

## Modern planktonic foraminifera from the eastern Indian Ocean

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### Abstract

A brief morphometric study of the recent planktonic foraminifera in the eastern Indian Ocean was provided with the taxonomic key to species, synonyms, SEM microphotographs of shells and chamber arrays. By recent classification, currently 20 species representing 13 genera and 6 families (Canderinidae, Heterohelicoidae, Hedbergellidae, Higerigerinoidae, Globigerinoidae, and Globorotaloidae) identified from the planktonic material of the eastern Indian Ocean up to a depth of 200 m. Their distribution in water (0–200 m) also reports on the new range of expansion in the eastern Indian Ocean, with *Dentigloborotalia anfracta*, *Hastigerina pelagica*, *Streptochilus globigerus*, *Globigerinella calida*, *Globigerinella adamsi*, *Orcadia reideli*, *Tenuitella parkerae*, *Tenuitella compressa*, reported for the first time in this study area. In general, only around 50 planktonic species are valid worldwide, more specifically the species, e.g., *H. pelagica*, *G. calida*, *G. adamsi*, *S. globigerus*, *O. reideli*, *T. parkerae*, *T. compressa*, which occur in the eastern Indian Ocean to fill the the paucity of the recent regional taxonomic literature and the problematic identification from the eastern Indian Ocean. This work aims to bridge this gap and help scientists, managers, educators and students to identify plankton foraminifers by using species notes and images.

**Key words:** planktonic foraminifera, Heterohelicoidae, Hedbergellidae and Higerigerinoidae, Globigerinoidae and Globorotaloidae, eastern Indian Ocean

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### 1 Introduction

The distribution of planktonic foraminifera in the major oceans, Atlantic to Indo-Pacific Ocean, Indian Ocean and Arctic Ocean is described from the poles to the equator, shallow intertidal region to the deep sea. More than 50 planktonic foraminifera are the tropical, subtropical, temperate, sub-polar and polar species that have the highest richness in the northeast Atlantic Ocean (Bé and Tolderlund, 1971; Loeblich and Tappan, 1988; Hemleben et al., 1989; Bradshaw, 1959), and it is diverse in the Caribbean Sea and the Red Sea (Bijma and Hemleben, 1994; Schmuker, 2000). Mostly dead forams shells of planktonic species have been recovered from the globigerina ooze on the ocean floor. These thick blankets of forams shells have been used for the biostratigraphy, paleoenvironment studies, and isotope geochemistry of all ocean's (Kucera et al., 2005; Aurahs et al., 2011) for example western Australia and around the eastern Indian Ocean (Sarkar and Olge, 2013), northern Arabian Sea (Zhang, 1985; Rao, 1972). *Globigerina bulloides*, *Globigerinoides sacculifer*, *Globigerinoides ruber* and *Globigerinita glutina* are the common species in the north-east of Atlantic Ocean and south-east of Arabian Sea. *Globigerinoides ruber* is also highly abundant in the eastern Arabian Sea especially in coast areas.

Planktonic foraminifera are the group of calciferous organisms which originally drove from the benthic lineages. Primit-

ively, major taxa were an evolutionary link from the late Cenozoic period to Quaternary time. In Quaternary periods, many changes in taxonomy and classification of modern planktonic foraminifera taxa have been extensively treated (Brady, 1877; Bermúdez, 1961a; Bé, 1967, 1977; Parker, 1962; Rögl and Bolli, 1973; Vincent and Berger, 1981; Loeblich and Tappan, 1988; Hemleben et al., 1989). The primitive paleoceanography and biostratigraphy studies was conducted from the sandy beaches (D'Orbigny, 1826) and then largely studies based on the sediments samples from the deep sea (Ehrenberg, 1861; Carpenter et al., 1862; Parker and Jones, 1865). Rotalidia, Textulariines and Globigerinina species appeared during the mesozoic period. Studies of sedimentation for planktonic foraminifera and other calcite organisms (e.g., coccolithophore and diatom) have been reported from the western Pacific Ocean, Arabian Sea, the Bengal Bay and the adjacent area of the eastern Indian Ocean (Martinez et al., 1998).

Taxonomic guidelines and checklist were dealt with the deep-sea water species of foraminifera from the Gulf of Mexico (Sen Gupta et al., 2009) and the monographs of the planktonic foraminifera from around the world Ocean has been published (Scheibel and Hemleben, 2005, 2017). Several literatures on both planktonic and benthic foraminifera species have been published from the North Pacific Ocean (Cushman, 1910–1917), East

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Pacific Ocean (Todd, 1965; McCullodi, 1977), the Southwest Pacific Ocean (Hayward et al., 1997; Debenay, 2012), continental shelf of Australian coast (Yassini and Johnes, 1995), the New Zealand (Hayward et al., 1997, 2010), and the western Australian (Parker, 2009), the Arctic Ocean, and the Mediterranean Sea (Cimmerman and Langue, 1991; Milker and Schmiedl, 2012).

The paucity of recent regional taxonomic literature and the problematic identification associated with the planktonic foraminifers represented the need for this regional guide. More specifically, some members of the *Orcadia redeli*, *Tenuitella compressa*, *Hastiginera pelagica*, appearing in the eastern Indian Ocean, have not been dealt from this region. This work aims to bridge this gap and to identify plankton foraminifers from depths 200 m in the eastern Indian Ocean by using keys, species notes and images.

## 2 Materials and methods

The specimens were collected during the months (10 April–13 May 2014) from 44 sites of the eastern Indian Ocean and represented three transects zones: Transect I (southeast zone), Transect II (equatorial zone) and Transect III (north, Bay of Bengal) (Fig. 1). The samples were collected through plankton net (20 µm mesh size) and preserved with formalin and stored in the laboratory. For identification and taxonomic studies, morphometric shapes and diagnostic characters of 19 species were examined using an inverted light microscope (MOTIC, AE2000) at 200× and 400× magnification and scanning electron microscopy (JEOL TM-5006). For SEMs, samples were pre-screened through net again to removed large zooplanktons and 3 mL of sub-samples were filtered through 0.6 µm pore-size Millipore filters and air-dried for 24 h, then mounted on a stub, sputter-coated, and examined with the SEM. Species were identified using published taxonomic keys (Kennett and Srinivasan, 1983; Schiebel and Hemleben, 2005, 2017). The basic taxonomic guide was followed from Leoblich and Tappan (1988). The recent classification of identified taxa were followed by WoRms taxon data system (Hayward, 2018a, b). The following abbreviations were used for the

key identifying characters on illustrations: a: aperture (opening); bu: bulla; Ch: last chamber; d: depression; P: pore; Pr: Proloculus; PAC: primary auxiliary chamber; St: suture; lp: lip; lpr: interpore ridge; Sp: spines; t: tooth; ws: whorl suture; K: keel; and Um: umbilical aperture. The measuring of these identifying characters was performed by using image analysis software of SEMs (IT300 JSM version 1:170).

## 3 Results

Table 1 showing the list of 20 planktonic foraminifera species were identified from the planktonic material of the eastern Indian Ocean up to a depth of 200 m. The identified taxa were classified into 6 families (Canderinidae, Heterohelicoidea, Hedbergellidae, Higerigerinoidae, Globigerinoidae, Globorotaloidae) and 5 subfamilies (Globigerininae, Orbulininae, Globigerinitinae, Tenuitellinae, Rotundininae) on the base of following sources (Loeblich and Tappan, 1988; Hayward, 2018a, b). Their illustration and taxonomic remarks and distribution in the eastern Indian Ocean has been described here.

### Taxonomic notes on families and species characterization of planktonic foraminifera in the eastern Indian Ocean

#### Superfamily Heterohelicoidea

##### Family Chiloguembelinidae

This family is classified on the basis of biserial and triserial chambers with tooth-like openings (apertures) exemplified by the two genera: *Streptochilus globigerus* and *Gallitella vivans*. *Gallitella vivans* is a tropical species occurring in the Arabian Sea and Red Sea, characterized by triserial chambers. While, *Streptochilus* is a genus of biserial planktonic foraminifera characteristically occurring in the equatorial Indo-Pacific Ocean; and used for stratigraphic indices (Resig and Kroopnick, 1983). Recently, a biserial species *Streptochilus globigerus* with spherical chambers was observed from the equatorial zone of the eastern Indian Ocean.

##### *Streptochilus globigerus* (Fig. 2a)

Synonymous: *Textilaria globigera* Schwager, 1866

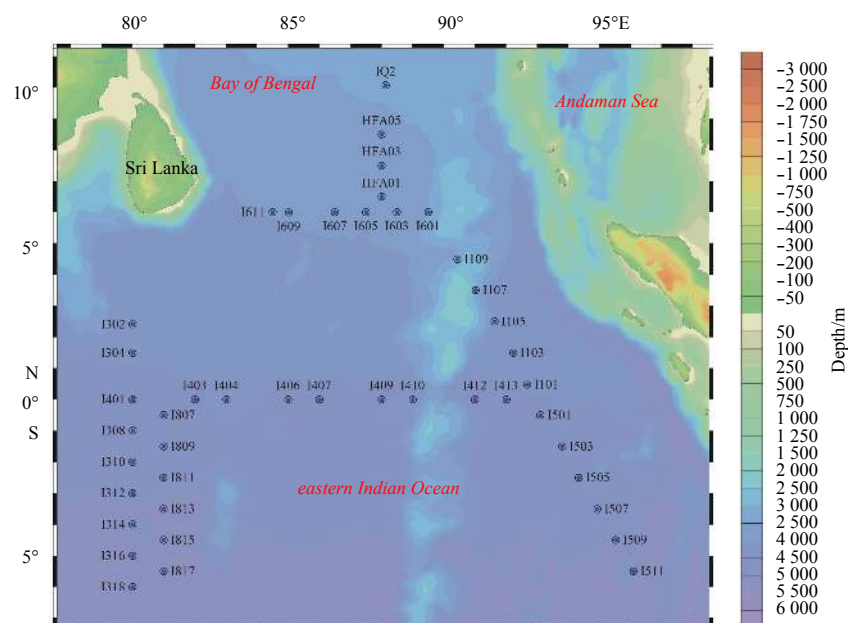


Fig. 1. The sampling sites from Transect I (southeast zone), Transect II (equatorial zone) and Transect III (Bay of Bengal) in the eastern Indian Ocean.

