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MARINE BIOLOGY

Benthic Foraminiferal Assemblages of the South China Sea

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Abstract—Based on the dominant species of benthic foraminifers in the bottom sediments sampled at 270 stations in the South China Sea, their 12 assemblages are defined and mapped. The distribution of these assemblages is controlled by environmental factors that are determined by bathymetric and latitudinal zonality, currents, upwellings, continental runoff, and water productivity. The communities established are indicative of different biotopes characterized by upwellings, higher or lower productivity, and intense or less intense impact of freshwater runoff.

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INTRODUCTION

This paper is dedicated to the biogeographic and ecological aspects of benthic foraminiferal assemblages defined on the continental slope and in the deep part of the South China Sea. The taxonomic composition of these assemblages and their bathymetric distribution were discussed in [14, 15, 19, 23, 25]. As was shown [16], there is a distinct correlation between their diversity and the influx of organic carbonate to a depth exceeding 1000 m.

The South China Sea is located within the Near-Equatorial climatic belt [5] and is separated from the Pacific by the Taiwan–Kalimantan island arc.

The dependence of currents on monsoons, which change their direction for the opposite one in different seasons, and the development of upwellings are among the main hydrological characteristics of the sea.

MATERIAL AND METHODS

Primary data on the abundance of benthic foraminiferal species in the bottom sediments (0–1 cm) sampled at 270 stations in the South China Sea [14–16, 19, 23, 25] served as a basis for this work. Figures 1–3 illustrate the location of these stations.

The foraminiferal assemblages were defined and named after the dominant taxa. The species second in abundance were considered as subdominant. The distribution areas were mapped with account for the occurrence depths and bottom topography.

The taxonomic affinity of the species is given according to recent classifications [6, 17].

ENVIRONMENTS

Bottom topography. The flat continental shelf of the South China Sea is usually 160–185 km wide being the widest (up to 280 km) in Bak-bo (Tonkin) Bay and the narrowest (30–50 km) near Hindustan Peninsula. The shelf of the island arc that separates the sea from the Pacific Ocean is approximately 20–30 km wide. The continental slope is steep and narrow. Southeast of Hainan Island and northwest of Kalimantan Island, it widens up to 300–400 km. The slope of the island arc is narrow (<10–20 km). The deep basin of the sea up to 5560 m deep is complicated by seamounts crowned by atolls [1, 4].

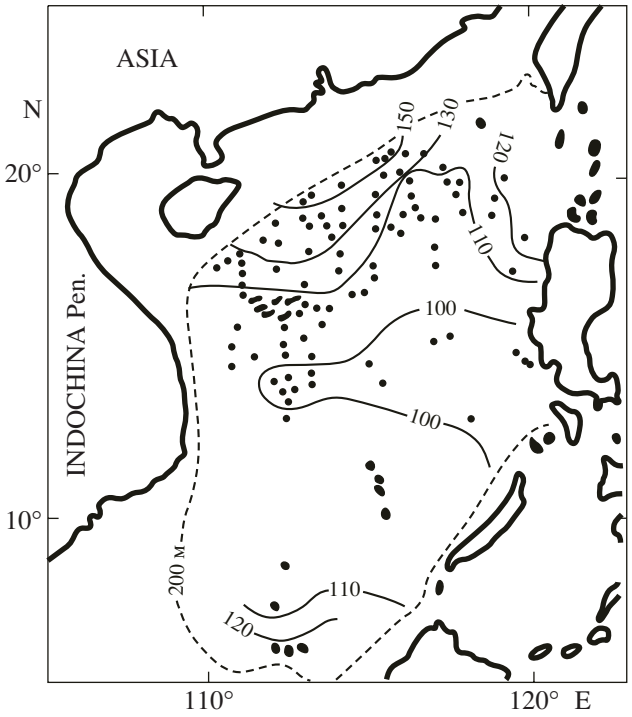

Fig. 1. Primary production of the South China Sea, g/m^2/year (after [20]). The dots designate the stations at depths exceeding 200 m.

