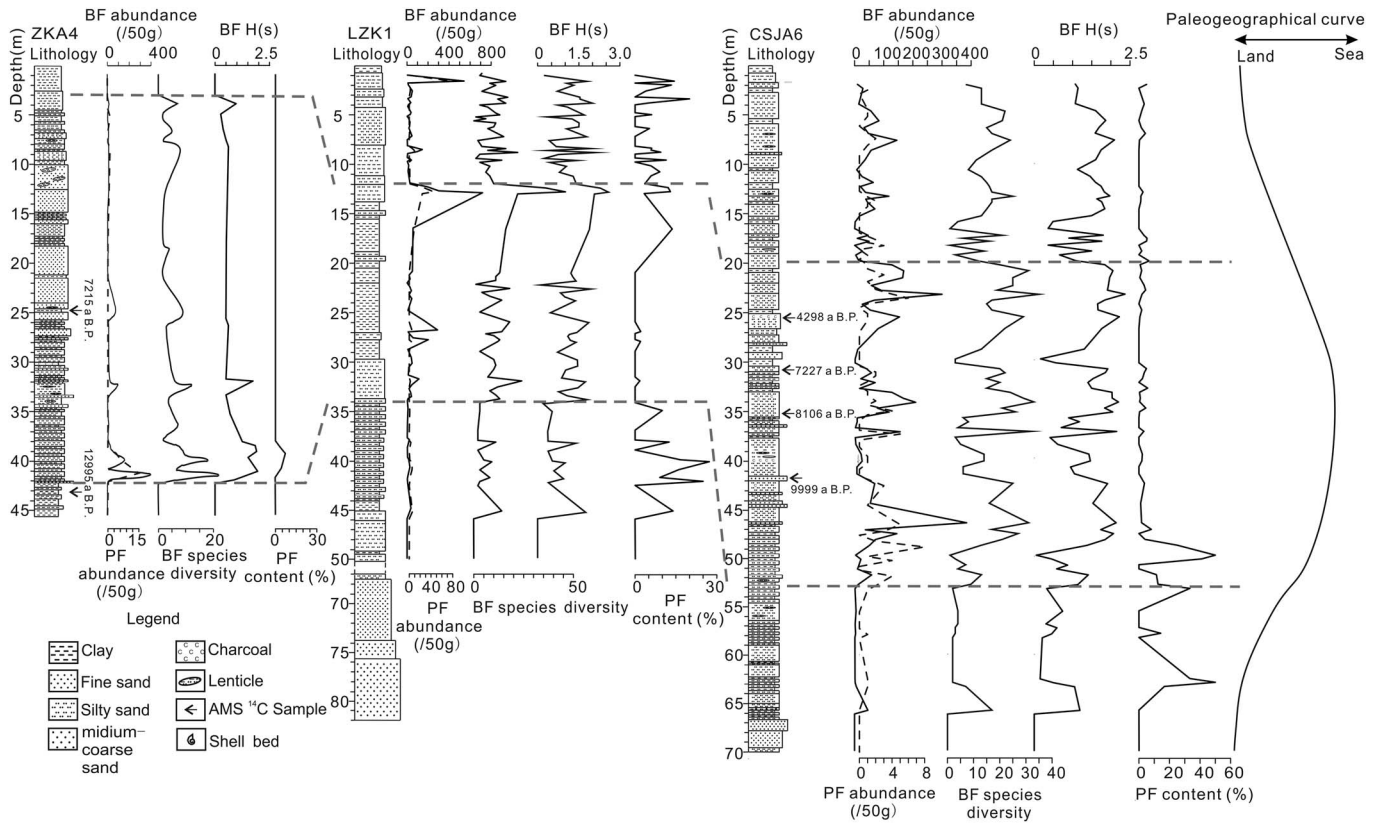


Figure 2. Variation of Lithology, benthic foraminiferal abundance, diversity, and H(s), planktonic foraminiferal content in the cores ZKA4, LZK1, and CSJA6, with reconstructed paleogeographic curve. Solid line represents BF abundance (/50 g); dashed line represents PF abundance (/50 g).

Table 1. AMS ¹⁴C dates of Core ZKA4 and CSJA6 (Yu et al., 2014; Ma et al., 2015).

Laboratory No.	Core	Core depth (m)	Material	Conventional Age (Myr)	Cal Age (2σ, Myr)
Beta-311252	ZKA4	24.8–24.9	plant debris	6280 ± 40	7160–7270
Beta-311253	ZKA4	43.15–43.30	organic sediment	11110 ± 50	12880–13110
BA120993	CSJA6	25.5	plant debris	3865 ± 30	4159–4412
BA120995	CSJA6	30.7–30.8	silty clay	6305 ± 50	7169–7272
BA120997	CSJA6	35.1	plant debris	7305 ± 30	8030–8176
BA120999	CSJA6	41.7	charcoal	8855 ± 35	9777–10157

housed at the National Museum of Natural History, Smithsonian Institution, Washington, D.C. (USNM), CC = Cushman collection; MO = mollusk collection; The Natural History Museum, London (BMNH), HA = Heron-Allen slide collection, ZF = Zoology: Foraminifera; Geological Museum, Louisiana State University, Baton Rouge, Louisiana (LSUGM); and Tongji University, Shanghai (TJU), H = Hai (Marine in phonetics Chinese).

Systematic paleontology

The classification of the order Foraminiferida follows that given by He et al. (1965), Wang et al. (1988), and Loeblich and Tappen (1988).

- Order Foraminiferida Eichwald, 1830
- Suborder Miliolina Delage and Hérouard, 1896
- Family Miliolidae Ehrenberg, 1839
- Genus *Quinqueloculina* d’Orbigny, 1826

Quinqueloculina lamarckiana d’Orbigny, 1839a
Figure 3.1–3.3

- 1839a *Quinqueloculina lamackiana* d’Orbigny, p. 189, pl. 11, figs. 14, 15.
- 1884 *Quinqueloculina cuvieriana*; Brady, p. 162, pl. 5, figs. 1–3.
- 1929 *Quinqueloculina lamarckiana*; Cushman, p. 26, pl. 2, figs. 6a–6c.
- 1965 *Quinqueloculina lamarckiana*; He, Hu, and Wang, p. 61, pl. 2, figs. 1a–1c.
- 1965 *Quinqueloculina lamarckiana minuscule* Ho, Hu, and Wang; He, Hu, and Wang, p. 61, pl. 2, figs. 2a–2c.
- 1988 *Quinqueloculina lamarckiana*; Wang et al., p. 127, pl. 13, figs. 10–12.

Occurrence.—Widely distributed in the world oceans; Recent coastal water and Quaternary sediments of Bohai Sea, Yellow

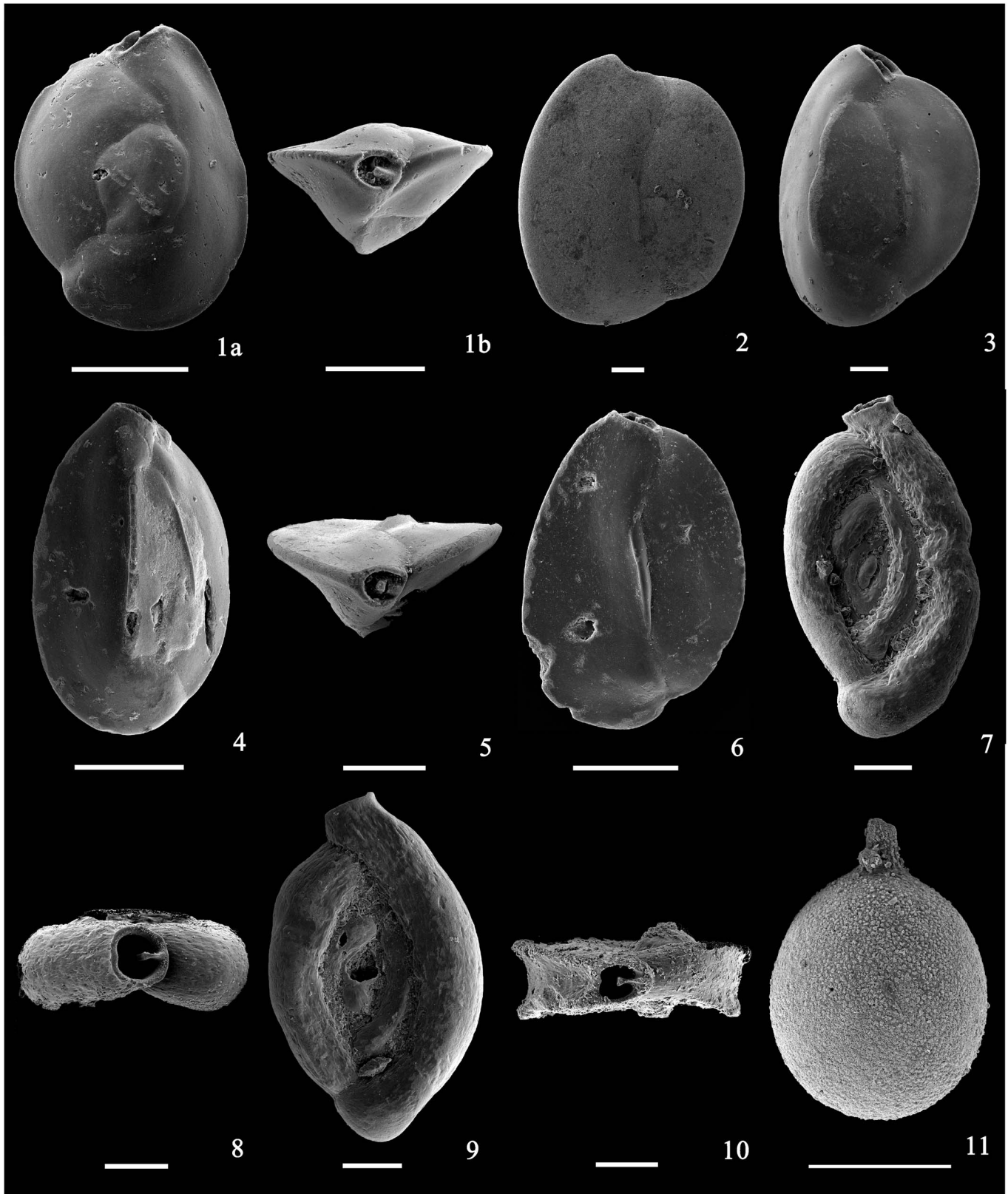


Figure 3. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1–3) *Quinqueloculina lamarckiana*: (1a) front view, CSJA6, depth 33.8–33.9 m, Reg. No. K2–036; (1b) apertural view, CSJA6, depth 33.8–33.9 m, Reg. No. K2–036; (2) rear view, LZK1, depth 31.9–32.0 m, Reg. No. K2–033; (3) front view, LZK1, depth 31.5–31.6 m, Reg. No. K2–032. (4–6) *Quinqueloculina venusta*: (4) front view, CSJA6, depth 33.8–33.9 m, Reg. No. K3–004; (5) apertural view, CSJA6, depth 47.6–47.7 m, Reg. No. K3–006 (6) rear view, CSJA6, depth 33.8–33.9 m, Reg. No. K3–005. (7, 8) *Spiroloculina eximia*: (7) side view, CSJA6, depth 47.6–47.7 m, Reg. No. K3–020; (8) apertural view, CSJA6, depth 47.6–47.7 m, Reg. No. K3–016. (9, 10) *Spiroloculina jucunda*: (9) side view, CSJA6, depth 34.2–34.3 m, Reg. No. K3–021; (10) apertural view, CSJA6, depth 33.8–33.9 m, Reg. No. K3–022. (11) *Lagena hispida*, side view, CSJA6, depth 17.2–17.3 m, Reg. No. K2–007.