**Diagnosis:** *Streptochilus globigerus* Schwager, 1866 has an elongated, lanceolate, and biserial-shaped test.

**Description:** Test is lanceolate, and biserial in shape, 25 µm

**Table 1.** Taxonomic list of the planktonic foraminifera found in the eastern Indian Ocean to 200 m

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Kingdom Chromista
Subkingdom Harosa
Infrakingdom Rhizaria
Phylum Foraminifera (d'Orbigny, 1826)
Class Globorotalia
Order Rotaliida
Suborder Globigerinina
Superfamily Heterohelicoidea
Family Chiloguembelinae
Genus <i>Streptochilus</i>
Species * <i>Streptochilus globigerus</i> Schwager, 1866
Superfamily Globigerinoidea
Family Hastigerinidae
Genus <i>Hastigerina</i>
Species * <i>Hastigerina pelagica</i> Pourtalès, 1868
* <i>Orcadia riedeli</i> Rögl and Bolli, 1973
Family Globigerinidae
Genus <i>Globigerina</i>
Species <i>Globigerina bulloides</i> d'Orbigny, 1826
Genus <i>Globigerinella</i>
Species * <i>Globigerinella calida</i> Parker, 1962
<i>Globigerinella siphonifera</i> d'Orbigny, 1839
Subfamily Globigerininae
Genus <i>Globigerinoides</i>
Species <i>Globigerinoides rubra</i> d'Orbigny, 1839
<i>Globigerinoides sacculifera</i> Brady, 1877
Subfamily Orbulininae
Genus <i>Orbulina</i>
Species <i>Orbulina universa</i> d'Orbigny, 1839
Superfamily Rotaliporoidea
Family Hedbergellidae
Subfamily Rotundininae
Genus <i>Turborotalita</i>
Species <i>Turborotalita humilis</i> Brady, 1884
<i>Turborotalia quinqueloba</i> Natland, 1938
Superfamily Globorotalioidea
Family Candeinidae
Subfamily Globigerinitinae
Genus <i>Globigerinita</i>
Species <i>Globigerinita glutina</i> Egger, 1893
Subfamily Tenuitellinae
Genus <i>Tenuitella</i>
Species * <i>Tenuitella parker</i> Bronniman and Resign, 1972
* <i>Tenuitella compressa</i>
Family Globorotaliidae
Genus <i>Dentigloborotalia</i>
Species * <i>Dentigloborotalia anfracta</i> Parker, 1967
Genus <i>Globorotalia</i>
Species <i>Globorotalia scitula</i> Brady, 1882
<i>Globorotalia inflata</i> d'Orbigny, 1839
<i>Globorotalia menardii</i> d'Orbigny in Parker, Jones and Brady, 1865
<i>Globorotalia menardii</i> var. <i>ungulata</i> Bermúdez, 1961
<i>Globorotalia tumida</i> Brady, 1877

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Note: \* Species recorded for the first time.

in length and 18 µm in width (Table 2). Test wall is smooth, macroperforated in general, clearly with bilocular chambers. The first plate of the bilocular chamber is spherical and with a proloculus connected to the chamber series. The proloculus chamber is 9.15 µm long, which is joined to the biserial test on the left and right margins of the double row of chambers (Fig. 2a). Suture distinct and aperture is at the primary auxiliary chamber without bulla. Cell texture is finely microperforated with dense pores, without spines.

**Occurrence and ecology:** *Streptochilus globigerus* was present at the station (Sta. 1314) of eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.86% to total foraminifera recorded when temperature was 23.02°C, salinity 34.88 and chlorophyll *a* 0.23 µg/L.

**Geographical distribution:** Arabian Sea (Table 3).

#### Superfamily Globigerinoidea

##### Family Hastigerinidae

##### Family Globigerinidae

##### Subfamily Globigerininae

##### Subfamily Orbulininae

#### Family Hastigerinidae

Hastigerinidae consisting of characteristic, planispiral shells with elongated or lobulated test. The chambers are six in number in the final whorls with wedge pillow or club-shaped final whorls. The surface is smooth and porous with medium pores, umbilical aperture situated in the equatorial position having thin lip openings. The test edge is round with tri-radiate spines that differentiate two species *Hastigerina pelagica* and *Hastigerina digitata* (Rhumbler, 1911). Recently, this family is represented by two species, *Hastigerina pelagica* and *Orcadia riedeli* (Table 1) in the eastern Indian Ocean.

##### *Hastigerina pelagica* (Figs 2b–d)

**Synonymous:** *Hastigerina murrayi* Thomson, 1876

**Diagnosis:** *Hastigerina pelagica* was characterized by its smooth, wedge-shaped chamber with 4.5 and 6 whorls, perforated test with tridate spines arranged on the rounded test margin (Figs 2b–d).

**Description:** *Hastigerina pelagica* shells are lobulate and plainispiral, 88.23–195 µm in length and 44.83–125 µm in width (Table 2). Test wall surface is smooth, perforated with tri-radiate spines on the round margin of the test. These spines are 192 µm long with 11 µm thickness. Shell composed of globular or wedge-shaped chamber at 135 µm long and 4.5 µm width in final whorls (Figs 2b–d). Perforated test wall with tri-radiate spines arranged on the rounded test margin. Umbilical aperture is at the equatorial position having a thin lip without bulla.

**Occurrence and ecology:** *Hastigerina pelagica* was present at the stations (Stas 1105, 1107, 1304, 1307, 1310, 1312 and 1314) of the eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and 0.90% to total foraminifera recorded when temperature was 22.92–24.09°C, salinity 34.95–35.05 and chlorophyll *a* 0.19–0.21 µg/L.

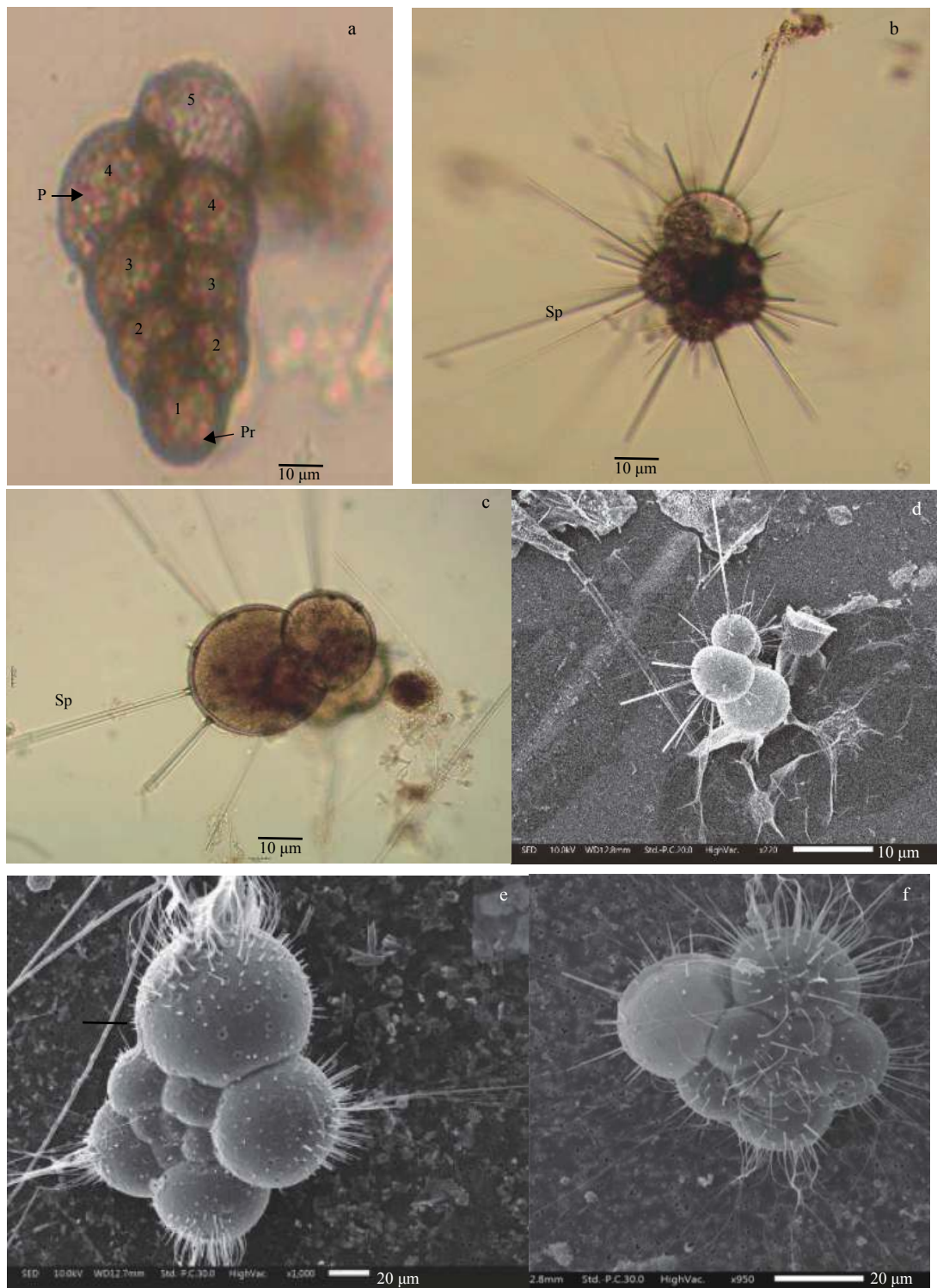
**Geographical distribution:** Mediterranean Sea, Atlantic Ocean, Caribbean Sea, and West Pacific Ocean (Table 3).

##### *Orcadia riedeli* (Figs 2e, f)

**Synonymous:** *Hastigerinella riedeli* Boltovskoy and Watanabe, 1982

**Diagnosis:** *Orcadia riedeli* Rögl and Bolli, 1973 observed with lobulated and compressed test with low trochospiral shape, having a left and right coiling direction (Fig. 2e).

**Description:** Shell is lanceolate, compressed, low trochospir-



**Fig. 2.** Light and scanning electron micrographs of foraminifera species, *Streptochilus globigerus* (a), *Hastigerina pelagica* (b-d), and *Orcadia riedeli* (e and f). *Streptochilus globigerus* showing the lanceolate shell with biserial chamber plates without spines, prominent with proloculus plate and primary auxiliary chamber, aperture is present (a). *Hastigerina pelagica* showing the smooth, wedge-shaped chamber with 4.5 and 6 whorls in umbilical view, perforated test with tridate spines arranged on the rounded test margin (c-e). Umbilical aperture is at the equatorial position (d). *Orcadia riedeli* showing the smooth to hispid and 5-6 chambers, spines bases at the chamber tips, ovate to ampullate umbilical aperture (f).

al shape ranging from 65-72  $\mu\text{m}$  in length and 45-55  $\mu\text{m}$  in width. Low trochospiral coiling is also either left or right. Test walls are smooth and hispid with rounded test marginally, perforated with small and large pores at 1.60  $\mu\text{m}$ . The length of the large subglob-

ular chamber is 39  $\mu\text{m}$  and total chambers are 2 or 3 in final whorls (Fig. 2e). Ovate to ampullate umbilical aperture is wider at 30  $\mu\text{m}$  in spiral view, which possesses lips other than bulla. Spines have 12  $\mu\text{m}$  bases occurring at the chamber tips.