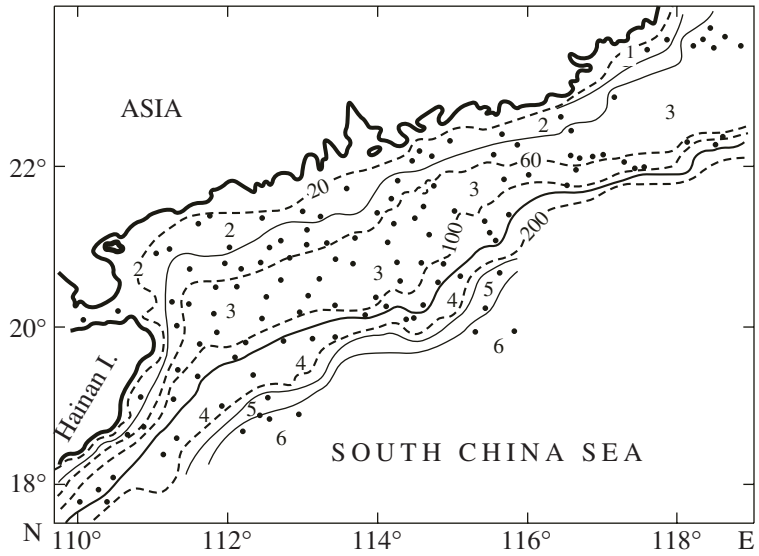

Fig. 2. Distribution of benthic foraminiferal assemblages in the open shelf areas and the upper parts of the continental slope of the South China Sea. (1) *Rotorbinella tepida*; (2) *Pseudononion japonicum–Hanzawaia nipponica*; (3) *Amphistegina lessonii*; (4) *Brizalina robusta*; (5) *Cassidulina* gr. *laevigata*; (6) *Euuvigerina auberiana.* The dots designate the stations or their groups; the dashed lines are the depth contours (m).

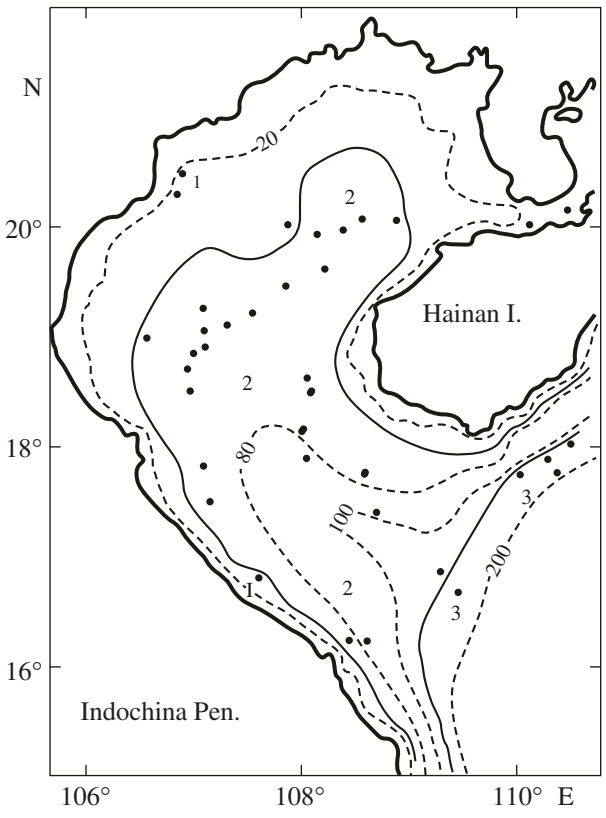

Fig. 3. Distribution of benthic foraminiferal assemblages on continental and island slopes in the Bak-bo (Tonkin) Bay of the South China Sea. (1) *Pseudononion japonicum–Hanzawaia nipponica*; (2) *Amphistegina lessonii*; (3) *Brizalina robusta.* The dots designate stations; the dashed lines are the depth contours (m).