Sea, East China Sea, and South China Sea (Wang et al., 1988); Pliocene in Taiwan, China (He et al., 1965); Tropical Pacific (11–174 m; Jones, 1994).

Remarks.—This species was recognized by the broad elliptical shape and the sharply keeled periphery of the test. In this study, a wide variety was observed from nearly 0.1 mm (Fig. 3.1a, 3.1b) to 1 mm (Fig. 3.2, 3.3). The third chambers of the front view in the adult forms usually elevated as a keel, while juvenile forms have the convex, round ridge for this chamber. He et al. (1965) erected the smaller specimens to a new subspecies, which is considered here as a juvenile form of *Quinqueloculina lamarckiana* d'Orbigny (1839a). Cushman (1929) pointed that the species has an elliptical neck with a narrow elongate tooth. He (1965) reported a bifurcate top of the tooth. The specimens observed in this study have a narrow elongate tooth with or without a much shorter neck.

Quinqueloculina venusta Karrer, 1868
Figure 3.4–3.6

- 1868 *Quinqueloculina venusta* Karrer, p. 147, pl. 2, fig. 6.
1917 *Quinqueloculina venusta*; Cushman, p. 45, pl. 11, fig. 1.
1957 *Quinqueloculina lamarckiana*; Todd and Bronnimann, p. 27, pl. 3, fig. 12.
1965 *Quinqueloculina venusta*; He, Hu, and Wang, p. 60, pl. 2, figs. 5a–5c.
1990 *Quinqueloculina venusta*; Ujjié, p. 15, pl. 3, figs. 3a, 3b, 4a, 4b.

Occurrence.—Pliocene in Japan; Miocene in Romania and Yugoslavia; Recent in Pacific and Atlantic oceans; Jiangsu and Shanghai, China (He et al., 1965).

Remarks.—Cushman (1917) reported that this species has a short contracted neck with thickened lip and a short simple tooth. He et al. (1965) presented specimens with slightly bifurcate top of the tooth. In this study, no definite lip can be observed. Due to its elongated test and wide short tooth, the specimens of *Quinqueloculina lamarckiana* d'Orbigny (1839a) described by Todd and Bronnimann (1957) are referred to *Quinqueloculina venusta* Karrer (1868).

Genus *Spiroloculina* d'Orbigny, 1826
Spiroloculina exmia Cushman, 1922a
Figure 3.7, 3.8

- 1922a *Spiroloculina exmia* Cushman, p. 61, pl. 11, fig. 2.
1929 *Spiroloculina exmia*; Cushman, p. 42, pl. 8, figs. 7a, 7b.
1965 *Spiroloculina exmia*; He, Hu, and Wang, p. 72, pl. 4, figs. 5a, 5b.

Occurrence.—Recent tropical Pacific; Jiangsu, China (He et al., 1965).

Remarks.—This species possesses rapidly increased and tapered chambers toward the apertural end. He et al. (1965) reported that the early chambers are inclined and convex. The specimens reported here have a comparatively shorter neck.

Spiroloculina laevigata Cushman and Todd, 1944
Figure 4.1, 4.2

- 1944 *Spiroloculina laevigata* Cushman and Todd, p. 67, pl. 9, figs. 26–29.
1965 *Spiroloculina laevigata*; He, Hu, and Wang, p. 72, pl. 4, figs. 7a, 7b.
1988 *Spiroloculina laevigata*; Wang et al., p. 126, pl. 12, fig. 17.

Holotype.—(USNM CC 41730) in National Museum of Natural History, Smithsonian Institution, Washington, D.C.

Occurrence.—Recent Pacific; Jiangsu, China (He et al., 1965).

Remarks.—This species is close to *Spiroloculina exmia* Cushman (1922a). Compared with the latter, the test of this species is more symmetric, and the chambers keep the same width from the base to the apertural end. The specimens illustrated here are more elongate than the holotype.

Suborder Lagenina Lankester, 1885
Family Nodosariidae Ehrenberg, 1838
Genus *Lagena* Walker and Jacob, 1798
Lagena hispida Reuss, 1858
Figure 3.11

- 1858 *Lagena hispida* Reuss, p. 434.
1884 *Lagena hispida*; Brady, p. 450, pl. 57, figs. 1–4.
1965 *Lagena hispida*; He, Hu, and Wang, p. 77, pl. 5, fig. 12.
1988 *Lagena hispida*; Wang et al., p. 135, pl. 16, fig. 12.
1990 *Lagena hispida*; Ujjié, p. 18, pl. 5, fig. 2.

Occurrence.—Oligocene in Germany; Quaternary in Denmark; Pliocene in U.S.A. and Japan; Recent in Pacific and Atlantic oceans; Yellow Sea and shelf of East China Sea (Wang et al., 1988).

Remarks.—The wall of this species is ornamented with fine spines. According to Brady (1884), the test varies from flask-shaped to subglobular, and in some specimens, the basal end is drawn out into a stout spine, which was also reported by Ujjié (1990). The stout spine out of the base was described, but not observed in the plates illustrated by He et al. (1965). The specimens here and reported by Wang et al. (1988) showed no spine for the subglobular test.

Lagena spicata Cushman and McCulloch, 1950
Figure 4.3, 4.4

- 1950 *Lagena sulcata* var. *spicata* Cushman and McCulloch, p. 360, pl. 48, figs. 3–7.
1965 *Lagena striata*; He, Hu, and Wang, p. 76, pl. 5, fig. 11.
1988 *Lagena spicata*; Wang et al., p. 135, pl. 16, figs. 9, 10.

Occurrence.—Widely distributed in world oceans; seldom found in shelf sediments of East China Sea (Wang et al., 1988).

Remarks.—There is a considerable amount of variation in this species. Cushman and McCulloch (1950) erected this species

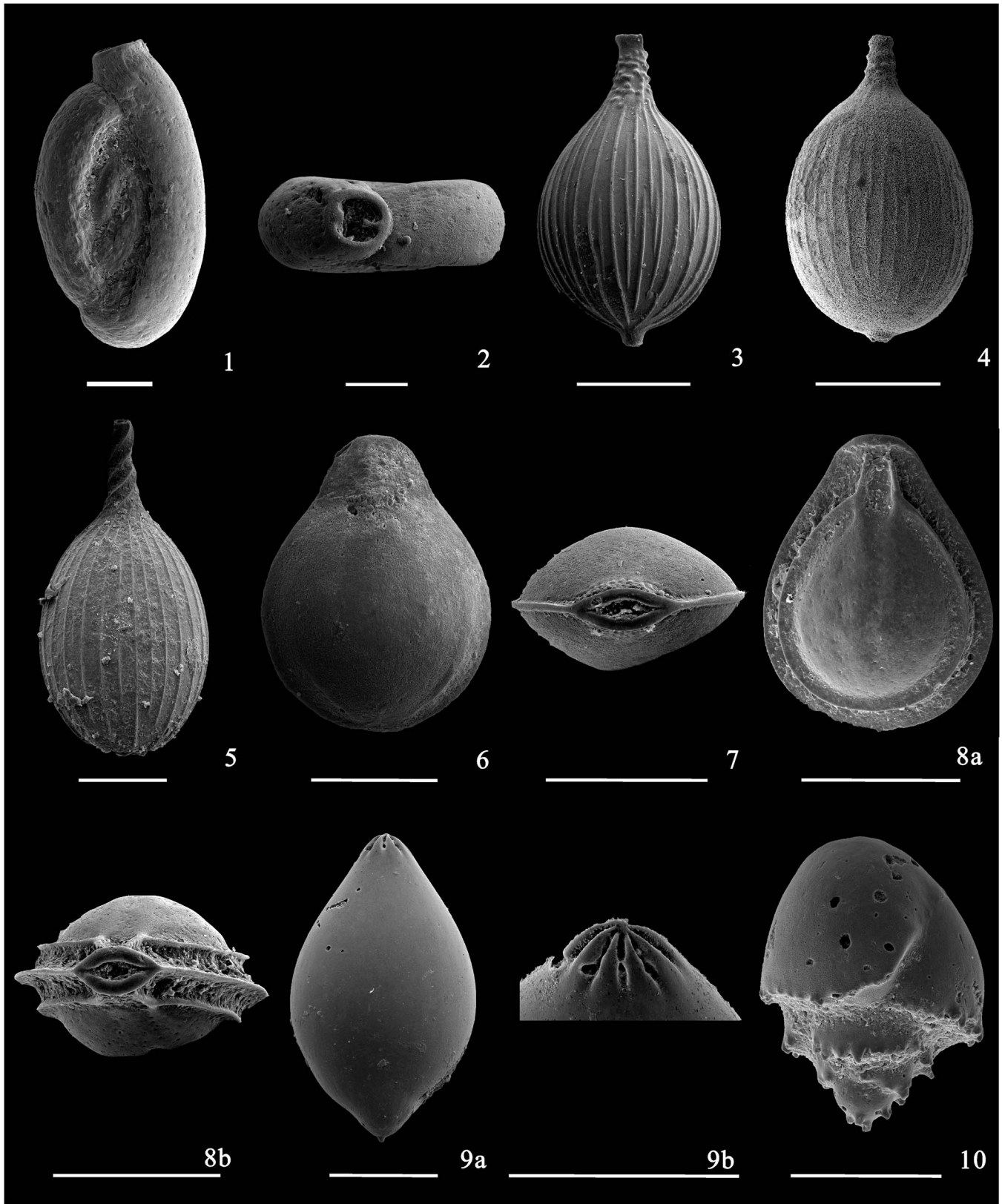


Figure 4. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μ m. (1, 2) *Spiroloculina laevigata*: (1) side view, CSJA6, depth 47.6–47.7 m, Reg. No. K3–018; (2) apertural view, CSJA6, depth 47.6–47.7 m, Reg. No. K3–019. (3, 4) *Lagena spicata*: (3) side view, CSJA6, depth 20.8–20.9 m, Reg. No. K2–005; (4) side view, CSJA6, depth 13.8–13.9 m, Reg. No. K2–003. (5) *Lagena substriata*: side view, LZK1, depth 9.5–9.6 m, Reg. No. K2–008. (6, 7) *Fissurina laevigata*: (6) side view, LZK1, depth 12.3–12.4 m, Reg. No. K1–080; (7) apertural view, CSJA6, depth 23.2–23.3 m, Reg. No. K1–079. (8a, 8b) *Fissurina orbignyana*: (8a) side view, CSJA6, depth 7.5–7.6 m, Reg. No. K1–083; (8b) apertural view, CSJA6, depth 23.2–23.3 m, Reg. No. K1–083. (9a, 9b) *Globulina minuta*: (9a) side view, LZK1, depth 12.3–12.4 m, Reg. No. K1–087; (9b) apertural view, LZK1, depth 12.3–12.4 m, Reg. No. K1–087. (10) *Bulmina marginata*, side view, CSJA6, depth 31.2–31.3 m, Reg. No. K4–010.

from *Lagena sulcata* in having the basal end drawn out into a stout spine while the latter has coarse longitudinal costae, extending to the base and forming numerous spines. The specimens reported here and by Wang et al (1988) have stronger stout spines than those from He et al. (1965). Circular costae can be observed on the neck of specimens in this study and in those of Wang et al (1988). The specimens in this study vary from flask-shaped to pyriform.

Lagena substriata Williamson, 1858
Figure 4.5

- 1858 *Lagena vulgaris* var. *substriata* Williamson, p. 7, pl. 1, fig. 14.
1913 *Lagena striata* var. *substriata*; Cushman, p. 20, pl. 8, figs. 1–3.
1923 *Lagena substriata*; Cushman, p. 56, pl. 10, fig. 11.
1965 *Lagena substriata*; He, Hu, and Wang, p. 77, pl. 5, figs. 7, 8.
1988 *Lagena substriata*; Wang et al., p. 134, pl. 16, fig. 17.
1990 *Lagena substriata*; Ujjié, p. 19, pl. 5, fig. 7.