**Table 2.** SEMs microscopic measurements of the body sizes (length and width), last chamber plate (Ch), test pores (p), umbilical aperture (a) and spines (Sp)

Specimens	Body size (length)/ $\mu\text{m}$	Body size (width)/ $\mu\text{m}$	Test pores/ $\mu\text{m}$	Last chamber / $\mu\text{m}$	Umbilical aperture/ $\mu\text{m}$	Spines / $\mu\text{m}$
<i>Dentiloborotalia anfracta</i>	57.91–82.32	51.53–70.01	1.20–1.53	30.50–43.42	5.47–6.18	2.5–37.01
<i>Globigerina bulloides</i>	79.64–281.5	40–229.2	21.60	45–165	13–25	1.57–198.3
<i>Globigerinella siphonifera</i>	94–150.5	52–126	1	44–92	15–40.26	50
<i>Globigerinella calida</i>	118–303	103–246	invisible	135	56	1
<i>Globigerinella adamsi</i>	106–167	80–104	1.98–3.68	45.79	35.57–84.94	1.45
<i>Globigerinella glutinita</i>						
<i>Globigerinoides rubera</i> (white)	116–287	95–141	2.88–20.34	23.08–56.58	10–60.58	1.85–3.50
<i>Globigerinoides sacculifer</i>	175–189	100–163	2–3	93	invisible	2
<i>Globorotalia inflata</i>	136	104	not visible	56	58	none
<i>Globorotalia scitula</i>	78–106	67–69.80	1.07–2.56	35–46.21	17.02	invisible
<i>Globorotalia menardii</i>	188	139	2.08–5.19	92.35	invisible	none
<i>Globorotalia tumida</i>	299–508	172–372	2.22	175–305	105	none
<i>Globorotalia menardii</i> var. <i>ungulata</i>	299	154	invisible	170	105	none
<i>Hastigerina pelagica</i>	83–195	75–137	invisible	135	invisible	192
<i>Orbulina universa</i>	100–290	82–241	1	none	none	197–202
<i>Orcadia riedeli</i>	65–72.78	45–55.09	1.60–1.49	38.39	30.39	12
<i>Streptochilus globigerus</i>	25	18	2	9	2	none
<i>Tenuitella compressa</i>	51.57–63.50	20–54	1.23	45	3.59–6.08	lip 11.00
<i>Tenuitella parekara</i>	103	72.59	1.54	60	17.86	4.81–24.28
<i>Turborotalita humilis</i>	57–63	50	1.03–2.36	21.53	invisible	none
<i>Turborotalita quiniqore</i>	17–88.43	67–75.09	1.45–2.14	33.21	39.66–41.45	37.44–50

**Table 3.** Geographical distribution of planktonic foraminifera from other oceans

Planktonic foraminifera	Geographical distribution	Reference
<i>Globigerinella glutinata</i>	Arabian Sea, North Atlantic Ocean, South Atlantic Ocean, Caribbean Sea, Gulf of Aden, West Pacific Ocean	Chapman (2010), Schmuker (2000), Ivanova et al. (2003), Martinez et al. (1998)
<i>Tenuitella parkerae</i>	Arabian Sea, Equatorial Atlantic Ocean and South Atlantic Ocean	Hemleben et al. (1989)
<i>Tenuitella compressa</i>	Caribbean Sea	Saito et al. (1981), Schumuker (2000)
<i>Streptochilus globigerus</i>	Arabian Sea	Schmuker (2000)
<i>Hastigerina pelagica</i>	Mediterranean Sea, Atlantic Ocean, Caribbean Sea, West Pacific Ocean	Schiebel and Hemleben (2017)
<i>Orcadia riedeli</i>	South Atlantic Ocean, Gulf of Mexico, Red Sea	Hemleben et al. (1989), Sen Gupta et al. (2009)
<i>Globigerina bulloides</i>	Northeast Pacific Ocean, Atlantic, Indian Ocean, Caribbean Sea, Red Sea, South Indian Ocean	Thompson et al. (1979), Bijma and Hemleben (1994), Schiebel and Hemleben (2005, 2017), Schmuker (2000), Martinez et al. (1998), Morard et al. (2013)
<i>Globigerinella siphonifera</i>	Equatorial and North Atlantic, Arabian Sea, Caribbean Sea, South Atlantic Ocean, Australia	Huber et al. (1997), Darling et al. (1996), Martinez et al. (1998), Stewart et al. (2001), Darling and Wade (2008), Aurahs et al. (2011), Sears et al. (2012), Weiner et al. (2014)
<i>Globigerinella adamsi</i>	Red Sea, Arabian Sea, Equatorial Pacific Ocean	Hemleben et al. (1989), Schmuker (2000), Schiebel and Hemleben (2017)
<i>Globigerinella calida</i>	South Atlantic Ocean, western Indian Ocean, Red Sea, Equatorial Atlantic Ocean	Weiner et al. (2014)
<i>Globigerinoides ruber</i>	South Atlantic Ocean, Equatorial Atlantic Ocean, Caribbean Sea, West Pacific Ocean, Indo-Pacific Ocean	Thompson et al. (1979), Hemleben et al. (1989), Schmuker (2000), Martinez et al. (1998)
<i>Trilobatus sacculifer</i>	South Atlantic Ocean, Equatorial Atlantic Ocean	Hemleben et al. (1989), Schmuker (2000)
<i>Turborotalita quinqueloba</i>	Equatorial and North-south Atlantic, Antarctic, Northeast Pacific Ocean and northeastern Arabian	Darling et al. (2000, 2003), Darling and Wade (2008), Darling et al. (2000, 2003), Darling and Wade (2008), Sears et al. (2012)
<i>Turborotalita humilis</i>	Equatorial and North-south Atlantic, Antarctic and Northeast Pacific Ocean and northeastern Arabian	Darling et al. (2000, 2003), Darling and Wade (2008)
<i>Orbulina universa</i>	Equatorial and North-south Atlantic Ocean and West Pacific Ocean	Weiner et al. (2014)
<i>Dentigloborotalia anfracta</i>	Equatorial Atlantic Ocean and Caribbean Sea, South Atlantic Ocean, Arabian Sea and Somalia coast	Schmuker (2000), Conan et al. (2002), Schiebel et al. (2004)
<i>Globorotalia scitula</i>	South Atlantic Ocean, Equatorial Atlantic Ocean and Caribbean Sea	Hemleben et al. (1989), Schmuker (2000)
<i>Globorotalia menardii</i>	South Atlantic Ocean, Equatorial Atlantic Ocean and Caribbean Sea	Hemleben et al. (1989), Schmuker (2000)
<i>Globorotalia menardii</i> var. <i>ungulata</i>	South Atlantic Ocean, Indian Ocean	Hemleben et al. (1989)
<i>Globorotalia tumida</i>	Equatorial Atlantic Ocean and Caribbean Sea, South Atlantic Ocean, South-Pacific and Indo-Pacific region, South Indian Ocean	Hemleben et al. (1989), Schmuker (2000), Srinivasan and Kennett (1981), Sinha and Singh (2008)

**Occurrence and ecology:** *Orcadia riedeli* was present at the stations (Stas 1101, 1103, 1306, 1310 and 1501) of the eastern Indian Ocean. The maximum abundance 63 ind./m<sup>3</sup> and relative abundance 3.03% of total foraminifera recorded when temperature was 22.20°C, salinity 34.80 and chlorophyll *a* 0.16 µg/L.

**Geographical distribution:** South Atlantic Ocean, Gulf of Mexico, Red Sea, and equator and south zones (Table 3).

#### Family Globigerinidae

##### Subfamily Globigerininae

Globigerinidae consisting on the shells which has microporated pores surface has spines around the test margin and some members has keel-shaped shells. Eight taxa from these families were recorded into 6 genera such as *Globigerina bulloides*, *G. calida*, *Globigerinella siphonifera*, *G. adamsi*, *Globigerinoides ruber* (white), *Trilobus sacculifer*, *Orbulina universa* (Table 1).

##### *Globigerina bulloides* (Figs 3a, b)

**Synonymous:** *Globigerina aequilateralis* or *Hastigerina*

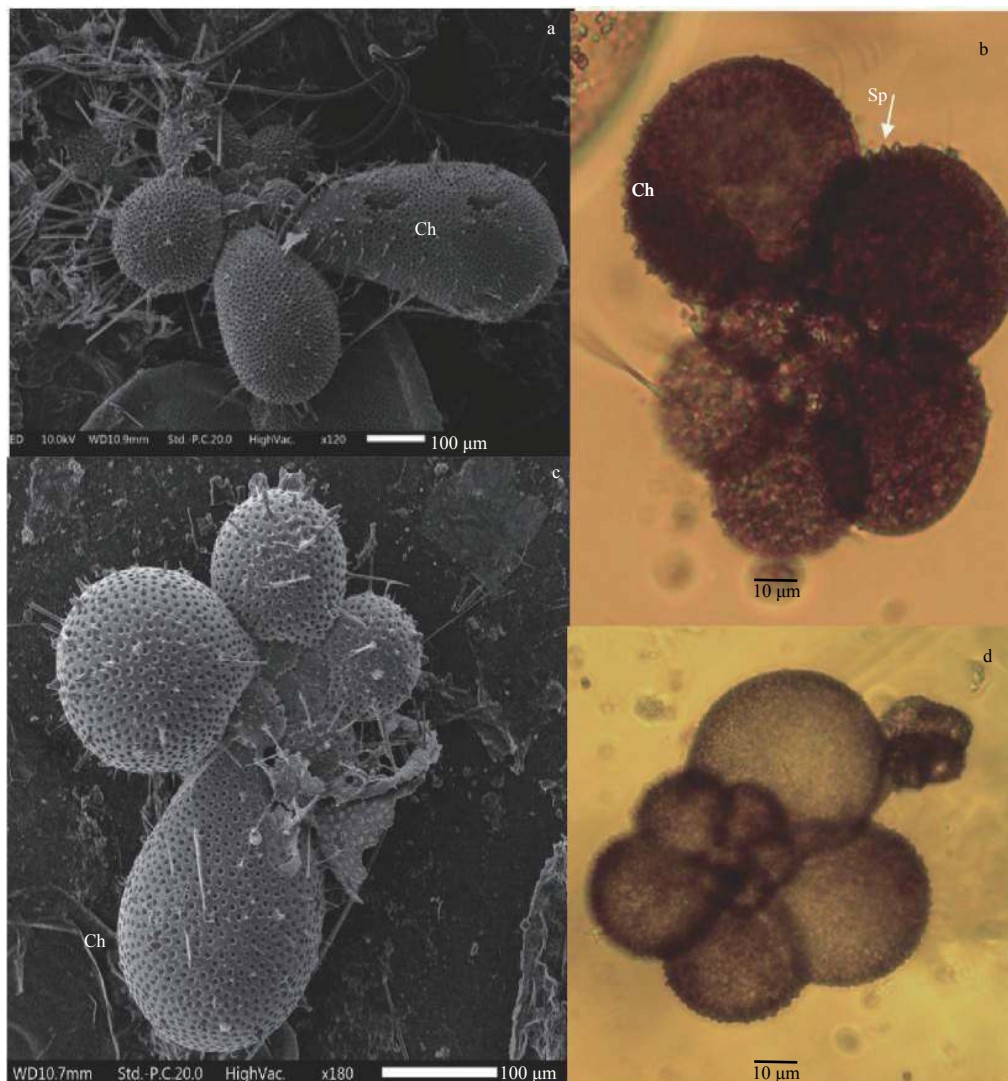
*aequilateralis* Brady, 1879

**Diagnosis:** *Globigerina bulloides* D'Orbigny, 1826 observed with the test having low trochospiral with final spherical and subglobular chambers (Figs 3a, b).