The sea is connected by several straits with the Pacific. The widest of them is the Luzon Strait 1800 m deep located between Taiwan Island and the Philippine Islands. The depth of the straits connecting the South China and Sulu seas does not exceed 450 m. The Karimata Strait connecting the South China Sea with the Java Sea is the widest one (<200 km) [4].

Bottom sediments. On the coastal shelf, the sediments are represented by terrigenous sands and silts. They are replaced by terrigenous slightly carbonate silts with a $CaCO_3$ content of <30% on the inner shelf and by sands with glauconite on its outer part. Island shelves are covered with organogenic highly carbonate sands ($CaCO_3$ > 50%). The sediments in the upper part of the continental slope down to depths of 500–700 m are composed of sands with glauconite ($CaCO_3$ > 30%). Downward, they give way to carbonate silts. In the deep basin, the sediments are low-carbonate silts and clays. Everywhere, the sediments contain an admixture of volcanic glass [1, 2, 4].

Hydrography. The direction of the currents in the South China Sea depends on the winds. In the winter, when northerly winds are dominant, the sea is influenced by Pacific waters, which enter the sea via the straits in the island arc. In the western part of the sea, they turn southward and flow via the Karimata Strait. In the summer, southerly winds bring waters from the Java Sea; they flow northward across the entire South China Sea to leave the latter and enter the Pacific Ocean and the Sulu Sea via the straits in the island arc. The velocities of both the winter and summer currents are approximately 30–50 cm/s. Near the continent, these currents remove the surface waters, which results in upwellings [4].

The bottom water temperature and salinity over the continental shelf are subjected to seasonal variations ranging from 25 to 25–28°C and from 32 to 33‰, respectively. In the inner shelf, the water temperature decreases downward down to 20°C, while the salinity increases up to 34‰. On the outer shelf beyond the influence of upwellings, the temperature declines down to 15°C and the salinity grows up to 34.5‰. In upwelling zones, these parameters are 8–10°C and 34.7‰ , respectively [23].

Over the continental slope, the water temperature decreases downward from 10 to 2°C. The salinity decreases as well to reach 34.3‰ at a depth of about 500 m. Deeper, it increases up to 34.50–34.65‰. In the deep basin of the sea, the bottom water temperature and salinity are 1.6–1.7°C and 34.65–34.7‰, respectively [18].

The South China Sea includes six water masses. The surface water down to depths of 60–70 m is characterized by a high oxygen content of 4.5 ml/l and seasonal temperature and salinity variations. The depth interval from 60–70 to 200–250 m is occupied by the high-salinity (34.6–34.7‰) subsurface water mass with an oxygen content of 3.0–3.5 ml/l. Downward to depths of 800–900 m, there is a high-salinity (34.3‰) water mass with oxygen and salinity minimums. In its core in the depth interval 400–500 m, the oxygen contents and salinity do not exceed 1.5–1.6 ml/l and 34.5‰, respectively. Down to a depth of 1500 m, this water mass is underlain by more saline (34.65‰) and colder water with an oxygen content of 2–3 ml/l, which is, in turn, replaced downward to a depth of 2700 m by a high-salinity (34.65‰) and cold (2°C) water mass with an oxygen content of approximately 2 ml/l. The maximal depths of the basin are occupied by the most saline (34.65–34.7‰) and coldest (1.6–1.7°C) water [4, 19].

Biota. The values of the primary production in the sea above the shelf, on the continental slope, and in the pelagic zone are 150–160, approximately 110–150, and 100–110 g/m^2/year, respectively [20]. The zooplankton biomass in the upper 100-m layer universally approximates 100 mg/m^3 [2]. The C_{org} flux at the water–sediment interface on the shelf exceeds 21 g/m^2/year to decrease to 16 g/m^2/year at a depth of 300 m. The biomass of the benthic organisms gradually decreases downward from 10 g/m^2 on the shelf to <1 g/m^2 at the maximal depths of the sea [3].