Occurrence.—Widely distributed in coastal water of the world oceans; inner and middle shelf of East China Sea (Wang et al., 1988).

Remarks.—This species is characterized by the costulate surface extending up on to the neck, often to its end, and usually spirally arranged on the neck (Cushman, 1913). He (1965) and Ujjié (1990) reported specimens similar to those illustrated here. The test is elongate compared with *Lagena spicata* Cushman and McCulloch (1950).

Family Polymorphinidae d'Orbigny, 1839a
Genus *Fissurina* Reuss, 1850
Fissurina laevigata Reuss, 1850
Figure 4.6, 4.7

- 1850 *Fissurina laevigata* Reuss, p. 366, pl. 46, fig. 1.
1965 *Fissurina laevigata*; He, Hu, and Wang, p. 79, pl. 5, fig. 14.
1988 *Fissurina laevigata*; Wang et al., p. 144, pl. 19, fig. 13.
1990 *Fissurina* sp.; Ujjié, p. 23, pl. 7, fig. 13.
1990 *Fissurina periperforata*; Ujjié, p. 25, pl. 8, fig. 10.

Occurrence.—Widely distributed in coastal water of the world oceans; shelf of East China Sea (Wang et al., 1988); 4–5715 m (Jones, 1994).

Remarks.—The species has a compressed chamber with single-keel periphery. The *Fissurina laevigata* specimen illustrated by Ujjié (1990) is different from the present species by lacking the distinct peripheral keel and having a smaller aperture. *Fissurina* sp. and *Fissurina periperforata* Ujjié (1990) are similar to the present species, although *Fissurina periperforata* Ujjié (1990) has a more elongate form.

Fissurina orbignyana Seguenza, 1862
Figure 4.8a, 4.8b

- 1862 *Fissurina orbignyana* Seguenza, p. 66, pl. 2, figs. 25, 26.
1971 *Fissurina orbignyana*; Murray, p. 99, pl., 40, figs. 1–5.
1988 *Fissurina orbignyana*; Wang et al., p. 144, pl. 19, figs. 6, 7.

Occurrence.—Widely distributed in coastal water of the world oceans; Recent Pacific, Atlantic, and Gulf of Mexico; shelf of East China Sea (Wang et al., 1988).

Remarks.—This species is distinguished by its three-keel periphery and the most-prominent central one.

Genus *Globulina* d'Orbigny, 1839a
Globulina minuta (Roemer, 1838)
Figure 4.9a, 4.9b

- 1838 *Polymorphina minuta* Roemer, p. 386, pl. 3, fig. 35.
1863 *Polymorphina sororia* Reuss, p. 71, fig. 16.
1930 *Globulina minuta*; Cushman and Ozawa, p. 83, pl. 20, figs. 3, 4.
1965 *Globulina minuta*; He, Hu, and Wang, p. 81, pl. 5, fig. 19.

Occurrence.—Early Pleistocene in Italy; inner shelf of East China Sea (Wang et al., 1988).

Remarks.—This species is distinguished by the fusiform test and fewer chambers. The last chamber is much bigger than others. *Polymorphina sororia* Reuss (1863) was considered a junior synonym of *Globulina minuta* (Roemer, 1838) by Cushman and Ozawa (1930). The specimen reported here is comparatively acute for both the basal and apertural ends, with a tiny acicular spine developed in the basal end.

Suborder Rotaliina Delage and Hérouard, 1896
Superfamily Buliminacea Jones in Griffith and Henfrey, 1875
Family Buliminidae Jones in Griffith and Henfrey, 1875
Genus *Bulimina* d'Orbigny, 1826
Bulimina marginata d'Orbigny, 1826
Figure 4.10

- 1826 *Bulimina marginata* d'Orbigny, p. 269, pl. 12, figs. 10–12.
1922b *Bulimina marginata*; Cushman, p. 91, pl. 21, figs. 4, 5.
1965 *Bulimina marginata*; He, Hu, and Wang, p. 84, pl. 6, fig. 7.
1965 *Bulimina marginospinata ovata*; He, Hu, and Wang, p. 85 pl. 6, fig. 8.
1988 *Bulimina marginata*; Wang et al., p. 144, pl. 21, fig. 6, pl. 34, figs. 11–15.

Occurrence.—Widely distributed in coastal water of the world oceans; inner and middle shelf of East China Sea (Wang et al., 1988).

Remarks.—This species has a great number of varieties for the juvenile and adult forms. Wang et al. (1988) conducted a morphometric analysis of 200 tests from the surface sediments of the East China Sea, and displayed a concentrated and continuous distribution for tests of different length and breadth,

which suggests that these short oval or/and high fusiform forms belong to the same species. The specimen illustrated here has a shorter test, resembling the juvenile form of *Bulimina marginata* d'Orbigny (1826). The rim of the early chambers has a series of short blunt spines, while the later chamber has a series of crenulations.

Family Bolivinitidae Cushman, 1927

Genus *Bolivina* d'Orbigny, 1839b

Bolivina robusta Brady, 1881

Figure 5.1, 5.2

- 1881 *Bolivina robusta* Brady, p. 57.
 1922b *Bolivina robusta* var.; Cushman, p. 46, pl. 6, fig. 6.
 1965 *Bolivina robusta*; He, Hu, and Wang, p. 87, pl. 6, fig. 13.
 1965 *Bolivina cochei*; He, Hu, and Wang, p. 88, pl. 6, figs. 16, 17.
 1965 *Bolivina obscura*; He, Hu, and Wang, p. 88, pl. 7, figs. 1–3.
 1988 *Bolivina robusta*; Wang et al., p. 147, pl. 34, figs. 1–5.
 1994 *Bolivina robusta*; Jones, pl. 53, figs. 7–9.

Holotype.—Syntype (BMNH ZF1194) from Challenger Sta. 191A, Kai Island, Central Pacific (1061 m); (BMNH ZF1195) from Challenger Sta. 174B, Fiji, Pacific (2041 m).

Occurrence.—Recent coastal water and Quaternary sediments of Bohai Sea, Yellow Sea, East China Sea and South China Sea (Wang et al., 1988); 13–3475 m (Jones, 1994).

Remarks.—This species has great variability in morphology. Wang et al (1988) reported the megalospheric and microspheric tests. The specimens illustrated here are elongated cuneiform with blunt basal end, resembling a microspheric test. It was also reported that a long sharp spine may exist for this species (Jones, 1994, p. 58, pl. 53, figs. 8, 9).

Superfamily Discorbacea Ehrenberg, 1838

Family Discorbidae Ehrenberg, 1838

Genus *Rosalina* d'Orbigny, 1826

Rosalina bradyi (Cushman, 1915)

Figure 5.7–5.9

- 1915 *Discobis globularis* var. *bradyi* Cushman, p. 12, pl. 8, fig. 1.
 1931 *Discobis globularis*; Cushman, p. 22, pl. 4, figs. 9a–9c.
 1960 *Rosalina bradyi*; Barker, pl. 86, fig. 8.
 1965 *Rosalina bradyi*; He, Hu, and Wang, p. 89, pl. 8, figs. 5a–5c, 6a–6c.
 1988 *Rosalina bradyi*; Wang et al., p. 156, pl. 23, fig. 12.

Holotype.—USNM 9027 from Alabatross station D4863 in 194 m off Japan (Cushman, 1915, pl. 8, fig. 1).

Occurrence.—Neogene to Recent in Japan; Recent Pacific; East China Sea, South China Sea; inner shelf in East China Sea (He et al., 1965; Wang et al., 1988).

Remarks.—The test of this species is compressed. The specimens illustrated here clearly show the wall difference between

the coarse-perforated dorsal and fine-perforated ventral sides (Figure 5.8). The umbilical lobe of specimens is scattered and thickened.

Genus *Buccella* Andersen, 1952

Buccella frigida (Cushman, 1922c)

Figure 5.10–5.12

- 1922c *Pulvinulina frigida* Cushman, p. 144.
 1931 *Eponides frigida*; Cushman, p. 45.
 1952 *Buccella frigida*; Anderson, p. 144, figs. 4–6.
 1965 *Buccella frigida*; He, Hu, and Wang, p. 93, pl. 8, figs. 4a–4c.
 1988 *Buccella frigida*; Wang et al., p. 157, pl. 23, figs. 3, 4.

Holotype.—Lectotype (USNM CC 3032) from station 5, bay between Black Whale and Olasks Harbors, east coast of Hudson Bay at 18 m water depth (Cushman, 1931).

Occurrence.—Recent Arctic, Okhotsk Sea, Japan Sea, Bering Sea, Pacific, northern Atlantic; Bohai Sea, Yellow Sea, north-west of East China Sea, and the South China Sea; Quaternary in Jiangsu Province (He et al., 1965, Wang et al., 1988); 34–402 m (Jones, 1994).

Remarks.—The dorsal side of this species is filled with an amorphous material radiating out from the umbilical region. These materials usually distribute along the sutures. Less amorphous material may be observed for the later sutures. Supplementary apertures lie at the ends of the sutures, forming bigger pores and usually covered by the same amorphous material (Fig. 5.11). The amorphous material may be more around the supplementary aperture than the central umbilical area. A slightly keeled periphery was also observed (NHM ZF 2220–2221). However, the keel is indistinct in the specimens of this study.

Genus *Helenina* Saunders, 1961

Helenina anderseni (Warren, 1957)

Figure 6.4–6.6

- 1957 *Pseudoeponides anderseni* Warren, p. 39, pl. 4, figs. 12–15.
 1957 *Helenina anderseni*; Saunders, p. 374.
 1961 *Helenina anderseni*; Saunders, p. 148.
 1988 *Helenina anderseni*; Wang et al., p. 158, pl. 24, figs. 1, 2.
 2011 *Helenina anderseni*; Gennari et al., p. 249, pl. 1, figs. 1–6, pl. 2, figs. 1–4.

Holotype.—(LSUGM 2009) from wet marsh on the northeast side of Crosscut Canal at Bay Pomme d'Or (Warren, 1957, pl. 4, fig. 12–15).

Occurrence.—Widely distributed in low-salinity coastal water; inner shelf of East China Sea (Wang et al., 1988).

Remarks.—Warren (1957) erected this species, which usually has supplementary apertures within the deeply incised sutures dorsally near the junction of spiral and septal sutures, and within the incised sutures ventrally near their middle points.