**Description:** Large test ranges from 79–229 µm in length and 40–281 µm in width. Small pores are ca. 1.60 µm covered with interpore area ca. 21 µm. Final whorls based on the four chambers and the length of last chamber is 45–165 µm (Figs 3a–d). Umbilical aperture plate is narrow as 13–25 µm and sutures is distinctly depressed. Surface uniformly and densely perforate with simple spines, 1.57 µm wide and 198.3 µm long. Umbilical aperture with a high symmetrical arch.

**Occurrence and ecology:** *Globigerina bulloides* was present at the stations (Stas 1101, 1304–1312, 1401, 1404, 1410, 1412, 1507, 1607 and 1611) of the eastern Indian Ocean. The maximum abundance 862 ind./m<sup>3</sup> and relative abundance 41% to total foraminifera recorded when temperature was 24.41°C, salinity 35.03 and chlorophyll *a* 0.23 µg/L.

**Geographical distribution:** Tropical and subtropical pro-



**Fig. 3.** Light and scanning electron micrographs of foraminifera species, *Globigerinella adamsi* (a) and *Globigerinella calida* (b–d). *Globigerinella adamsi* showing the subglobular and elongated last chamber (a) and *G. calida* showing the subglobular chambers with low trochospire shell (b–d). Surface is densely perforated and hispid with spines, aperture is the interior marginal, having rather low arch with a narrow lips (a–c).

vines, e.g., Northeast Pacific, Atlantic, Indian Ocean, Caribbean Sea, Red Sea, and South Indian Ocean (Table 3).

***Globigerinella siphonifera* (Figs 3c, d)**

**Synonymous:** *Globigerina aequilateralis* or *Hastigerina aequilateralis* Brady, 1879

**Diagnosis:** *Globigerinella siphonifera* Brady, 1879 observed with low trochospiral to planispiral test in globular to subglobular chambers, consisting of 5 to 6 rapidly enlarging chambers in the final whorl (Figs 3c, d).

**Description:** Planispiral test with roduantae chambers are 94–150  $\mu\text{m}$  in length and 50–126  $\mu\text{m}$  in width (Table 2). The test wall procellenous with long, 50- $\mu\text{m}$  size spines. The wall has small pores are ca. 1.26  $\mu\text{m}$  in size; hispid or densely perforated, which are uniformly distributed in a circular arrangement inside the interpore area (ipr). The last chamber is 44–92  $\mu\text{m}$  defined by radial sutures and interiomarginal aperture at 15–40  $\mu\text{m}$  size (Figs 3c–d and Table 2). Intermarginal aperture is at the equatorial arch without a lip or rim.

**Occurrence and ecology:** *Globigerinella siphonifera* was present at the stations (Stas 1101, 1304–1312, 1401, 1404, 1410, 1412, 1507, 1607 and 1611) of the eastern Indian Ocean. The maximum abundance 229 ind./ $\text{m}^3$  and relative abundance 10% to total foraminifera recorded when temperature was 24.63°C, salinity 34.97 and chlorophyll *a* 0.23  $\mu\text{g/L}$ .

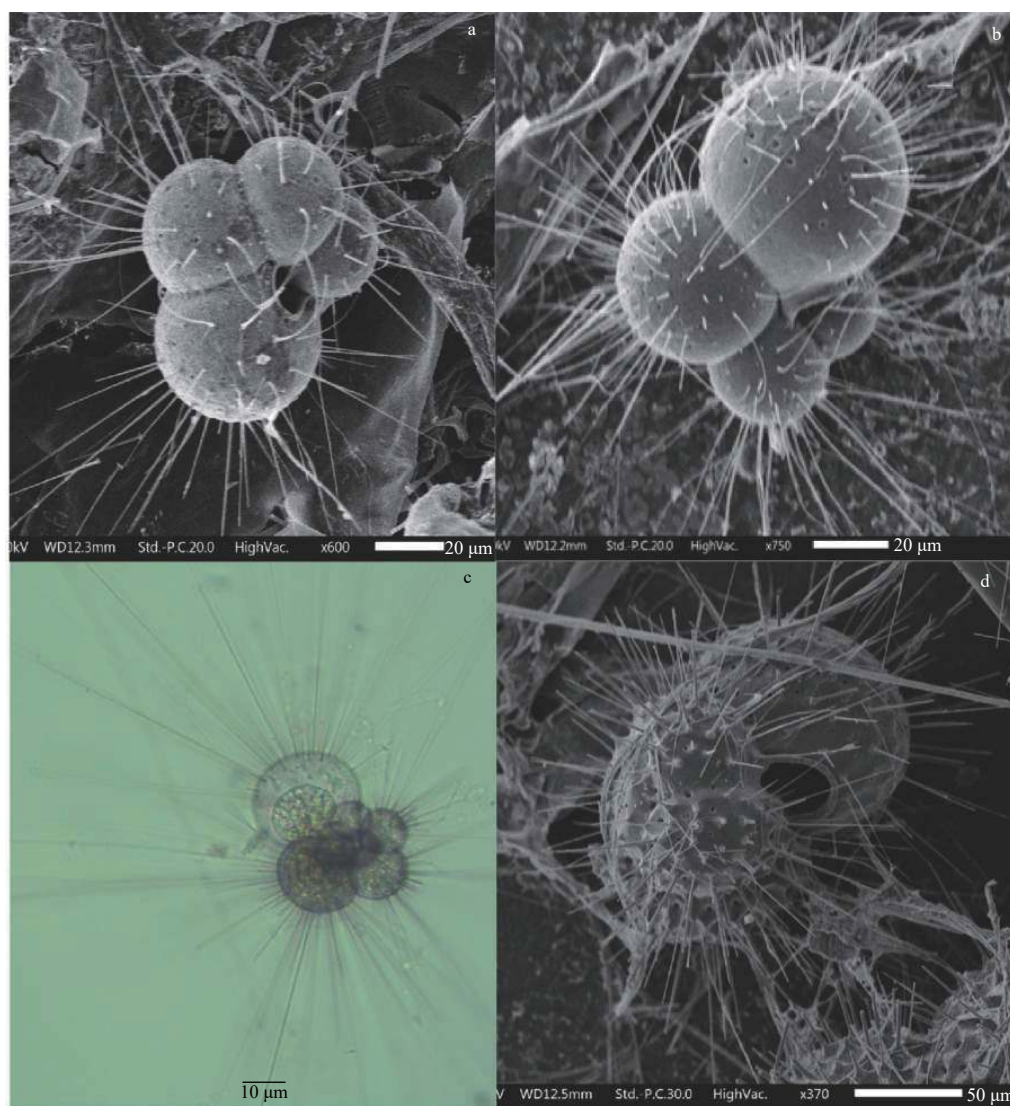
**Geographical distribution:** Tropical and subtropical provinces, e.g., equatorial and North Atlantic, Arabian Sea, Caribbean Sea, South Atlantic Ocean, and Australia (Table 3).

***Globigerinella adamsi* (Fig. 4a)**

**Synonymous:** *Beella discors* McCulloch, 1979

**Diagnosis:** *Globigerinella adamsi* Banner and Blow, 1959 observed with lobulated, elongated and club shaped chambers, trochospiral test is similar mostly to *Globigerinella* species with the left to right coiling direction (Fig. 4a).

**Description:** Large test ranges from 118–303  $\mu\text{m}$  in length and 103–246  $\mu\text{m}$  in width. The test wall is hispid with medium or large pore surfaces. Spines are present with round or triangular shape



**Fig. 4.** Light and scanning electron micrographs of foraminifera species, *Globigerinella siphonosphaera* (a and b) and *Globergina bullodies* (c and d). *Globigerinella siphonosphaera* showing spherical chamber with low trochospire shells (a and b). Surface is densely perforated and hispid with spines, aperture is the interiomarginal, wide, equatorial arch without a lip or rim (b). *Globergina bullodies* showing 4 chambers in the final whorl. Surface uniformly and densely perforate with spines and umbilical aperture with high symmetrical arch with short spines (c and d).

at 1.02  $\mu\text{m}$  size (Fig. 4a and Table 2). Its last chamber is 135  $\mu\text{m}$  in size with elongated shape including a total of 5–7 chambers in the final whorls. Umbilical aperture plate is small (56  $\mu\text{m}$ ) and interiomarginal to equatorial in position.

**Occurrence and ecology:** *Globigerinella adamsi* was present at the stations (Sta. 1609) of the eastern Indian Ocean. The maximum abundance 18 ind./ $\text{m}^3$  and relative abundance 0.1% to total foraminifera recorded when temperature was 23.35°C, salinity 34.61, chlorophyll *a* 0.19  $\mu\text{g/L}$ .

**Geographical distribution:** Indo-Pacific, subpolar to tropical ocean, Red Sea, Arabian Sea, and Equatorial Pacific Ocean (Table 3).

***Globigerinella calida* (Figs 4b–d)**

**Synonymous:** *Globigerina calida praecalida* Kennett and Srinivasan, 1983

**Diagnosis:** *Globigerinella calida* Parker, 1962 observed with a low trochospiral test, lobulated with equatorial periphery and axial periphery rounded, including subglobular chambers.

**Description:** Large test ranges from 118–303  $\mu\text{m}$  in length and 103–246  $\mu\text{m}$  in width. The shape of the shell is ovate with 4 or 5 chambers in final whorls as 135  $\mu\text{m}$  (Figs 4b–d). Sutures are distinct, radial and depressed. Surface is hispid and densely perforate. Umbilical aperture or extra-umbilical at 56  $\mu\text{m}$  size has a low arch with a narrow lip. Spines are short (1.02  $\mu\text{m}$ ).

**Occurrence and ecology:** *Globigerinella calida* was present at the stations (Stas 1308, 1314, 1316, 1409, 1410, 1413, 1506 and 1607) of the eastern Indian Ocean. The maximum abundance 86 ind./ $\text{m}^3$  and relative abundance 4% to total foraminifera recorded when temperature was 24.41°C, salinity 35.0, chlorophyll *a* 0.23  $\mu\text{g/L}$ .

**Geographical distribution:** Tropical and subtropical provinces such as south Atlantic Ocean, western Indian Ocean, Red Sea, equatorial Atlantic Ocean (Table 3).