RESULTS

The benthic foraminiferal community of the South China Sea consists of approximately 300 species. Their maximal diversity is characteristic of the intermediate and outer shelf and the upper part of the continental slope, where it ranges from 120 to 150 species. Benthic foraminifers are least diverse in the coastal areas, particularly near the river estuaries, where they are represented by single species; at depths exceeding 3500–4000 m, their diversity is less than 45 species.

The abundance of foraminifers increases from single individuals near the shore to 300–500 ind./cm^2 on the outer shelf and continental slope (to a depth of 400 m). At depths of 400–950 m, it decreases down to 20–35 ind./cm^2; then, it increases again to reach 100–120 ind./cm^2 in the depth interval of 1000–1300 m. On the lower part of the continental slope, this parameter decreases downward from 35 to 12–20 ind./cm^2 at a depth of 3500 m and to 2–4 ind./cm^2 in the deepest parts of the basin.

Only three of 12 assemblages of benthic foraminifers established in the study areas are dominated by agglutinate species of *Reophax, Saccammina*, and *Trochammina* genera. In the former two assemblages, subdominant taxa are also represented by agglutinate forms. Secretory species dominate in all the remaining assemblages. Most of their subdominant taxa are also characterized by carbonate tests.

The dominant species constitute 20–40% of the assemblages of the open shelf and continental slope. In extreme environments near river estuaries and in the deepest areas of the sea, their share amounts to 70% or higher.

The table presents the taxonomic compositions and the occurrence depths of the assemblages and Figs. 2–4 illustrate their spatial distribution.

DISCUSSION

Both published and original data were used when analyzing the distribution of the foraminiferal assemblages. In the South China Sea, most of the assemblages populate the outer shelf and continental slope and only some of them occur in the deep-water basin. The following genera dominate on different parts of the sea bottom: *Rotorbinella* and *Pseudononion* on the coastal areas of the shelf; *Amphistegina* on the sediments of the inner shelf; *Brizalina* on its outer part; *Cassidulina, Globocassidulina*, and *Euuvigerina* on the upper part of the slope; *Pacinonion* and *Bulimina* on its lower part; and *Reophax* and *Saccammina* in the deep-water basin.

The *Rotorbinella tepida* assemblage occupies the coastal areas of the continental shelf (Fig. 2) and the shelf of Kalimantan Island. These bottom areas covered with terrigenous sands are washed by waters with a seasonally variable temperature and a constant salinity (32‰). In other areas of the ocean, this assemblage is recorded in the East China and Yellow seas; near the southern Japanese Islands; in the Persian Gulf and gulfs of Panama, California, and Mexico; in the tropical areas of North and South America; and near the Hindustan Peninsula. In all these areas, it occurs only in near-shore biotopes [10–12].

Similar to the previous assemblage, the *Pseudononion japonicum–Hanzawaia nipponica* assemblage

Taxonomic composition of benthic foraminiferal assemblages in the South China Sea and depths of their distribution