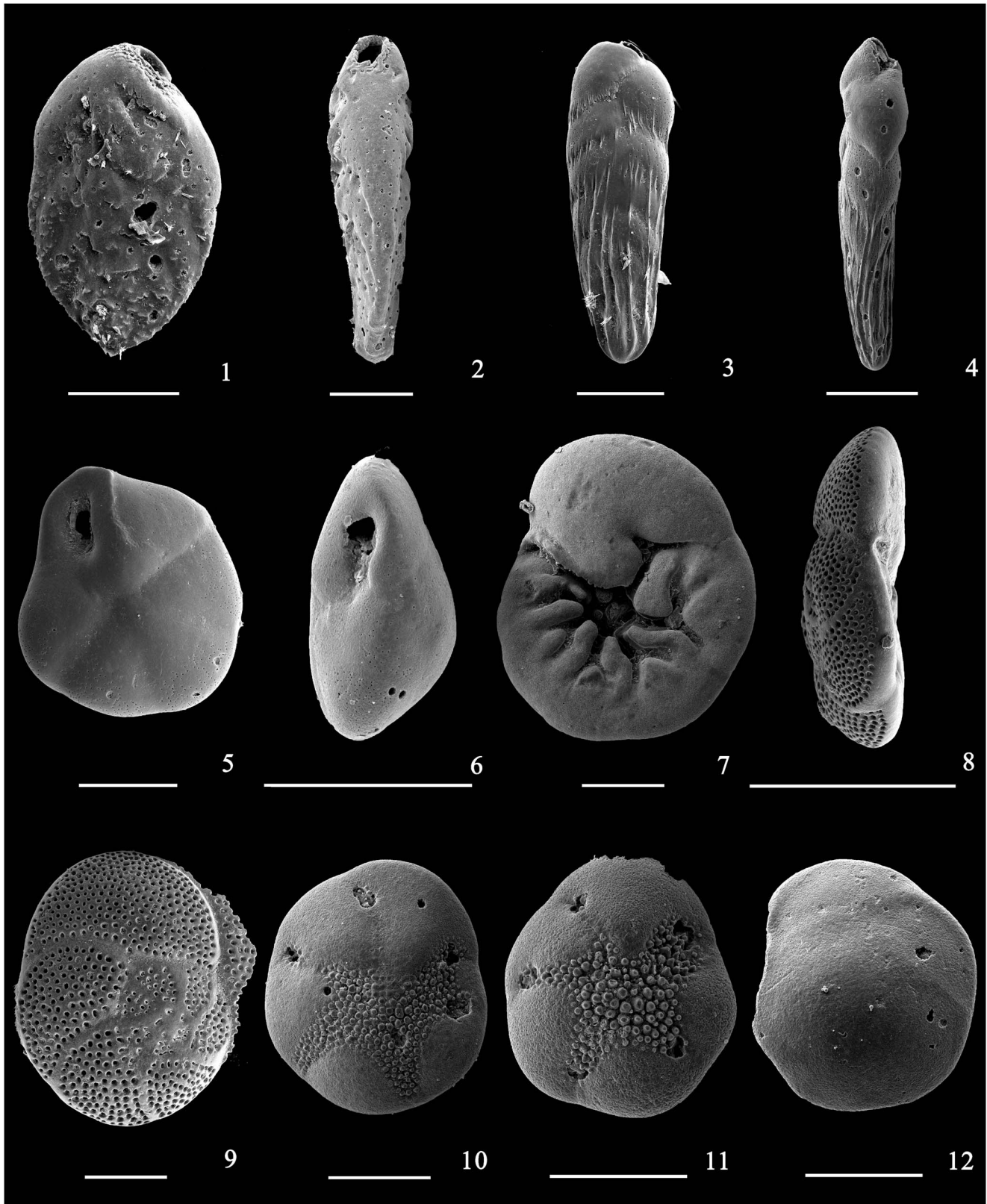


Figure 5. SEM photos of the foraminifers from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1, 2) *Bolivina robusta*: (1) side view, CSJA6, depth 13.2–13.3 m, Reg. No. K1-023; (2) edge view, CSJA6, depth 13.2–13.3 m, Reg. No. K1-025. (3, 4) *Brizalina striatula*: (3) side view, LZK1, depth 12.7–12.8 m, Reg. No. K1-034; (4) edge view, LZK1, depth 12.3–12.4 m, Reg. No. K4-009. (5, 6) *Epistominella naraensis*: (5) ventral view, right-coiled, LZK1, depth 12.7–12.8 m, Reg. No. K1-067; (6) edge view, left-coiled, LZK1, depth 12.7–12.8 m, Reg. No. K1-069. (7–9) *Rosalina bradyi*: (7) ventral view, LZK1, depth 30.7–30.8 m, Reg. No. K3-012; (8) edge view, CSJA6, depth 30.8–30.9 m, Reg. No. K4-038; (9) dorsal view, CSJA6, depth 34.2–34.3 m, Reg. No. K3-013. (10–12) *Buccella frigida*: (10) ventral view, CSJA6, depth 20.8–20.9 m, Reg. No. K1-036; (11) ventral view, CSJA6, depth 36.2–36.3 m, Reg. No. K4-008; (12) dorsal view, CSJA6, depth 25.5–25.6 m, Reg. No. K1-033.

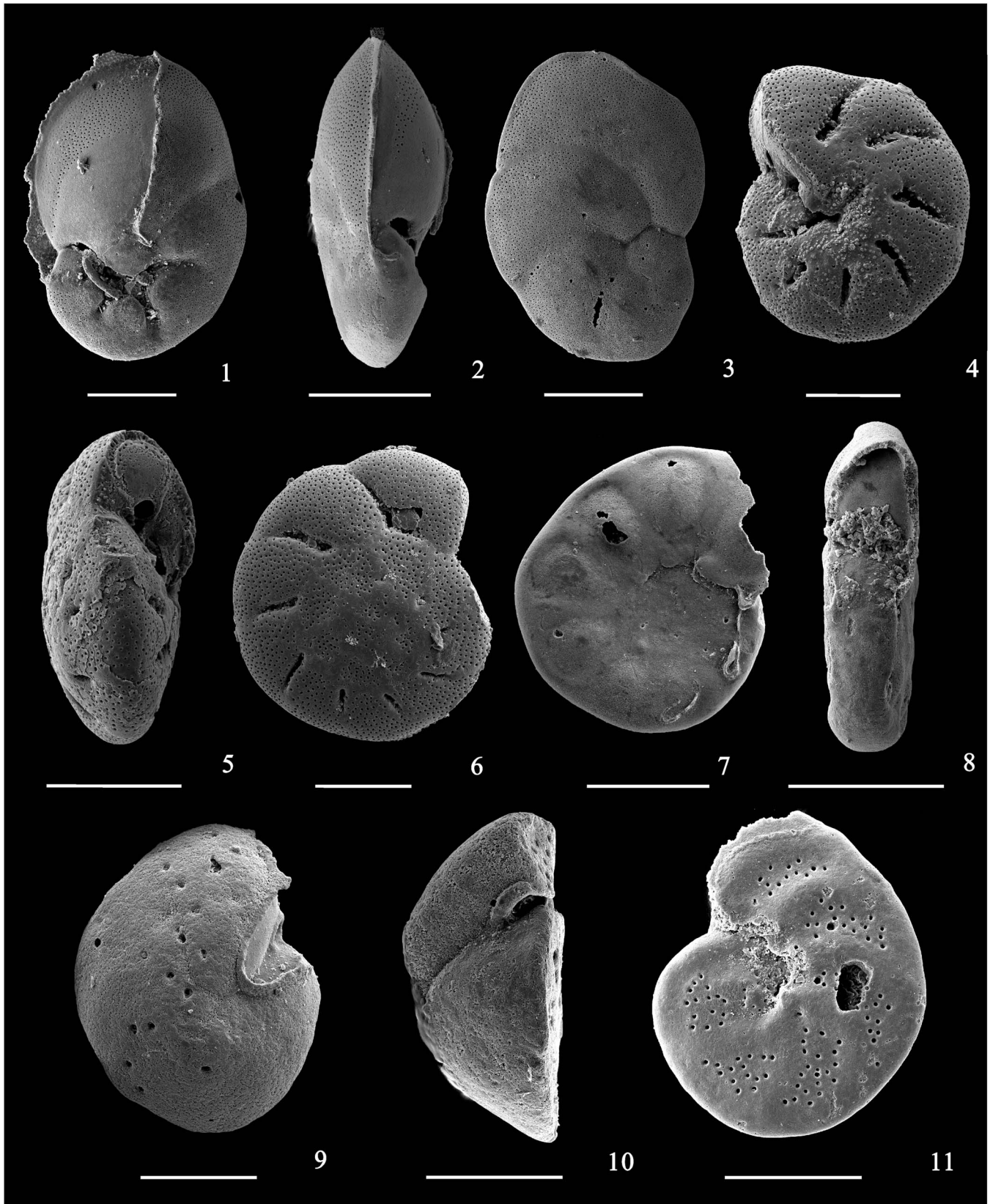


Figure 6. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1–3) *Cancris auriculus*: (1) ventral view, CSJA6, depth 34.8–34.9 m, Reg. No. K1–044; (2) edge view, CSJA6, depth 34.8–34.9 m, Reg. No. K1–046; (3) dorsal view, CSJA6, depth 34.8–34.9 m, Reg. No. K1–045. (4–6) *Helenina anderseni*: (4) ventral view, CSJA6, depth 46.5–46.6 m, Reg. No. K1–029; (5) edge view, CSJA6, depth 46.5–46.6 m, Reg. No. K4–009; (6) dorsal view, CSJA6, depth 46.5–46.6 m, Reg. No. K1–030. (7, 8) *Hyalinea balthica*: (7) side view, CSJA6, depth 35.2–35.3 m, Reg. No. K4–023; (8) edge view, CSJA6, depth 34.8–34.9 m, Reg. No. K4–024; (9–11) *Cibicides lobatulus*: (9) ventral view, CSJA6, depth 11.8–11.9 m, Reg. No. K1–047; (10) edge view, CSJA6, depth 17.2–17.3 m, Reg. No. K1–049; (11) dorsal view, CSJA6, depth 7.5–7.6 m, Reg. No. K1–048.

Gennari et al. (2011) reported a large number of morphological varieties, especially for different shapes of the sutures. The specimens here are more inflated. The supplementary apertures of specimens can be observed on the middle part of the septal sutures instead of near the junction, and are much narrower, showing a deeply incised slit. The supplementary apertures reported by Gennari (2011) are wider near umbilical region, and even triangular.

Family Cibicididae Cushman, 1927

Genus *Cibicides* de Montfort, 1808

Cibicides lobatulus (Walker and Jacob, 1798)

Figure 6.9–6.11

- 1798 *Nautilus lobatulus* Walker and Jacob, p. 642, pl. 14, fig. 36.
 1884 *Truncatulina lobatulus* (Walker and Jacob); Brady, pl. 92, fig. 10, pl. 93, figs. 1, 4, 5.
 1931 *Cibicides lobatula*; Cushman, p. 118, pl. 21, figs. 3a–3c.
 1978 *Cibicides lobatulus*; Cheng and Zheng, p. 232, pl. 21, figs. 2a–2c.
 1988 *Cibicides lobatulus*; Wang et al., p. 162, pl. 25, figs. 12–14.

Holotype.—(BMNH ZF2532) from Challenger Station 172, Friendly Islands, Pacific (33 m) (Brady, 1884, pl. 92, fig. 10).

Occurrence.—Widely distributed in coastal water of the world oceans; middle and outer shelf of East China Sea and South China Sea (Wang et al., 1988).

Remarks.—Large variations in morphology are assigned to this species. Specimens with keeled periphery or depressed umbilicus were reported by Brady (1884). The specimens here are more inflated with a round periphery, while those of Cushman (1931) and Wang (1988) have compressed chambers with obviously lobulated periphery.

Superfamily Rotaliacea Ehrenberg, 1839

Family Rotaliidae Ehrenberg, 1839

Genus *Ammonia* Brünnich 1772

Ammonia pauciloculata (Phleger and Parker, 1951)

Figure 7.1–7.3

- 1951 “*Rotalia*” *pauciloculata* Phleger and Parker, p. 23, pl. 12, figs. 8, 9.
 1965 *Ammonia nantongensis* Ho, Hu, and Wang; He, Hu, and Wang, p. 104, pl. 11, figs. 5a–5c.
 1988 *Ammonia pauciloculata*; Wang et al., p. 166, pl. 27, figs. 8–10.

Holotype.—(Sample 1) from Core 498 (Phleger and Parker, 1951, pl. 12, figs. 8, 9).

Occurrence.—Gulf of Mexico; coastal water in China seas, inner shelf of East China Sea; Quaternary coastal sediments in China; 0–50m (Wang et al., 1988).

Remarks.—Supplementary apertures that are perpendicular to the middle of the septal sutures on the ventral side, as noted by Wang et al. (1988), can be observed in the holotype illustrated

by Phleger and Parker (1951). The specimens in this study and *Ammonia nantongensis* Ho, Hu, and Wang (1965) also show this morphological character, while the subspecies *Ammonia pauciloculata major* described by He et al. (1965) cannot be assigned to this species because it has a large number of chambers for the last whorl and straight sutures.