***Globigerinoides ruber white* (Figs 5a, b)**

**Synonymous:** *Globigerina ruber* D'Orbigny, 1839

**Description:** Spherical test ranges from 116–287  $\mu\text{m}$  in length and 95–141  $\mu\text{m}$  in width. *Globigerinoides ruber white* have a medium, low to high trochospire test with three subspherical chambers in the final whorl, increasing moderately in size from 23.08–56.58  $\mu\text{m}$  (Figs 5a, b). Deep depressions are ca. 20  $\mu\text{m}$  and pores ca. 2.8  $\mu\text{m}$  inside. Sutures are radial and distinctly depressed. Surface coarsely perforated. Umbilical aperture is narrow and 10–60  $\mu\text{m}$  in size; and interiomarginal bordered by a rim. Short spines are 1.85  $\mu\text{m}$  and large spine are 3.50  $\mu\text{m}$  in size.

**Occurrence and ecology:** *Globigerina ruber* was present at the stations (Stas 1101–1105, 1304–1509, 1811–1815 and 1605–1611) of the eastern Indian Ocean. The maximum abundance 225 ind./ $\text{m}^3$  and relative abundance 10% to total foraminifera recorded when temperature was 24.41°C, salinity 35.08 and chlorophyll *a* 0.19  $\mu\text{g/L}$ .

**Geographical distribution:** South Atlantic Ocean, equatorial Atlantic Ocean, Caribbean Sea, West Pacific Ocean, and Indo-Pacific Ocean (Table 3).

***Trilobatus sacculifer* (Figs 5d–f)**

**Synonymous:** *G. sacculifer* Galloway and Wissler, 1927

**Diagnosis:** *Trilobatus sacculifer* Galloway and Wissler, 1927 observed with a low trochospiral test, chambers spherical except the final one, which is elongate, sac-like with 3.5–4 chambers in the final whorl (Figs 5d–f).

**Description:** Spherical test with large triangular chamber ranges from 175–189  $\mu\text{m}$  in length and 100–163  $\mu\text{m}$  in width (Figs 5d–f and Table 2). The last chamber may be rather small, or it may be elongate and lobulated at 93  $\mu\text{m}$  size. Sutures on both sides slightly curved and depressed (Figs 5d–f). Thin secondary calcite

crusts surround the spine bases and form a honeycomb-shaped surface. Surface has regular subhexagonal pore pits of 2–3  $\mu\text{m}$  size. Umbilical aperture is narrow and interiomarginal, with distinct arch bordered by rim, and prominent supplementary apertures on spiral side.

**Occurrence and ecology:** *Trilobatus sacculifer* was present at the stations (Stas 1101, 1310, 1401, 1501, 1505, 1609 and 1611) of the eastern Indian Ocean. The maximum abundance 33 ind./ $\text{m}^3$  and relative abundance 1.6% to total foraminifera recorded when temperature was 23.85°C, salinity 34.60 and chlorophyll *a* 0.32  $\mu\text{g/L}$ .

**Geographical distribution:** South Atlantic Ocean, equatorial Atlantic Ocean (Table 3)

**Subfamily Orbulininae**

***Orbulina universa* (Figs 6a, b)**

**Synonymous:** *Globigerina bilobata* D'Orbigny, 1846

**Diagnosis:** *Orbulina universa* D'Orbigny, 1846 observed with a spherical or rounded test shell with monocular chamber, perforated surface with small pores and large spiral spines (Figs 6a, b).

**Description:** Spherical test ranges from 60–128  $\mu\text{m}$  in length and 172  $\mu\text{m}$  in width. The outer spherical chamber is 22  $\mu\text{m}$  and completely covered the whole test, and is densely perforated with numerous small equally distributed pores at 2–3  $\mu\text{m}$ , spines are present (Figs 6a, b and Table 2).

**Occurrence and ecology:** *Orbulina universa* was present at the stations (Stas 1306, 1312, 1402, 1406, 1410, 1503–1511, 1607 and IQ) of eastern Indian Ocean. The maximum abundance 72 ind./ $\text{m}^3$  and relative abundance 3.4% to total foraminifera recorded when temperature was 22.64°C, salinity 34.85 and chlorophyll *a* 0.17  $\mu\text{g/L}$ .

**Geographical distribution:** Equatorial and north-south Atlantic Ocean and West Pacific Ocean (Table 3)

**Superfamily Rotaliporoidea**

**Family Hedbergellidae**

**Subfamily Rotundininae**

Family Hedbergellidae has been classified on the base of trochospirally coiled test with at least 5 to 8 chamber plates. Shell has primary aperture at the interiomarginal as well as extraumbilical-umbilical plate. Well developed prominent apertural lip around the umbilical region. Shell has no sutural secondary apertures. Two species, e.g. *Turborotalita quinqueloba* and *Turborotalita humulis* was identified from the eastern Indian Ocean

***Turborotalita quinqueloba* (Figs 6c, d)**

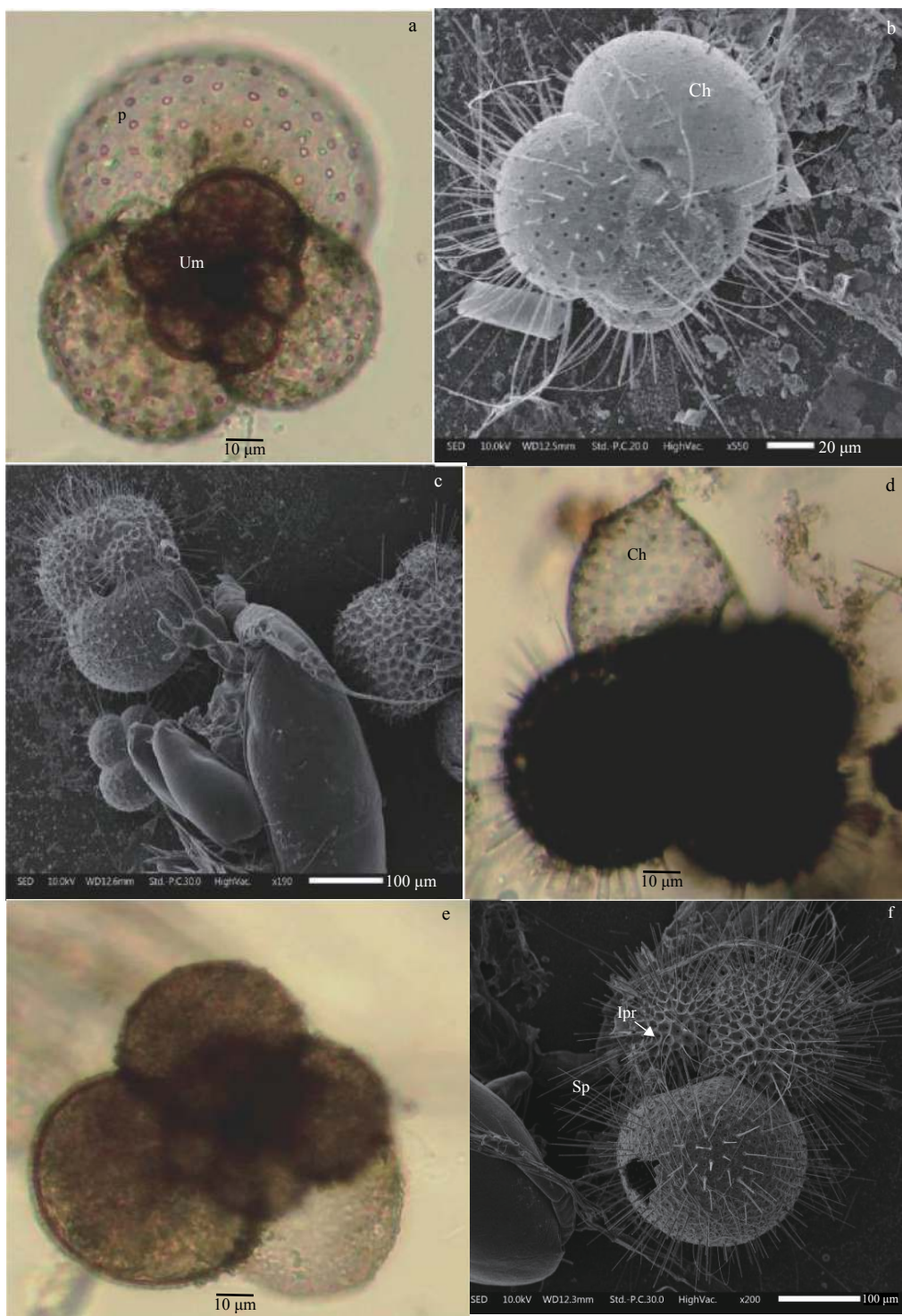
**Synonym:** *Globigerina quinqueloba* Natland, 1938

**Diagnosis:** *Turborotalita quinqueloba* Natland, 1938 with small and slightly compressed and trochospiral shape with 5 chambers in final whorls, distinctly spinose (Figs 6c, d).

**Description:** The test size ranges from 17–88  $\mu\text{m}$ . Aperture with elongate slit often at the end of a flap-like structure of the final chamber (Figs 6a, b and Table 2). The test size ranges from 17–88  $\mu\text{m}$  with small to medium pores 1.45–2.14  $\mu\text{m}$  and large chamber of 33.21  $\mu\text{m}$ . Umbilical aperture is 39–41  $\mu\text{m}$ , and spines are long up to 50  $\mu\text{m}$  (Figs 6a, b and Table 2).

**Occurrence and ecology:** *Turborotalita quinqueloba* was present at the stations (Stas 1101, 1107, 1304, 1306, 1308–1312, 1412, 1501–1509 and 1601–1611) of the eastern Indian Ocean. The maximum abundance 155 ind./ $\text{m}^3$  and relative abundance 7.04% to total foraminifera recorded when temperature was 23.86°C, salinity 34.71 and chlorophyll *a* 0.26  $\mu\text{g/L}$ .

**Geographical distribution:** Equatorial and north-south Atlantic, Antarctic and Northeast Pacific Ocean and northeastern



**Fig. 5.** Light and scanning electron micrographs of foraminifera species, *Globigerinoides ruber* (a–c) and *Trilobus sacculifer* (d–f). *Globigerinoides ruber* showing the rounded or globulose shell with 3 chambers (a and b), wall surface rugose with macroperforated pores with umbilical aperture at the central position (b and c). *Trilobus sacculifer* showing the spherical shell with last honeycomb chamber, three and a half to four chambers in the final whorl, surface with the regular subhexagonal pore and spines (d–f).

Arabian (Table 3).