Dominant species	Subdominant species	Depth, m
Rotorbinella tepida	*Bigenerina cuneata, Textularia candeina, Lobatula lobatula*	10–40
Pseudononion japonicum–Hanzawaia nipponica	*R. tepida, Elphidium sagrum, E. advenum, Cellanthus craticulatum, L. lobatula*	16–45
Amphistegina lessonii	*Hanzawaia nipponica, Loxostomum mayori, P. japonicum, R. tepida, C. craticulatum*	40–115
Brizalina robusta	*Hofkeruva sphwageri, Euuvigerina auberiana, Cassidulina loevigata, A. lessonii, H. nipponica*	110–198
Cassidulina gr. laevigata	*B. robusta, Uvigerina curticostata, E. auberiana, Bulimina marginata.* Below 629 m – *Globocassidulina gr. subglobosa, Reophax bilocularis, Lagenammina diflugiformis, Chilostomella ovoidea*	329–629
Euuvigerina auberiana	*C. gr. laevigata, G. gr. subglobosa, R. bilocularis, L. difflugiformis, Trochammina globigeriniformis, Parreloides robertsonianus.* South of 7° N, plus *Ammobaculites filiformis, A. catenatus*	700–1365
Globocassidulina gr. subglobosa	*U. curticostata, Osangularia culter, Cibicides bradyi, Gavelinopsis lobatulus, R. bilocularis, L. difflugiformis*	917–1200
Pacinononion novozealandicum	Everywhere – *R. bilocularis, L. difflugiformis, T. globigerinoformid.* Western slope – *Bulimina aculeata, P. robertsonianus, O. culter, E. auberiana.* Eastern slope – *G. gr. subglobosa, Fontobotia wuellerstorfi, Eratidus foliaceus, Eggerella bradyi, Gyroidinus lamarkiana*	1517–2581
Trochammina globigeriniformis	*Oridorsalis umbonatus, P. novozealandicum, F. wuellerstorfi, R. bilocularis, Saccorhiza ramose*	1868–1970
Bulimina aculeata	*P. novozealandicum, E. bradyi, T. globigeriniformis, R. bilocularis*	2404–2665
Saccammina sphaerica	*R. bilocularis, L. difflugiformis, T. globigeriniformis, Hormosinella distans, Cyclammina trullissata, S. ramosa, Rhizammina algaeformis*	2835–3438
Reophax bilocularis	*S. sphaerica, T. globigeriniformis, C. trullissata, L. difflugiformis, E. bradyi, S. ramosa, R. algaeformis*	2841–4309

is widespread in the coastal shelf areas (Figs. 2, 3) at the same depths and over similar substrates, although under a higher salinity (33.0–33.5‰). It is also registered near the Japanese Islands.

The *Amphistegina lessonii* assemblage is widespread on the inner shelf (Figs. 2, 3) washed by the waters with higher salinity (34.0–34.5‰) than those where the *P. japonicum – H. nipponica* communities dwell and constant temperature (24–26°C) values. In other areas of the ocean, it occurs in the Yellow Sea, Indonesian and Polynesian seas, near the Hawaiian Islands and Easter Island, and on the eastern tropical shelf of Africa. In all these areas, the assemblage is confined to carbonate shelf sediments washed by permanently warm waters with an oxygen content exceeding 4.5 ml/l.

The *Brizalina robusta* assemblage populates the outer continental shelf south of 21° N (Figs. 2, 3) in the waters characterized by lower temperatures (8–12°C) and lower oxygen contents (2.5–3.0 ml/l) as compared with the *A. lessonii* assemblage. The pimary production in the waters of this area exceeds 170 g/m^2/year, and the substrate is represented by carbonate sands with glauconite. The assemblage is also registered in the Banda, East China [26], and Andaman seas and near the Malay Peninsula, where it occurs in the sediments of the upper part of the continental and island slopes or in the shelf areas with lowered near-bottom water temperatures untypical of these latitudes.

The *Cassidulina* gr. *laevigata* assemblage occurs on the upper part of the continental slope at 19°–21° N (Fig. 2) on carbonate sands with glauconites or silts in waters with a salinity of 34.3–34.4‰, a temperature of 5–10°C, and an oxygen content of 1.5–2.0 ml/l. The primary production in this area varies from 144 to 167 g/m^2/year. The assemblage is also recorded in the shelf sediments of the East China Sea.

The *Euuvigerina auberiana* assemblage is distributed at 18°–20° N on carbonate silts with glauconite on the upper part of the continental slope and the slope of Kalimantan Island (Figs. 2, 4) at greater depths as compared with the *C.* gr. *laevigata* assemblage. It prefers waters with temperatures of 4–5°C, salinities of 34.5–34.6‰ and oxygen contents of 1.6–2.5 ml/l. The area is characterized by a production of 120–140 g/m^2/year. The assemblage also occurs on the upper part of island slopes in the Banda and Sulu seas [21].