Genus *Cavarotalia* Müller-Merz, 1980

Cavarotalia annectens (Parker and Jones, 1865)

Figure 8.1–8.3

- 1865 *Rotalia beccarii* var. *annectens* Parker and Jones, p. 387, pl. 19, figs. 11a–11c.
 1940 *Streblus annectens*; Ishizaki, p. 49, pl. 3, figs. 12a, 12b, 13a, 13b.
 1965 *Ammonia annectens*; He, Hu, and Wang, p. 103, pl. 11, figs. 3a–3c.
 1980 *Cavarotalia annectens*; Müller-Merz, p. 37, figs. 26, 27.
 1988 *Cavarotalia annectens*; Wang et al., p. 168, pl. 27, figs. 12, 13.

Occurrence.—Miocene in India; shallow water in Pacific and Indian oceans; shelf of China seas; Quaternary in Taiwan, China; Quaternary coastal sediments in East China; 0–50 m, East China Sea (Wang et al., 1988).

Remarks.—Deeply incised, fishbone-like sutures taper from the middle to the periphery in ventral side. The large transparent umbilical plug also distinguishes it from *Ammonia*.

Family Elphidiidae Galloway, 1933

Genus *Cribronion* Thalmann, 1947

Cribronion subincertum (Asano, 1950)

Figure 8.4, 8.5

- 1950 *Elphidium subincertum* Asano, p. 10, figs. 56, 57.
 1965 *Cribronion gnathosuturatum*; He et al., p. 115, pl. 14, figs. 5a, 5b.
 1965 *Cribronion* sp.; He et al., p. 115, pl. 14, figs. 3a, 3b.
 1978 *Cribronion incertum*; Zheng et al., p. 58, pl. 8, figs. 15, 16.
 1980a *Cribronion subincertum*; Wang et al., pl. 9, figs. 22, 23.
 1988 *Cribronion subincertum*; Wang et al., p. 168, pl. 28, figs. 1–4.

Occurrence.—Shallow water in high-latitude North Pacific and North Atlantic; Recent and Quaternary coastal sediments in Bohai Sea, Yellow Sea, and East China Sea; 0–50m in East China Sea; 10–30‰ salinity, coastal water off Jiangsu and Zhejiang, China (Wang et al., 1988).

Remarks.—The specimens in this study possess the long slit sutures. Test slightly compressed, as show in Figure 8.4, or inflated (Fig. 8.5). Wang et al. (1988) pointed out that the juvenile forms are often more inflated than the adult. It was reported that the aperture is made up of a row of pores (He et al., 1965). Due to the granular cover on the base of the apertural face, the pores cannot be observed in the specimens illustrated here.

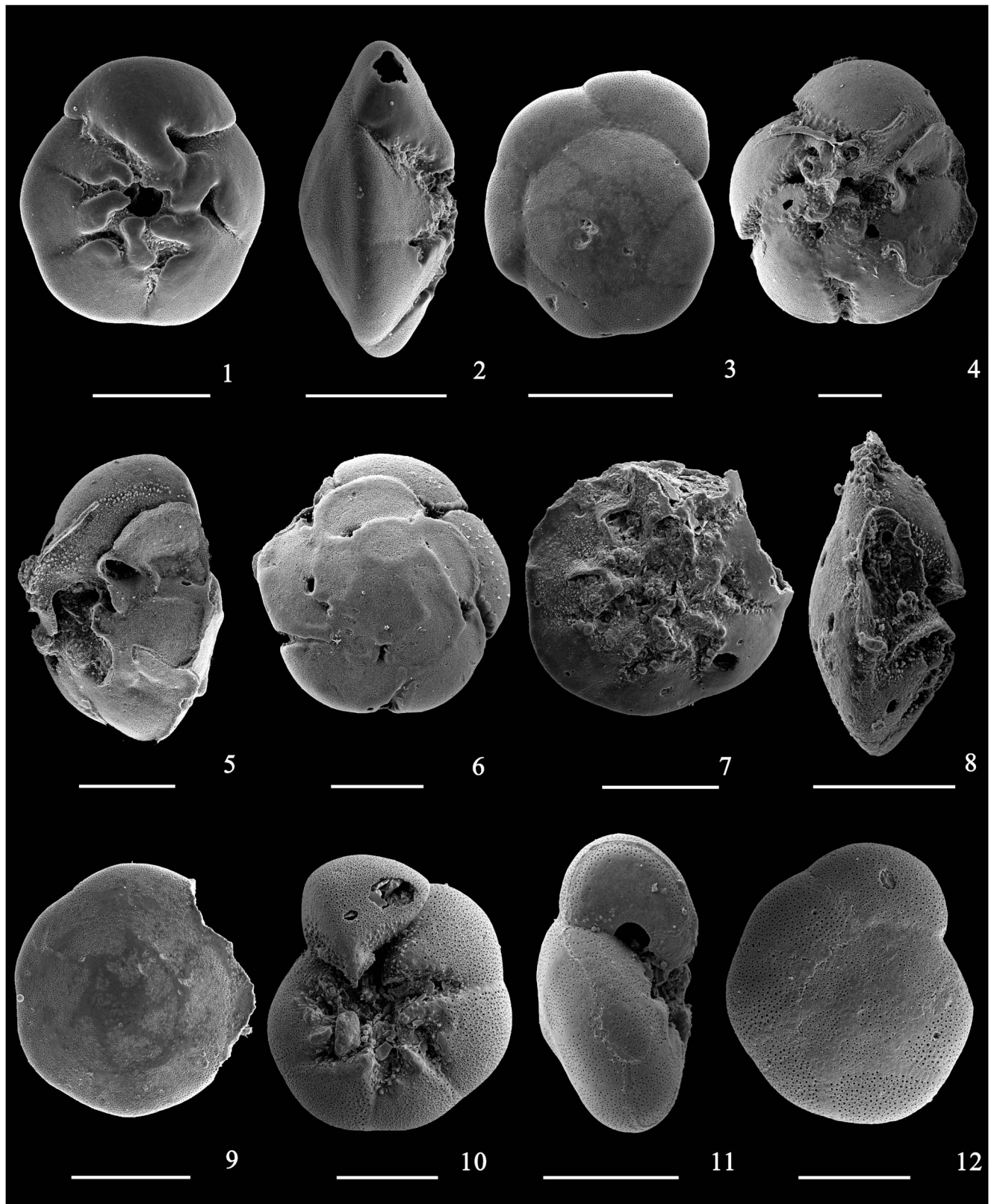


Figure 7. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1–3) *Ammonia pauciloculata*: (1) ventral view, CSJA6, depth 31.2–31.3 m, Reg. No. K4–003; (2) edge view, LZK1, depth 27.7–27.8 m, Reg. No. K4–005; (3) dorsal view, CSJA6, depth 31.2–31.3 m, Reg. No. K4–004. (4–6) *Ammonia compressiuscula*: (4) ventral view, CSJA6, depth 34.2–34.3 m, Reg. No. K1–018; (5) edge view, CSJA6, depth 34.2–34.3 m, Reg. No. K1–019; (6) dorsal view, CSJA6, depth 21.5–21.6 m, Reg. No. K1–017. (7–9) *Ammonia ketienziensis*: (7) ventral view, CSJA6, depth 33.8–33.9 m, Reg. No. K4–035; (8) edge view, CSJA6, depth 34.2–34.3 m, Reg. No. K4–034; (9) dorsal view, CSJA6, depth 34.2–34.3 m, Reg. No. K4–033. (10–12) *Ammonia beccarii*: (10) ventral view, CSJA6, depth 7.5–7.6 m, Reg. No. K1–007; (11) edge view, CSJA6, depth 7.5–7.6 m, Reg. No. K1–009; (12) dorsal view, CSJA6, depth 7.5–7.6 m, Reg. No. K1–008.

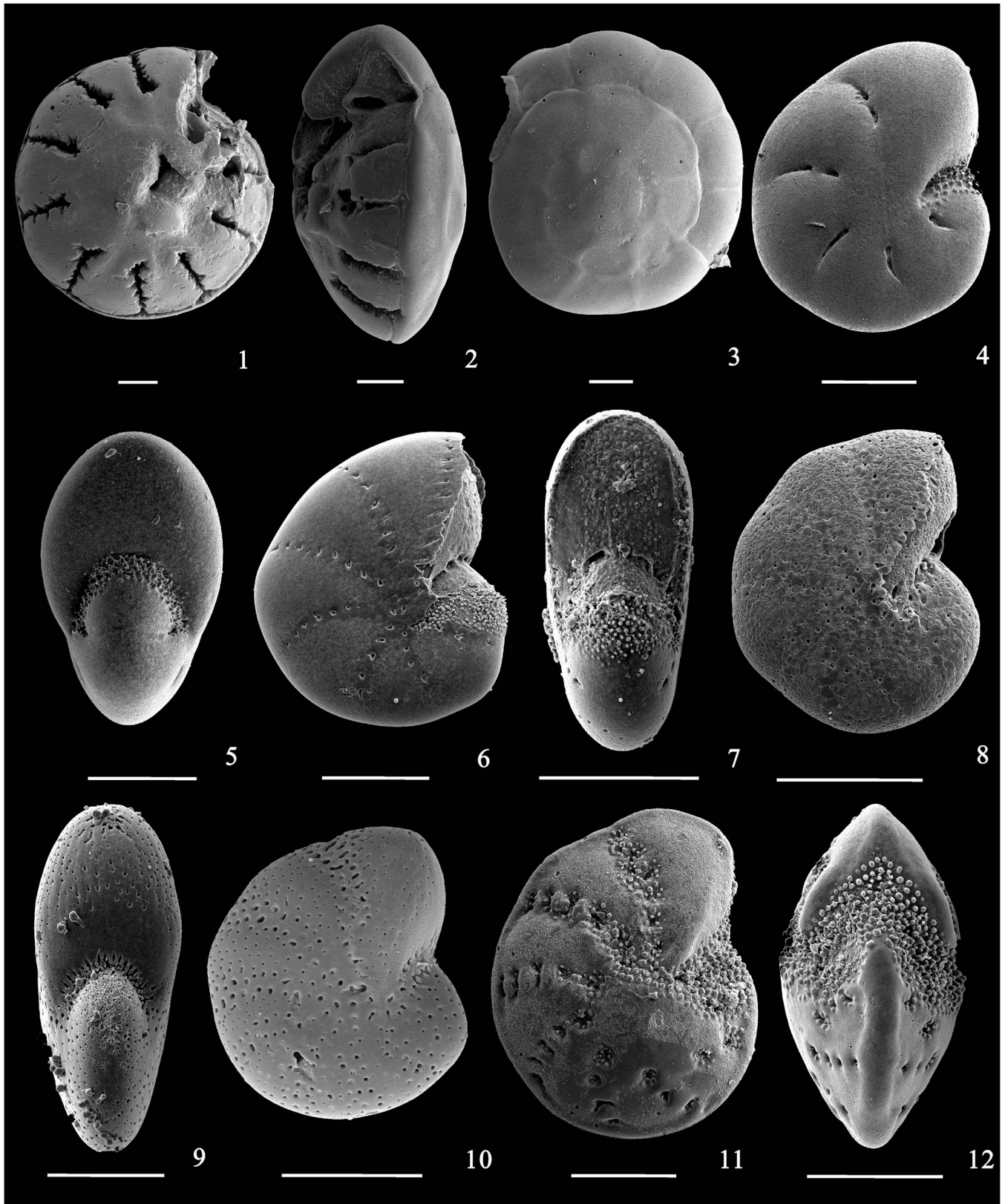


Figure 8. SEM photos of the foraminifers from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1–3) *Cavarotalia annectens*: (1) ventral view, LZK1, depth 21.7–21.8 m, Reg. No. K1–004; (2) edge view, LZK1, depth 21.7–21.8 m, Reg. No. K4–001; (3) dorsal view, LZK1, depth 21.7–21.8 m, Reg. No. K1–005. (4, 5) *Cribrononion subincertum*: (4) side view, CSJA6, depth 23.2–23.3 m, K4–012; (5) edge view, CSJA6, depth 23.2–23.3 m, Reg. No. K4–013. (6, 7) *Cribrononion vitreum*: (6) side view, CSJA6, depth 23.2–23.3 m, Reg. No. K4–014; (7) edge view, LZK1, depth 12.3–12.4 m, Reg. No. K4–015. (8–10) *Elphidiella kangsuensis*: (8) side view, CSJA6, depth 23.2–23.3 m, Reg. No. K4–026; (9) edge view, CSJA6, depth 5.5–5.6 m, Reg. No. K1–055. (10) side view (Guo et al., 2014). (11, 12) *Elphidium advenum*: (11) side view, CSJA6, depth 47.6–47.7 m, Reg. No. K1–056; (12) edge view, CSJA6, depth 47.6–47.7 m, Reg. No. K1–057.