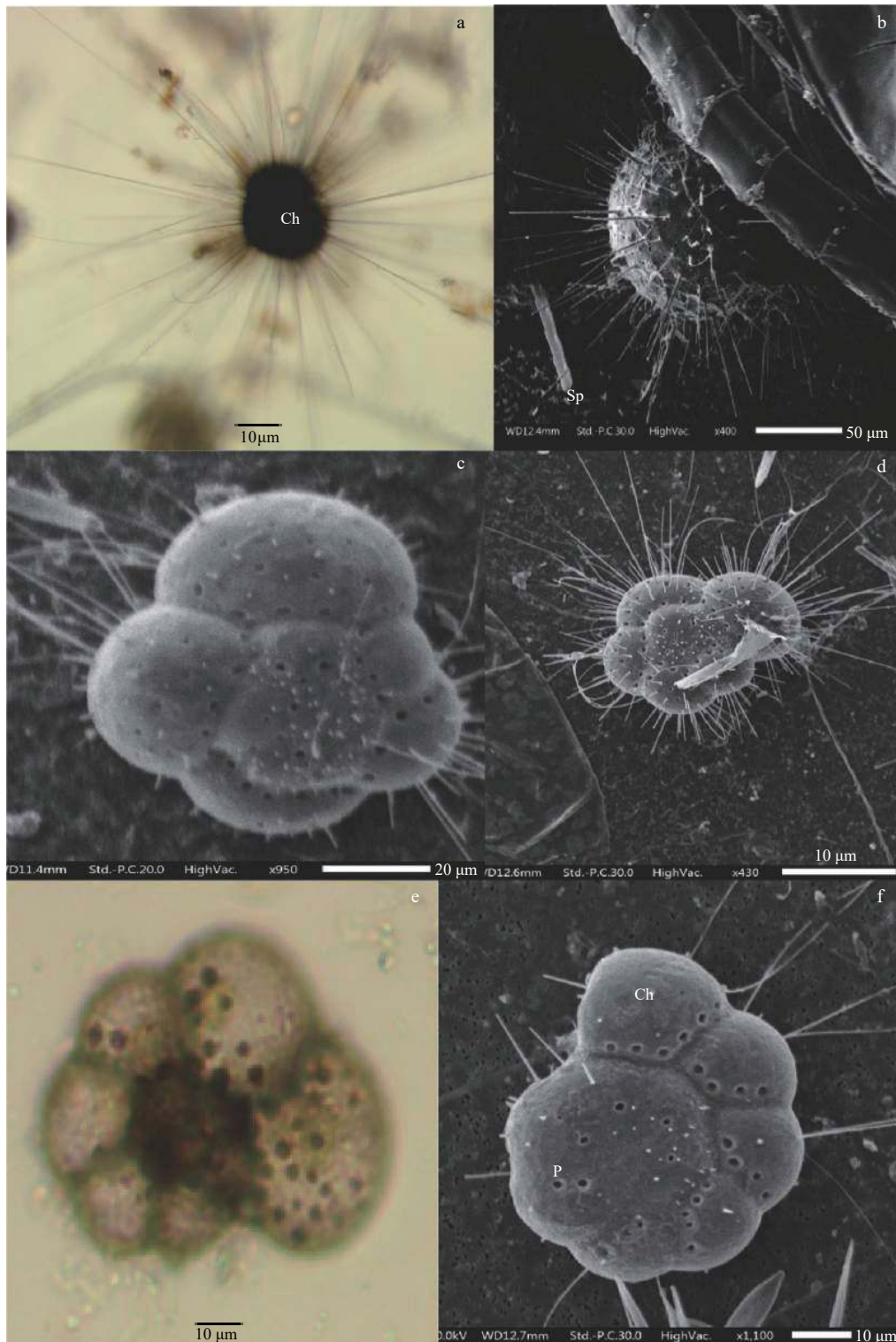
***Turborotalita humilis* (Figs 6e, f)**

**Synonymous:** *Globigerina humilis* Brady, 1884

**Diagnosis:** *Turborotalita humilis* Brady, 1884 observed to have small and low trochospiral test, and almost circular equatorial periphery, lobulated and rounded axial periphery. There are 6 to 8 chambers in the final whorls (Figs 6e, f).

**Description:** The small test ranges from 57–63  $\mu\text{m}$  in length and 50  $\mu\text{m}$  in width (Table 2). The final chamber is prolonged at 21.53  $\mu\text{m}$  size and has several infralaminar openings (Figs 6e, f). Radial suture is depressed. Smooth surface with finely perforated large pores at 1.02–2.36  $\mu\text{m}$ , distributed at the periphery. Extraumbilical aperture is interiomarginal.

**Occurrence and ecology:** *Turborotalita humilis* was present



**Fig. 6.** Light and scanning electron micrographs of foraminifera species, *Orbulina universa* (a and b), *T. quinqueloba* (c and d), and *T. humilis* (e and f). *Orbulina universa* showing the spherical shell with monolocular chamber, perforated surface with small pores and large spiral spines (a and b). *Turborotalita quinqueloba* showing the small, slightly compressed, trochospiral, five chambers, final chamber distinctly spinose; aperture is elongate slit often at the end of a flap-like structure of the final chamber (c and d). *Turborotalita humilis* (e and f) showing the low trochospiral, almost circular equatorial periphery, 6–8 chambers with extension of the final chamber, umbilical-extraumbilical interiomarginal except when covered by bulla. Many infralaminar apertures (e and f).

at the stations (Stas 1101, 1107, 1304, 1306, 1308–1312, 1412, 1501–1509, and 1601–1611) of the eastern Indian Ocean. The maximum abundance 155 ind./m<sup>3</sup> and relative abundance 7.04%

to total foraminifera recorded when temperature was 23.86°C, salinity 34.71 and chlorophyll *a* 0.26 μg/L.

**Geographical distribution:** Equatorial and north-south At-

lantic, Antarctic and Northeast Pacific Ocean and northeastern Arabian (Table 3).

#### Superfamily Globorotalioidea

#### Family Candeinidae

#### Subfamily Globigerinitinae

#### Subfamily Tenuitellinae

Candeinidae family was classified on the basis of globular, or ovate to bulb-shaped shells, consisting of 4.5 or 5 chambers. Each chamber is round and keel-shaped connected with the primary aperture (opening) called umbilical aperture and extra umbilical aperture from which secondary apertures (bulla) arise. The extra-umbilical aperture developed a deep arch with a thin or thick lips cover. The test wall is microperforated with medium to large pores, which are distributed unevenly upon the smooth surface. The three species, *Globigerinita glutinata*, *Tenuitella parkerae* and *Tenuitella compressa*, were identified from the eastern Indian Ocean. These species are grouped in the Candeinidae family which further classified into subfamilies as Globigerinitinae and Tenuitellinae.

#### *Globigerinita glutinata* (Fig. 7a)

**Synonymous:** *Globigerina glutinata* Gazelle and Egger, 1893

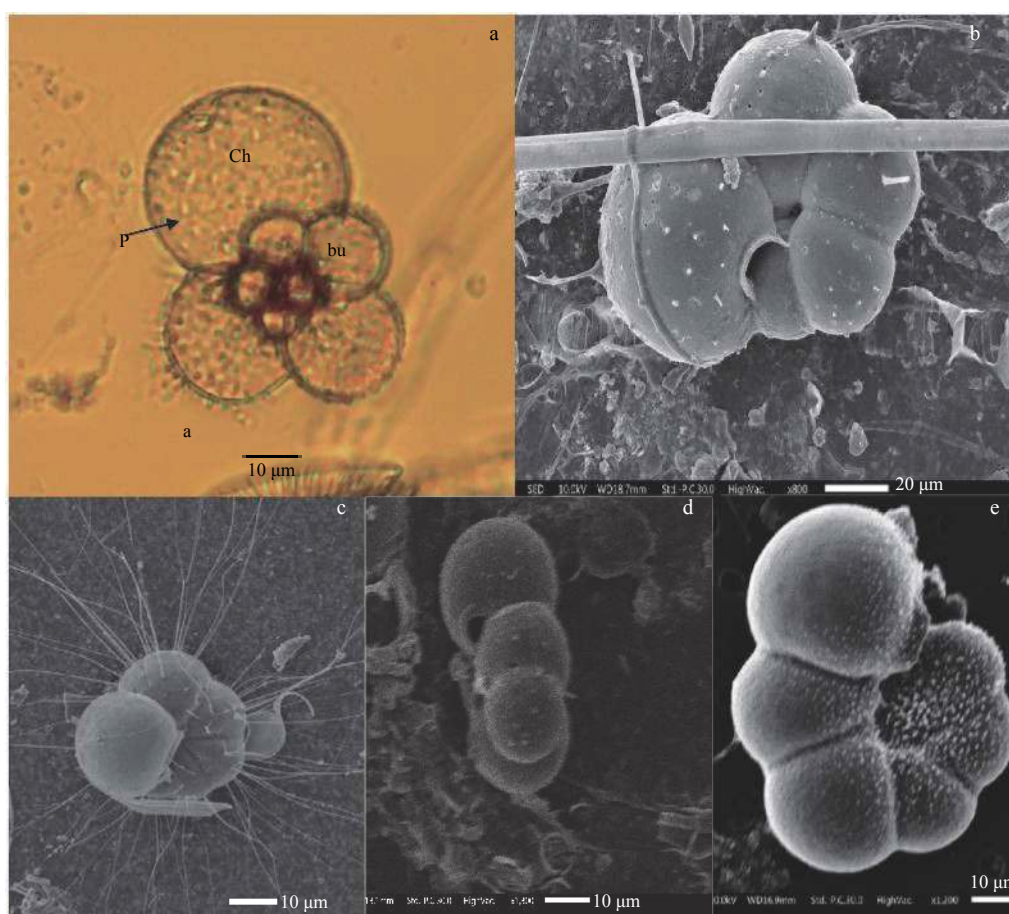
**Diagnosis:** *Globigerina glutinata* was originally described by

Gazelle and Egger, 1893 as low trochospiral, small-shelled, distinguished by the spherical and subglobular shaped chambers (Fig. 6a).

**Description:** Shells are rotundate, globular with 4.5 chambers and umbilical apertures in frontal view. The shell has a low trochospiral test with smooth surface and lobulated, equatorial peripherals, (100–167)  $\mu\text{m}$  length and (80–104)  $\mu\text{m}$  width (Fig. 7a and Table 2). The surface of the test wall is porous, with medium and irregular pores (1.98–3.68)  $\mu\text{m}$  in size distributed over the entire shell. The shell has 3 chambers in the final whorl, the last chamber is broader (45.79  $\mu\text{m}$ ) than the others and is covered with thin lips. The umbilical aperture plate (35–86)  $\mu\text{m}$  long, is interiomarginal, with deep arch. Secondary aperture bulla also observed at irregular locations on the earlier sutures with numerous infralaminar supplementary apertures bordered by very small arched or tubulose openings.