Globocassidulina gr. *subglobosa* is distributed on the upper part of the continental slope south of the *C. laevigata* assemblage at 15°–19° N (Fig. 4) in the

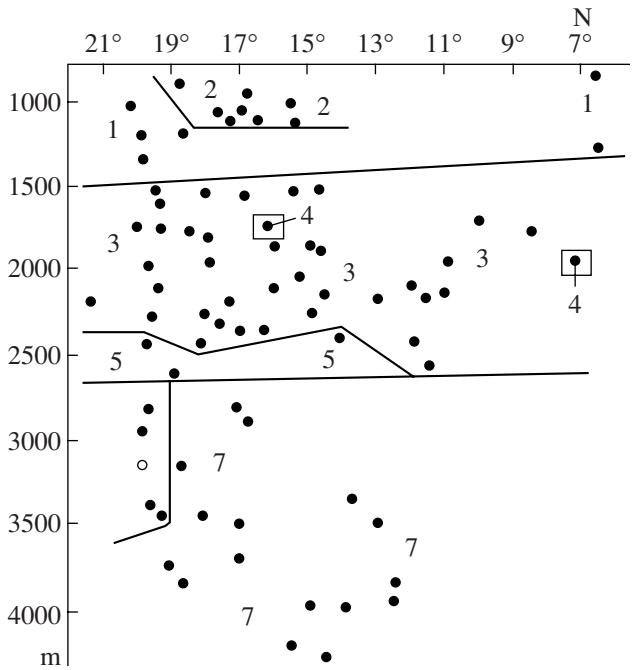

Fig. 4. Distribution of benthic foraminiferal assemblages at different depths and latitudes on continental and island slopes and in the deep-water basin of the South China Sea. (1) *Euuvigerina auberiana*; (2) *Globocassidulina* gr. *subglobosa*; (3) *Pacinonion novozealandicum*; (4) *Trochammina globigeriniformis*; (5) *Bulimina aculeata*; (6) *Saccammina sphaerica*; (7) *Reophax bilocularis.*

The dots designate the stations or their groups (for their location, see Fig.1).

waters characterized by lower primary production values of 100–110 g/m^2/year on substrates lacking glauconite. In other areas of the ocean, it occurs in the East China, Banda, and Andaman seas; near the Solomon and Nicobar islands; in the Gulf of Mexico; in tropical areas of the Atlantic Ocean; and near North and South America. In all these areas, the assemblage is confined to the upper part of continental and island slopes and the outer shelf washed by waters with temperatures that are lower as compared with their typical values [9, 11, 12].

The *Pacinonion novozealandicum* assemblage is widespread in the lower part of the continental and island slopes (Fig. 4) occurring on carbonate silty substrates covered by waters with temperatures of 2.4–5.0°C, salinities of 34.5–34.6‰ and oxygen contents of 2.0–2.5 ml/l. The primary production of the surface waters in these areas ranges from 103 to 110 g/m^2/year.

The *Trochammina globigeriniformis* assemblage occurs locally within the distribution area of the latter assemblage (Fig. 4) on slightly carbonate substrates.

The *Bulimina aculeata* assemblage is mapped on the lower part of continental and island slopes deeper as compared with the *P. novozealandicum* assemblage (Fig. 4) on slightly carbonate silts washed by waters with a temperature of 1.6–2.0°C and a salinity of 34.65‰. The primary production over this area varies from 105 to 139 g/m^2/year. The assemblage is also registered in the East China, Philippine, Banda, and Tasman seas; in the open areas of the tropical Pacific Ocean; and in the Bay of Bengal and gulfs of Oman and Mexico. In all these areas, the assemblage is confined to the lower part of the continental slope [12].

The *Saccammina sphaerica* assemblage is defined on the northern slope of the South China Sea north of 19° N (Fig. 4) on silty–clayey slightly carbonate substrates in waters with a temperature of 1.6–1.7°C and a salinity of 34.65‰. The primary production in this area is approximately 110 g/m^2/year.