Cribrononion vitreum Wang and Gu, 1980
Figure 8.6, 8.7

- 1980 *Cribrononion vitreum*; Wang and Gu, pl. 16, fig. 13.
1988 *Cribrononion vitreum*; Wang et al., p. 169, pl. 27, figs. 14, 15.
2012 *Cribrononion vitreum*; Li et al., pl. 2, figs. 11, 12.

Holotype.—(TJU H1560) from Core Lp25, depth 24–35.91 m, east coast of Liaohe estuary, Panshan, Liaoning Province (Wang and Gu, 1980, pl. 16, fig. 13).

Occurrence.—Recent and Quaternary coastal sediments of Bohai Sea, East China Sea, and Yellow Sea; inner shelf and estuary in East China Sea, 10–30% salinity (Wang et al., 1988).

Remarks.—Wang et al. (1988) pointed out that there are several pores on the middle of the aperture face, which also has been observed by Li et al. (2012). The specimens illustrated here have lost the last chamber. But the aperture, a row of slits, is the same as those described by Wang et al. (1988). The pores on the aperture face in this study cannot be observed.

Genus *Elphidiella* Cushman, 1936a
Elphidiella kiangsuensis (Ho, Hu, and Wang, 1965)
Figure 8.8–8.10

- 1965 *Cribrononion kiangsuensis* Ho, Hu, and Wang; He, Hu, and Wang, p. 114, pl. 13, fig. 13.
1978 *Elphidiella kiangsuensis*; Zheng et al., p. 60, pl. 9, figs. 1, 13.
1988 *Elphidiella kiangsuensis*; Wang et al., p. 171, pl. 29, figs. 12, 13.
2014 *Elphidiella kiangsuensis*; Guo et al., pl. 1, figs. 5, 6.

Holotype.—(NIGP 14685) from Binhai, Jiangsu, China (He et al., pl. 13, fig. 13).

Description.—Test planispiral, entirely involute, oval in side view, bilaterally symmetrical, sides nearly parallel in edge view; periphery rounded; chambers 8–10 in the last whorl, increasing gradually, gently inflated; umbilicus flattened; sutures curved, nearly flush with the surface, often consisting of two rows of small round pores; wall smooth, translucent, finely perforate; oval apertural face; aperture comb-like on the base of the face.

Occurrence.—Quaternary and Recent coastal sediments in Bohai Sea, Yellow Sea and East China Sea (Wang et al., 1988).

Remarks.—The pores in the sutures of specimens in this study are less distinct, the same as shown by He et al. (1965). The suture pores are more clear in the specimens (Fig. 8.10) reported by Guo et al. (2014), in which two rows of pores form a wide suture zone. Depressed slit-like sutures also were reported in the East China Sea (Wang et al., 1988).

Genus *Elphidium* de Montfort, 1808
Elphidium hispidulum Cushman, 1936b
Figure 9.1, 9.2

- 1936b *Elphidium hispidulum* Cushman, p. 83, pl. 14, figs. 13a, 13b.
1978 *Elphidium hispidulum*; Zheng et al., p. 55, pl. 7, fig. 9.
1988 *Elphidium hispidulum*; Wang et al., p. 170, pl. 29, figs. 16, 17.

Holotype.—(USNM CC 23028) from 7–26 m, Albany Passage, Australia (Cushman, 1936b, pl. 14, figs. 13a, 13b).

Occurrence.—Southern Australia and Gulf of Paria; surface sediments in Bohai Sea, Yellow Sea and East China Sea.

Remarks.—The bosses in the umbilicus are partially separated for specimens in this study. A row of low papillae in the early portion of the sutures is more distinct than those of Wang et al. (1988) and He et al. (1965).

Elphidium magellanicum Heron-Allen and Earland, 1932
Figure 9.4, 9.5

- 1932 *Elphidium (Polystomella) magellanicum* Heron-Allen and Earland, p. 440, pl. 16, figs. 26–28.
1978 *Elphidium magellanicum*; Zheng et al., p. 56, pl. 8, fig. 3.
1978 *Elphidiononion magellanicum*; Banner and Culver, pl. 9, fig. 16.
1980b *Elphidium magellanicum*; Wang et al., p. 98, pl. 11, fig. 16.
1988 “*Elphidium magellanicum*”; Wang et al., p. 169, pl. 28, figs. 5, 11–13.

Holotype.—(BMNH HA508-90) from WS 89, depth 23 m, eastern entrance to the Straits of Magellan (Heron-Allen and Earland, pl. 16, figs. 26–28).

Occurrence.—Coastal water and Quaternary coastal sediments in Bohai Sea, Yellow Sea, and East China Sea (Wang et al., 1988).

Remarks.—Wang et al. (1988) pointed out that the specimens in the East China Sea are different from those of the Atlantic samples by a much inflated test. The specimens in this study have a less lobulate peripheral edge, close to that reported by Wang et al. (1988). The umbilicus and the base of the apertural face are filled with fine granular matter in this study, but the granular region is much narrower and smaller than those described by Heron-Allen and Earland (1932).

Genus *Protelphidium* Haynes, 1956
Protelphidium tuberculatum (d’Orbigny, 1846)
Figure 9.6, 9.7

- 1846 *Nonion tuberculatum* d’Orbigny, p. 108, pl. 5, figs. 13, 14.
1939 *Nonion tuberculatum*; Cushman, p. 13, pl. 3, figs. 12, 16, 17.
1980a *Protelphidium tuberculatum*; Wang and Gu, p. 60, pl. 16, fig. 7.
1988 *Protelphidium tuberculatum*; Wang et al., p. 171, pl. 29, figs. 14, 15.

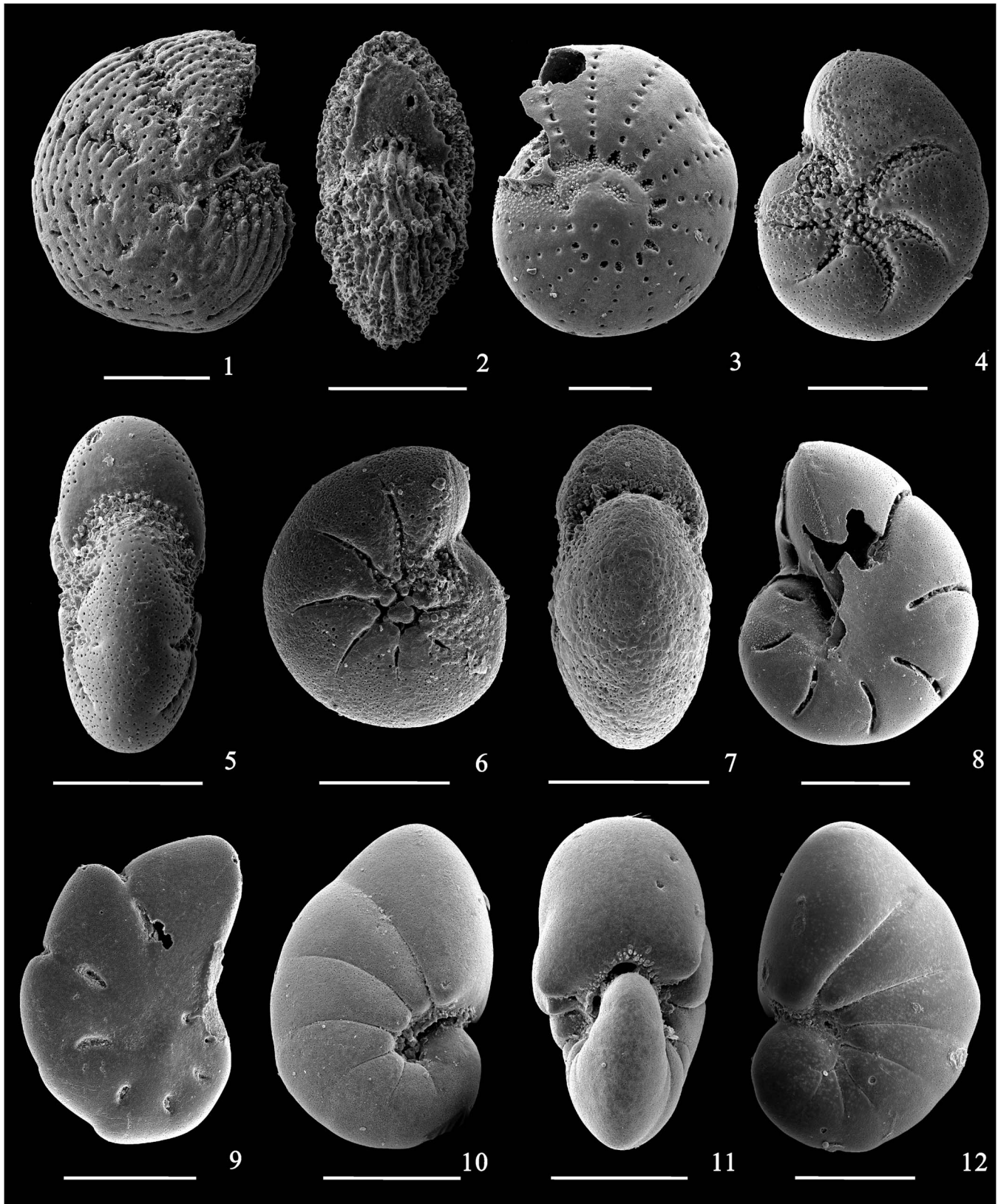


Figure 9. SEM photos of the foraminifers from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1, 2) *Elphidium hispidulum*: (1) side view, CSJA6, depth 46.5–46.6 m, Reg. No. K1–060; (2) edge view, CSJA6, depth 25.5–25.6 m, Reg. No. K4–029. (3) *Elphidium limpidum*: side view, CSJA6, depth 46.5–46.6 m, Reg. No. K1–062. (4, 5) *Elphidium magellanicum*: (4) side view, CSJA6, depth 2.2–2.3 m, Reg. No. K1–065; (5) edge view, CSJA6, depth 20.8–20.9 m, Reg. No. K1–066. (6, 7) *Protelphidium tuberculatum*: (6) side view, CSJA6, depth 13.5–13.6 m, Reg. No. K2–022; (7) edge view, CSJA6, depth 25.5–25.6 m, Reg. No. K2–023. (8, 9) *Pseudonionella variabilis*: (8) ventral view, CSJA6, depth 7.5–7.6 m, Reg. No. K2–024; (9) dorsal view, CSJA6, depth 36.8–36.9 m, Reg. No. K2–025. (10–12) *Florilus scaphus*: (10) ventral view, LZK1, depth 12.3–12.4 m, Reg. No. K1–076; (11) edge view, LZK1, depth 12.3–12.4 m, Reg. No. K1–078; (12) dorsal view, LZK1, depth 12.7–12.8 m, Reg. No. K4–022.