**Occurrence and ecology:** *Globigerina glutinata* was present at the stations (Stas 1308, 1314, 1316, 1410, 1412 and 1505) of the eastern Indian Ocean. The maximum abundance 34 ind./ $\text{m}^3$  and relative abundance 1.64% of total foraminifera recorded when the temperature was 23.86°C, salinity 34.72 and chlorophyll *a* 0.26  $\mu\text{g/L}$ .

**Geographical distribution:** Arabian Sea and the North At-



**Fig. 7.** Light and scanning electron micrographs of foraminifera species, *Globerginoides glutinita* (a), *Tenuitella paraker* (b and c), and *Tenuitella compressa* (d and e). *Globerginoides glutinita* showing the globules shell with 4 or 4.5 chambers, with perforated cell texture with short spines, secondary aperture bulla with extra-umbilical plate (a). *Tenuitella paraker* showing the elongate with low trochospires and planispiral, smooth cell surface with rounded marginal plate test, 4.5–5 chambers in final whorls; umbilical aperture is ovate except of bulla, and spines are improforated from the walls (b and c). *Tenuitella compressa* showing the compressed cells with low trochospiral and perforated surface (d and e).

lantic Ocean, South Atlantic Ocean, Caribbean Sea, Gulf of Aden, and West Pacific Ocean (Table 3).

***Tenuitella parkerae* (Figs 7b, c)**

**Synonymous:** *Globorotalia (Turborotalia) parkerae* Brönnimann and Resig, 1971

**Diagnosis:** *Tenuitella parkerae* Brönnimann and Resig, 1971 characterized by a compressed test and that may be somewhat elongated, low trochospheric and planispiral with left and right coiling directions (Figs 7b, c).

**Description:** Test walls are cancellate and microperforated, ca. 103  $\mu\text{m}$  in length and ca. 72.59  $\mu\text{m}$  in width. Shell surface has small pores 1.54  $\mu\text{m}$  distributed on the smooth and round marginal test (Figs 7b, c and Table 2). Spherical or ovate chamber differentiated with 4.5 to 5 final whorls, the large spherical chamber plate measures as 60  $\mu\text{m}$  (Figs 2b, c and Table 2). Umbilical aperture is ovate in shape as 17.86  $\mu\text{m}$  wide. There is no secondary aperture, lacks bulla. Spines are small, 4.81  $\mu\text{m}$  wide and 24.48  $\mu\text{m}$  long arising from largely imperforated walls.

**Occurrence and ecology:** *T. parkerae* was present at the station (Sta. 1107) located to north zone of the eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.86% of total foraminifera recorded when temperature was 22.7°C, salinity 34.76 and chlorophyll *a* 0.22  $\mu\text{g/L}$ .

**Geographical distribution:** Arabian Sea, equatorial Atlantic Ocean and South Atlantic Ocean (Table 3).

***Tenuitella compressa* (Figs 7d, e)**

**Synonymous:** *Tenuitella Fleisheri*, 1974

**Diagnosis:** *Tenuitella compressa* Fleisher, 1974, observed specimens had been compressed, trochospiral tests with left and right coiling direction (Figs 7d, e).

**Description:** Single shell, compressed with low trochospiral test measured as (51–63)  $\mu\text{m}$  in length and (20–54)  $\mu\text{m}$  in width. In front view, trochospiral is at the left and right coiling position, has spherical test, wall is smooth, hispid and perforate with small and finite pores 1.23  $\mu\text{m}$  (Fig. 7d and Table 1). The final whorls consist of 4.5 and 5 subglobular chambers up to 45  $\mu\text{m}$  and extraumbilical aperture with deep arch (3–6)  $\mu\text{m}$  covered with lip 11  $\mu\text{m}$ , no secondary aperture, bulla present.

**Occurrence and ecology:** *Tenuitella compressa* was present at the station (Sta. 1607) to the north zone of the eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.86% to total foraminifera recorded when temperature was 22.92°C, salinity 34.52 and chlorophyll *a* 0.15  $\mu\text{g/L}$ .

**Geographical distribution:** Caribbean Sea (Table 3).

**Family Globorotaliidae**

Globorotaliidae consist of species with microperforated shells that are smooth textured and spineless. Test are rounded or keel-shaped with medium to large pores on the surface. Chambers can be either a flattened tetrahedron or angular conical and composed of 4.5 to 6 whorls. Extraumbilical aperture has lips other than bulla. Only four taxa from these families were recorded: *Dentagloborotalia anfracta*, *Globorotalia scitula*, *Globorotalia menardii*, *Globorotalia tumida*, *Globorotalia unguolata* (Table 1) which widely distributed from the equatorial Atlantic (Hemleben et al., 1989) to the Caribbean (Schmuker, 2000).

***Dentigloborotalia anfracta* (Figs 8a, b)**

**Synonymous:** *Globorotalia anfracta* Parker, 1967

**Description:** *Dentigloborotalia anfracta* Parker, 1967 observed with small test of 57–72  $\mu\text{m}$  in length and 51–70  $\mu\text{m}$  in width, low trochospiral and flattened at the spiral side, lobulation equatorially and rounded axially with compressed final whorls at 30–43  $\mu\text{m}$  (Figs 8a, b and Table 2). The chambers are 4

to 5 at the final whorl and inflated (Figs 8a, b). Sutures on the spiral side, and the umbilical is radially depressed. Smooth, translucent surface covered with teeth-like pustules with a 3.35  $\mu\text{m}$  size in spiral view. The umbilical-extraumbilical aperture has low arch with a narrow lip of 5–6  $\mu\text{m}$ .

**Occurrence and ecology:** *Dentigloborotalia anfracta* was present at the station (Sta. 1409) located in the equatorial zone of the eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.8% to total foraminifera recorded when temperature was 24.17°C, salinity 34.75 and chlorophyll *a* 0.26  $\mu\text{g/L}$ .

**Geographical distribution:** Equatorial Atlantic Ocean and Caribbean Sea, South Atlantic Ocean, Arabian Sea and Somalia coast (Table 3).

***Globorotalia scitula* (Figs 8c, d)**

**Synonymous:** *Globorotalia bermudezi* Rögl and Bolli, 1973

**Diagnosis:** *Globorotalia scitula* Brady, 1882 observed with medium to low trochospiral and biconvex test, lobate at the equatorial periphery; and axial periphery is subangular to angular with keel-like rim (Figs 8c, d).

**Description:** Large test ranges from 78–106  $\mu\text{m}$  in length and 67–70  $\mu\text{m}$  in width. Low trochospiral test has strongly compressed and crescent-shaped chambers occurring as 4–5 chambers in final whorls. The chambers are strongly compressed and crescent-shaped to form final whorls at a size of 35–46  $\mu\text{m}$  forming 4 to 5 chambers, gradually increasing in size (Figs 8c, d and Table 2). The sutures on the spiral side are strongly curved, slightly elevated. On the umbilical side, sutures are radially arranged, slightly curved or depressed. The surface is smooth, perforated with numerous circular pores at 1.07–2.56  $\mu\text{m}$  size. Pustule is present on early umbilical chambers (Figs 8c, d). Umbilical aperture is narrow at the interiomarginal and extraumbilical positions with low slit and pronounced lip.

**Occurrence and ecology:** *Globorotalia scitula* was identified from two stations (Stas 1507 and 1607) that located between the south and north zone of eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.86% to total foraminifera recorded when temperature was 21.94°C, salinity 34.52 and chlorophyll *a* 0.18  $\mu\text{g/L}$ .

**Geographical distribution:** South Atlantic Ocean, equatorial Atlantic Ocean and Caribbean Sea (Table 3).

***Globorotalia menardii* (Figs 9a–d)**

**Synonymous:** *Globorotalia cultrata* Kennett and Srinivasan, 1983

**Diagnosis:** *Globorotalia menardii* Kennett and Srinivasan, 1983 observed with large test has low trochospiral, compressed and lobular equatorial periphery, acute axial periphery with a prominent keel (Figs 9a–d)

**Description:** Large test ranges in size from 188  $\mu\text{m}$  in length and 139  $\mu\text{m}$  in width. Test consists of 5 to 6 wedge-shaped chambers in the final whorl at 92  $\mu\text{m}$  size (Figs 9a–d). Sutures on the spiral side strongly curved and depressed: smooth surface, densely perforated with circular pores at 2.56–5.19  $\mu\text{m}$  (Figs 9a–d and Table 2). Intermarginal opening, umbilical-extraumbilical, with a low arc bounded by a large lip.

**Occurrence and ecology:** *Globorotalia menardii* was present on one stations (Sta. 1607) to the north of EIO. The maximum abundance 36 ind./m<sup>3</sup> and relative abundance 1.7% to total foraminifera recorded when temperature was 22.92°C, salinity 34.52 and chlorophyll *a* 0.15  $\mu\text{g/L}$ .

**Geographical distribution:** South Atlantic Ocean, equatorial Atlantic Ocean and Caribbean Sea (Table 3).

***Globorotalia menardii* var. *ungulata* (Fig. 9e)**

**Synonymous:** *Globorotalia unguolata* Bermúdez, 1961

**Diagnosis:** *Globorotalia menardii* var. *ungulata* Bermúdez, 1961 observed with small and more elongated test, oval or lobulated in spiral view and at the equatorial periphery, biconvex axial perimeter considerably with a thin keel (Fig. 9e).

**Description:** Large test ranges from 250  $\mu\text{m}$  in length and 220  $\mu\text{m}$  in width. Five chambers are in the final whorl at 118  $\mu\text{m}$  size (Fig. 9e and Table 2). Suture is spirally limbed and slightly raised with the keel on the periphery with radial, depressed umbilical. Slim and densely perforated surface with circular pores at 1.50  $\mu\text{m}$  size and flat and smooth surface interlocking pore area. Umbilical aperture or plate narrows to 105  $\mu\text{m}$  with low arch surrounded by a lip. There are large spines as long as 192  $\mu\text{m}$ .

**Occurrence and ecology:** *Globorotalia menardii* var. *ungulata* was found from the station (Sta. 1607) located at the north zone of eastern Indian Ocean. The maximum abundance 18 ind./ $\text{m}^3$  and relative abundance 0.86% to total foraminifera recorded when temperature was 22.92°C, salinity 34.52 and chlorophyll *a* 0.15  $\mu\text{g/L}$ .