The *Reophax bilocularis* assemblage dwells on silty–clayey substrates of the slopes and bottom in the deepest parts of the sea south of the distribution area of the *S. sphaerica* assemblage (Fig. 4). The primary production in the waters over these areas is 100 g/m^2/year and lower. This assemblage is also reported from the slopes of the Arabian deep basin.

CONCLUSIONS

The floor of the South China Sea is populated by 12 widespread assemblages of benthic foraminifers. The most diverse and abundant are the assemblages of the outer and inner shelves and the upper part of the continental slope down to depths of 300–400 m in upwelling zones and the most productive areas. The assemblages with the lowest diversities and abundances occupy near-shore areas washed by freshened waters and deep basins, where the surface waters and bottom sediments are characterized by the lowest primary production and C_{org} contents, respectively.

The *Rotorbinella tepida* assemblage prefers the freshened waters of shelf biotopes, while the *Pseudononion japonicum–Hanzawaia nipponica* assemblage is confined to areas covered with more saline waters due to the limited freshwater runoff.

The shelf areas influenced by the highly saline permanently warm subsurface waters are occupied by the *Amphistegina lessonii* assemblage. The upwelling areas, where the water temperature is lower and the salinity is higher as compared with their values typical of these waters, are favorable for the development of the *Brizalina robusta* assemblage.

The upwelling zones with oxygen and salinity minimums confined to the upper part of the continental slope host the *Cassidulina* gr. *laevigata* assemblage, while the *Euuvigerina auberiana* and *Globocassidulina* gr. *subglobosa* assemblages prefer more saline oxygen-saturated intermediate waters. According to statistical studies of the ecology of the bolivinitid, buliminid, and cassidulinid taxocoenoses, the upwelling assemblages of the South China Sea are the most cold-resistant among all the assemblages of secretory calcareous benthic foraminifers [7].

The *Pacinonion novozealandicum* and *Bulimina aculeate* assemblages populate carbonate substrates on the lower part of the continental slope influenced by highly saline cold waters.

In the areas characterized by the lowest primary production of the surface waters, deep-sea low-carbonate substrates washed by highly saline waters are populated by the *Saccammina sphaerica* and *Reophax bilocularis* assemblages. Deep-sea basins of the Indian Ocean and abyssal plains of the Pacific are also occupied by agglutinate foraminifers [8, 9].

SYNONYMY

Taxonomy of benthic foraminifers cited in [14–16, 19, 23, 25, 26].

Alabaminoides exiguous (*Brady*) = *Epistominella exigua*.

Brizalina robusta (*Brady*) = *B. spathulata, Bolivina striatula, B. robusta.*

Cellanthus craticulatus (*Fichtel et Moll*) = *Elphidium craticulatum.*

Cyclammina trullissata (*Brady*) = *Reticulophragmium trullissatum.*

Euuvigerina auberiana (*Orbigny*) = *Uvigerina auberiana.*

Fontobotia wuellerstorfi (*Schwager*) = *Cibicides wuellerstorfi.*

Gyroidinus lamarckianum (*Orbigny*) = *Gyroidina lamarckiana.*

Hofkeruva sphwageri (*Brady*) = *Uvigerina schwageri.*

Hormosinella distans (*Brady*) = *Hormosina distans.*

Lagenammina difflugiformis (*Brady*) = *Reophax difflugiformis.*

Lobatula lobatula (*Wolker et Jacob*) = *Cibicides lobatulus.*

Osangularia culter (*Parker et Jones*) = *Osangulariella culter.*

Pacinonion novozealandicum (*Cushman et Edwards*) = *Astrononion novozealandicum.*

Parrelloides robertsonianus (*Brady*) = *Cibicidoides robertsonianus.*

Pseudononion japonicum (*Asano*) = *Nonion japonicum.*

Rotorbinella tepida (*Cushman*) = *Streblus tepidus.*

Uvigerina curticostata (*Cushman*) = *U. peregrina, U. proboscidea.*

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