Occurrence.—Coastal water and Quaternary coastal sediments in Bohai Sea, Yellow Sea, and East China Sea; Yellow Sea coastal cold water; inner shelf and Late Pleistocene outer shelf sediments in East China Sea (Wang et al., 1988).

Remarks.—This species differs from *Elphidium magellanicum* by a small elevated umbilicus filled with a few tuberculations, and evident slit sutures. It was reported that the early whorls in this species usually appears yellow in China seas (Wang et al., 1988).

Superfamily Cassidulinacea d'Orbigny, 1839a
 Family Caucasinidae Bykova, 1959
 Genus *Fursenkoina* Loeblich and Tappen, 1961
Fursenkoina pauciloculata (Brady, 1884)
 Figure 10.1, 10.2

- 1884 *Virgulina pauciloculata* Brady, p. 414, pl. 52, figs. 4, 5.
 1965 *Fursenkoina pauciloculata*; He, Hu, and Wang, p. 84, pl. 6, fig. 7.
 1994 *Virgulina pauciloculata* Brady; Jones, pl. 52, figs. 4, 5.

Occurrence.—Recent South Pacific; Jiangsu, China (He et al., 1965).

Remarks.—The shorter and wider specimens (Fig. 10.1) reported here are the same as those described by He et al. (1965); the elongate specimen (Fig. 10.2) is referred to those specimens described by Brady (1884), but lacks the short spine in the earliest chamber.

Superfamily Nonionacea Schultze, 1854
 Family Nonionidae Schultze, 1854
 Genus *Nonionella* Cushman, 1926
Nonionella jacksonensis Cushman, 1933
 Figure 10.5, 10.6

- 1933 *Nonionella jacksonensis* Cushman, p. 10, pl. 1, figs. 23a–23c.
 1965 *Nonionella jacksonensis*; He, Hu, and Wang, p. 119, pl. 14, figs. 11a, 11b.
 1988 *Nonionella jacksonensis*; Wang et al., p. 176, pl. 32, figs. 1, 2.

Holotype.—(USNM MO 371678) from Cooper marl, 1.6 km (1 mile) south of Moncks Corner, Berkeley Co., S.C. (Cushman, 1933, pl. 1, figs. 23a–23c).

Occurrence.—Upper Eocene in U.S.A.; surface shelf and Quaternary coastal sediments in Yellow Sea and East China Sea; common in inner shelf and estuary of East China Sea (Wang et al., 1988).

Remarks.—It was reported that there is a slit-like aperture on the base of last chamber (He et al., 1965). The aperture of specimens presented here cannot be observed due to the granular cover on the base of the apertural face. The latter chambers in this study increase slowly, comparatively.

Results

Foraminiferal specimens were only found from the depth intervals of 3–42.07 m, 1.8–65.7 m, and 0.6–46.1 m in cores ZKA4, CSJA6 and LZK1, respectively (Fig. 2). The foraminiferal abundance in Core ZKA4 is generally lower than those of the other two cores (Fig. 2). In cores CSJA6 and LZK1, the average abundance of benthic foraminifers is 50 and 33 specimens /50 g, respectively. In Core LZK1, the highest benthic foraminiferal abundance is 718 specimens /50 g at 13 m depth, while in Core CSJA6, the highest of benthic foraminiferal abundance is 385 specimens /50 g at 46.6 m depth. Most of the foraminifers are benthic forms, with planktonic types being <5% in each core.

Benthic foraminiferal species diversity trend is similar to the abundance trend, varying from a low of 20 in Core ZKA4 to 35–46 in cores CSJA6 and LZK1. The middle and upper parts of the Rudong Formation in the three cores have higher foraminiferal abundance and diversity. Of the benthic foraminifers, 115 species in 53 genera have been identified, most of which are hyaline tests. The porcellaneous forms are frequent in some layers, and arenaceous forms are occasionally observed.

The dominant species in the three cores is *Ammonia beccarii* var., which approaches 50% on average. Other species, such as *Ammonia compressiusula*, *Ammonia ketienziensis*, *Ammonia pauciloculata*, *Cribrononion subincertum*, *Elphidium advenum*, *Elphidium magellanicum*, and *Florilus decorus* are also present at high frequency. Some species, such as *Hazawaia nipponica* and *Melonis barleeanum*, are seldom found (Fig. 11).

Discussion

Based on the occurrences of benthic foraminifers in the cores, three assemblages can be recognized (Fig. 2). In Core CSJA6, for example, the three foraminiferal assemblages are, in ascending order, the *Ammonia beccarii-Florilus decorus* assemblage, the *Ammonia beccarii-Elphidium advenum* assemblage, and the *Ammonia beccarii-Elphidium magellanicum* assemblage (Figs. 2, 12).

The lower parts of the cores (below 42.07 m, 34 m, and 52.9 m for ZKA4, LZK1, and CSJA6, respectively) are characterized by lower foraminiferal abundance and diversity, dominated by *Ammonia beccarii* var. and *Florilus decorus*. In addition, *Cribrononion subincertum*, *Elphidium advenum*, and *Elphidium magellanicum* occur in moderate abundance, indicating a hypohaline, low-temperature water environment. The *Ammonia beccarii-Florilus decorus* assemblage is comparable with the *Ammonia beccarii* assemblage of the lower part of Bed H I -1 in the South Yellow Sea shelf, both of which have low foraminiferal abundance and diversity (Yang, 1985, 1993; Yang and Lin, 1996).

The foraminifers are abundant and more diverse in the middle parts of the cores (depth intervals of 3–42.07 m, 12–34 m, and 19.9–52.9 m for ZKA4, LZK1, and CSJA6, respectively), where the shallow-water species *Ammonia beccarii* var. and *Elphidium advenum* are dominant. In this interval, the porcellaneous benthic foraminifers are often relatively common. *Cavarotalia annectens* and *Pararotalia nipponica* are

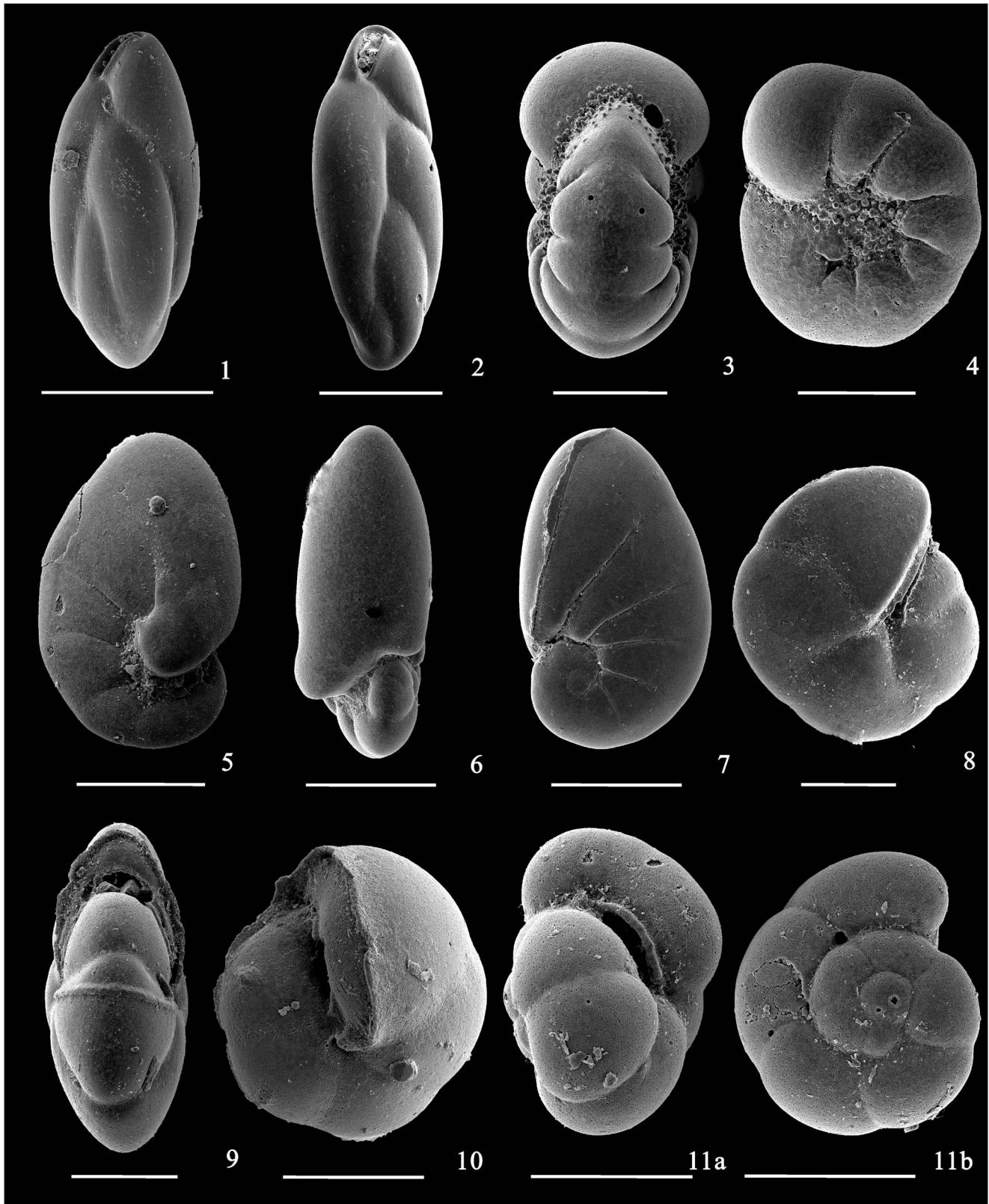


Figure 10. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu and Core LZK1, Hengsha Island, Shanghai. All scale bars are 100 μm . (1, 2) *Fursenkoina pauciloculata*: (1) side view, CSJA6, depth 34.8–34.9 m, Reg. No. K1–086; (2) apertural view, LZK1, depth 25.5–25.6 m, Reg. No. K3–023. (3, 4) *Nonion akitense*: (3) side view, CSJA6, depth 23.2–23.3 m, K2–011; (4) edge view, CSJA6, depth 23.2–23.3 m, Reg. No. K2–012. (5–7) *Nonionella jacksonensis*: (5) ventral view, LZK1, depth 12.3–12.4 m, Reg. No. K2–015; (6) edge view, LZK1, depth 12.3–12.4 m, Reg. No. K2–013; (7) dorsal view, LZK1, depth 12.7–12.8 m, Reg. No. K2–014. (8, 9) *Pullenia quinqueloba*: (8) side view, ZKA4, depth 41.1–41.2 m, Reg. No. K2–027; (9) edge view, LZK1, depth 4.5–4.6 m, Reg. No. K2–028. (10, 11) *Gyroidina nipponica*: (10) ventral view, LZK1, depth 19.8–19.9 m, Reg. No. K1–089; (11a) edge view, LZK1, depth 5.1–5.2 m, Reg. No. K1–090; (11b) dorsal view, LZK1, depth 5.1–5.2 m, Reg. No. K1–090.

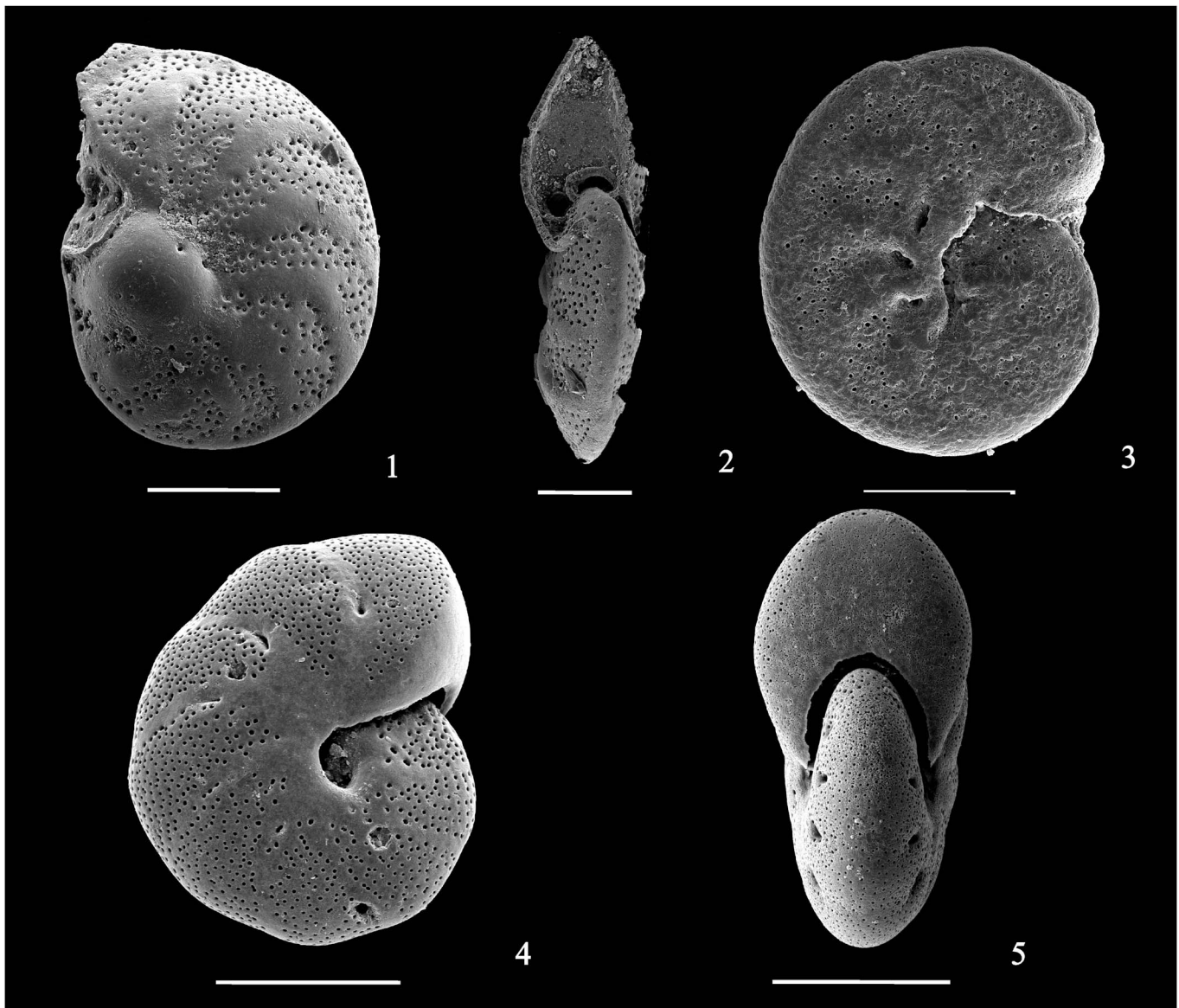


Figure 11. SEM photos of the foraminifera from Core CSJA6, Nantong, Jiangsu; Core ZKA4, Yangzhou, Jiangsu; and Core LZK1, Hengsha Island, Shanghai. (1–3) *Hazawaia nipponica*: (1) ventral view, LZK1, depth 26.9–27.0 m, Reg. No. K1-092; (2) edge view, CSJA6, depth 47.6–47.7 m, Reg. No. K1-094; (3) dorsal view, CSJA6, depth 21.5–21.6 m, Reg. No. K1-093. (4, 5) *Melonis barleeanum*: (4) side view, CSJA6, depth 23.2–23.3 m, Reg. No. K2-009; (5) edge view, CSJA6, depth 23.2–23.3 m, Reg. No. K2-010.

relatively abundant. For example, the *Cavarotalia annectens* content is up to 18% at the depth 32.2–32.3 m in Core CSJA6. The benthic foraminifera were typical of warm-water forms. This is corroborated by the relative large size of the foraminiferal tests, which also suggests an influence of high energy water. The *Ammonia beccarii-Elphidium advenum* assemblage can be correlated with the *Ammonia beccarii-Elphidium advenum* assemblage of the upper part of Shanghai Formation in the Shanghai region (Wang and Min, 1979). It is also comparable with the *Ammonia beccarii-Elphidium advenum* assemblage of the middle part of the Beijian Formation in the Pearl River Mouth Basin (Yang and Lin, 1996).

The foraminifera observed at the upper part of Core ZKA4 do not indicate a direct influence of sea water in this area. The other two cores, however, suggest that their vicinities were under continued influence of marine environment. The upper

parts of LZK1 and CSJA6 have a relatively low benthic foraminiferal abundance and diversity, dominated by *Ammonia beccarii* var. and *Elphidium magellanicum*. The assemblage also includes *Ammonia compressiuscula*, *Ammonia ketienziensis angulata*, *Ammonia pauciloculata*, *Cribronion subincertum* and *Elphidium advenum*. The *Ammonia beccarii-Elphidium magellanicum* assemblage may be correlated to the *Ammonia ketienziensis-Astronion tasmensis* assemblage and *Elphidium magellanicum* assemblage of the upper part of Bed HI-1 in South Yellow Sea Shelf (Yang, 1985, 1993; Yang and Lin, 1996) based on the common presence of *Ammonia beccarii*, *Elphidium magellanicum*, and *Ammonia ketienziensis angulata* in each fauna.

AMS ^{14}C dating suggests that the studied sediments of the three cores accumulated during the post-glacial period. The three benthic foraminiferal assemblages can be correlated with the faunas of this region in previous work

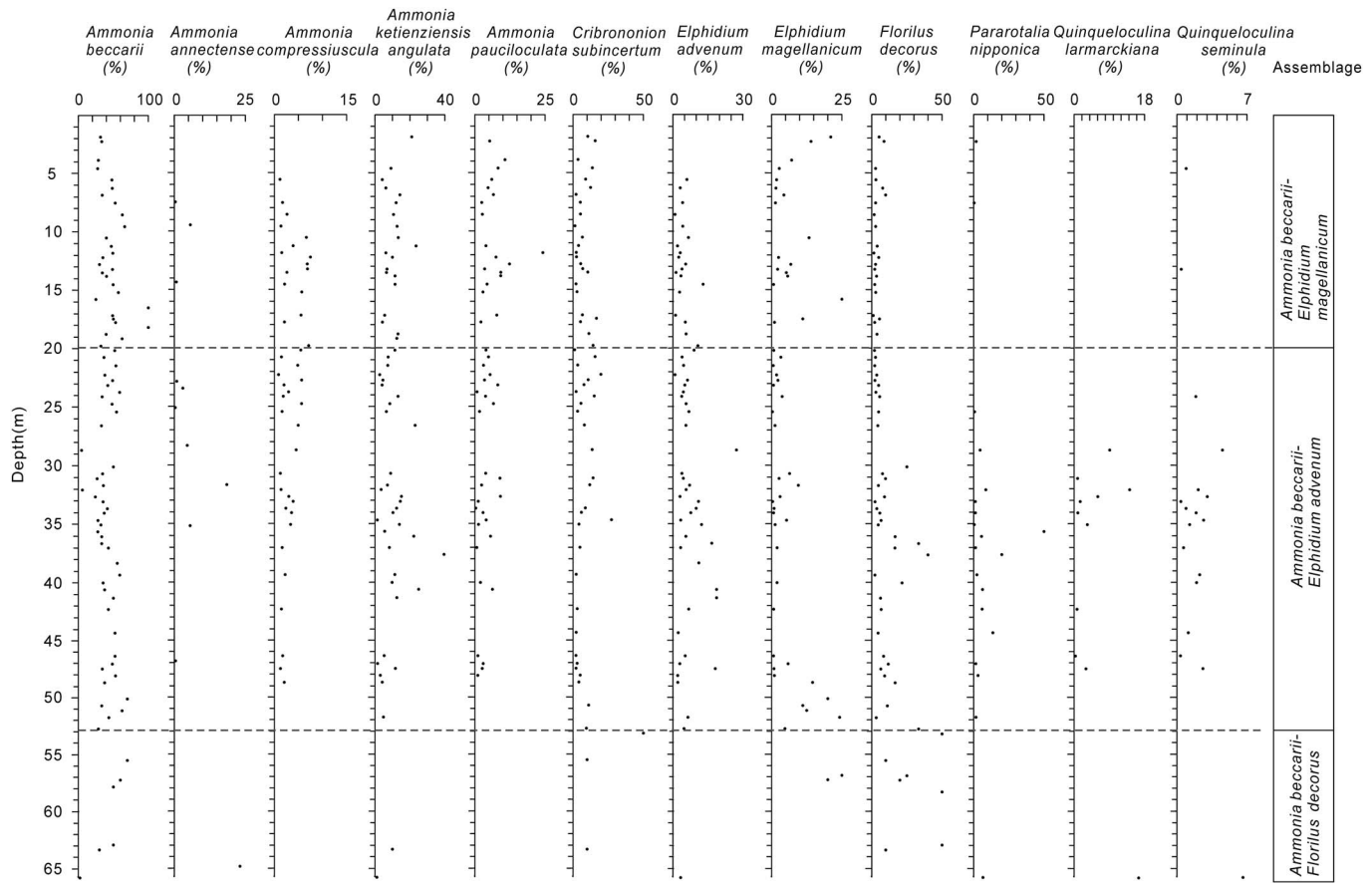


Figure 12. Down-core variations of main species and assemblages of benthic foraminifers in Core CSJA6.

(Min and Wang, 1979), which documented the post-glacial transgression-regression history, referred to as the “*Ammonia* transgression” during the Holocene (Wang et al., 1981).

The *Ammonia beccarii-Florilus decorus* assemblage points to a weak marine transgression during the early post-glacial period. The *Ammonia beccarii-Elphidium advenum* assemblage, however, suggests the strongest transgression during the early–middle Holocene, when the warm and relatively deep sea water invaded this region. The *Ammonia beccarii-Elphidium magellanicum* assemblage corresponds to the late Holocene marine regression, an episode of global sea level drop. Due to the difference in the locations of the studied cores, the results suggest that Core ZKA4 is first out of the influence of the marine water during the late middle Holocene, when the other two cores were still of marine environment during the late Holocene.

Conclusions

The occurrence of abundant foraminifers in three cores drilled in the incised Yangtze paleo-valley revealed post-glacial environmental changes. Three benthic foraminiferal assemblages are present, including the *Ammonia beccarii-Florilus decorus* assemblage during the early post-glacial period, the *Ammonia beccarii-Elphidium advenum* assemblage during the early-middle Holocene, and the *Ammonia beccarii-Elphidium magellanicum* assemblage in the late Holocene. The assemblages can be correlated with the “*Ammonia* marine transgression” during the Holocene (Wang et al., 1981). The early–middle Holocene benthic foraminiferal assemblage also

implies a warm environment because of the occurrence of abundant *Cavarotalia annectens* and *Pararotalia nipponica*, and porcelaneous forms. The difference in foraminiferal abundance and diversity suggests that the cores in the modern coastal area are influenced by ocean water since the early post-glacial period, while the upstream core witnessed the transgression only during the middle Holocene. With the global sea level drop, the ocean water retreated from the west since the late middle Holocene and gradually formed the estuary environment in the Yangtze Delta.

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