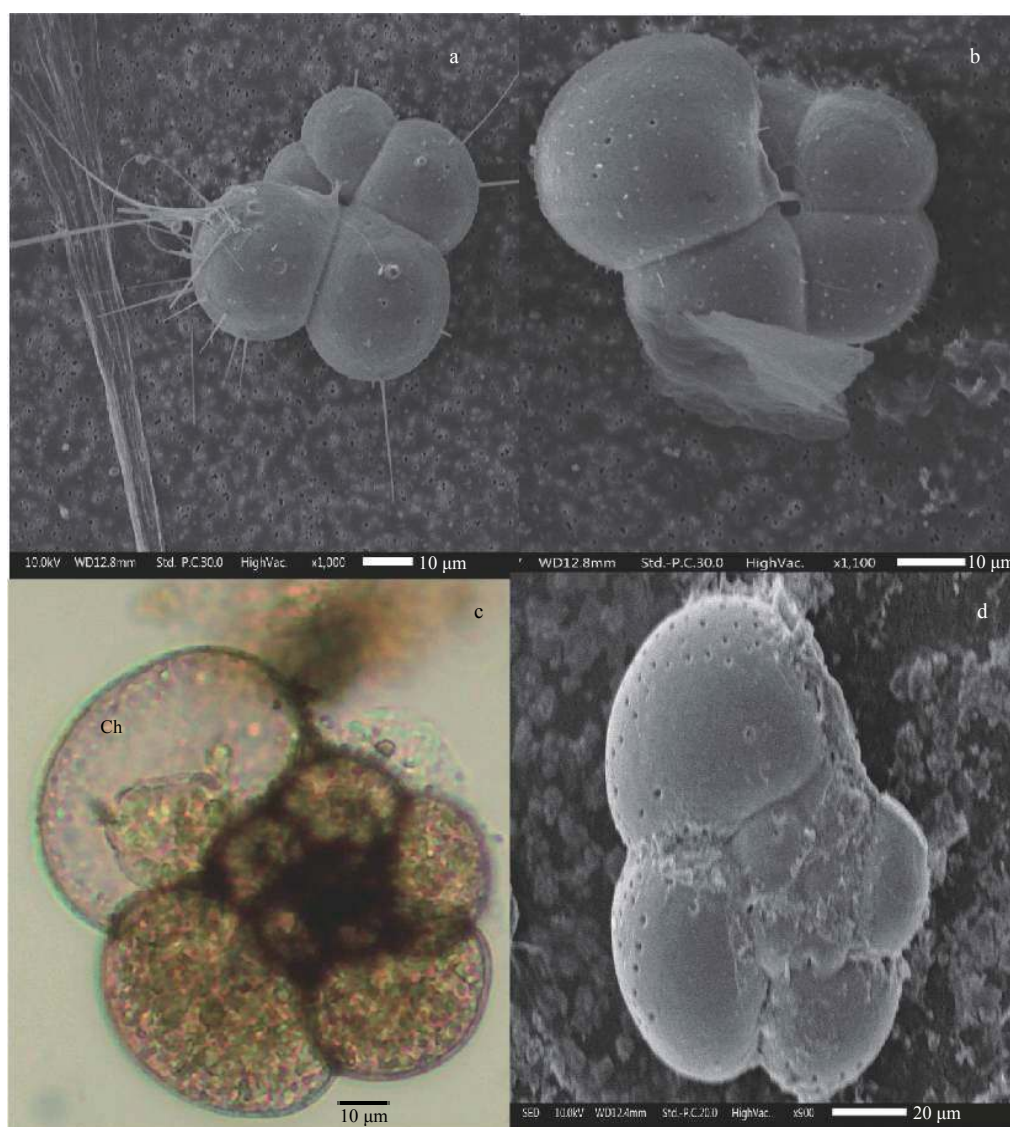
**Geographical distribution:** South Atlantic Ocean, Indian Ocean (Table 3).

***Globorotalia tumida* (Fig. 9f)**

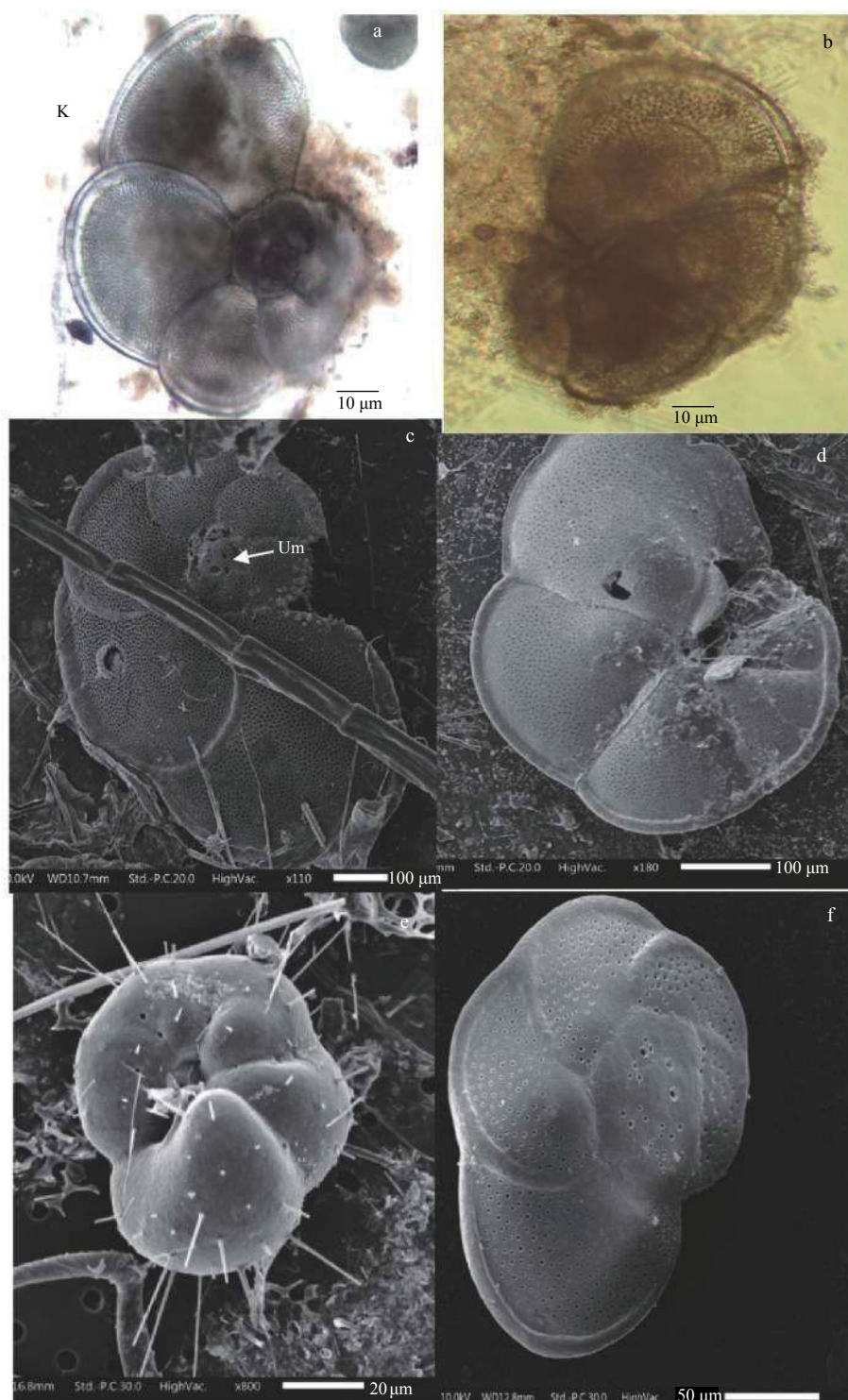
**Synonymous:** *Pulvinulina menardii* var. *tumida* Brady, 1877

**Diagnosis:** *Globorotalia tumida* Brady, 1877 observed with large test and trochospiral shape, equatorial periphery is ovate and slightly lobulated (Fig. 9f).

**Description:** Large test ranges from 299–508  $\mu\text{m}$  in length and 172–372  $\mu\text{m}$  in width. Periphery is axial with a heavy keel (175–305  $\mu\text{m}$ ), and with 5 to 6 wedge-shaped chambers at the final whorl (Fig. 9f and Table 2). Sutures are spirally limbed and raised to curve backwards on the test margin. Sutures similarly depressed. Surface is densely and roughly perforated with pores of uniform size at 1.50–2.22  $\mu\text{m}$ , with the exception of the pustular areas on the umbilical and spiral side. Umbilical aperture is narrow at 105  $\mu\text{m}$  size and deep while the extra-umbilical opening has a low arch covered by a large lip appearing similar to a dish. There are no spines.



**Fig. 8.** Light and scanning electron micrographs of foraminifera species: *Dentigloborotalia anfracta* (a and b) showing the 4.5 to 5 chambers in final whorls with extraumbilical aperture having distinct tooth pustules in front apparatus and surface with microperforated pores (b); *Globorotalia scitula* (c and d) having discoid-shaped shells with 4.5 to 5.5 chamber arrays, small, more elongated umbilical side and smooth surface perforated with circular pores.



**Fig. 9.** Light and scanning electron micrographs showing the discoid-shaped shells with 4.5 to 5.5 chamber arrays, small, more elongated umbilical side, e.g., *Globorotalia menderi* (a–d), *G. unguulate* (e), and *G. tumida* (f). Dorsal view showing the compressed chamber from 4 to 5 at final whorls, densely perforated surface with circular pores in *G. menderi* (c), flat and smooth surface interlocking in *G. unguulate* (e) and *G. tumida* (f). Sutures are the merging with keel on the periphery shown in *G. menderi* (a–d), *G. unguulate* (e), and *G. tumida* (f). Umbilicus narrow and interiomarginal have low arch covered by lip shown in *G. menderi* (a–d), *G. unguulate* (e) and *G. tumida* (f).

**Occurrence and ecology:** *Globorotalia tumida* was present at the station (Sta. 1505) located south zone of the eastern Indian Ocean. The maximum abundance 18 ind./m<sup>3</sup> and relative abundance 0.80% to total foraminifera recorded when temperat-

ure was 20.72°C, salinity 34.82 and chlorophyll *a* 0.21 µg/L.

**Geographical distribution:** Equatorial Atlantic Ocean and Caribbean Sea, South Atlantic Ocean, South-Pacific and Indo-Pacific region, South-Indian Ocean (Table 3).

## 4 Discussion

### 4.1 Planktonic foraminifera in the eastern Indian Ocean

The eastern Indian Ocean defined as the most oligotrophic waters of the Central Indian Ocean including the Bay of Bengal, South of the Java up-welling coast and West Australia. [Martinez et al. \(1998\)](#) have described the oceanic settling in the eastern Indian Ocean and the discrete population during the Last Glacial maximum and west pool of the Pacific Ocean. Previous research studies on silicate depositing and calcifying organisms, such as radiolarians and foraminifera's, respectively, in the eastern Indian Ocean, have shown that their assemblage boundaries in the vicinity of the eastward circumpolar flow are not strictly zonal. This may indicate significant deviations from the mean eastward flow as a necessary condition for conservation of potential vortices when the flow encounters topographic irregularities. Particularly in the southern and western part of Pacific Ocean, the only certain reference is the report of Globigerinoides, Globorotalida, and Globigerinella species ([Martinez et al., 1998](#)). [Martinez et al. \(1998\)](#) found three species, e.g., *G. sacculifer* (*T. sacculifer*) at the depth (50 m), *N. duterteri* at the depth (50–100 m) and *G. inflanta* at the depth (below 100 m) during the Last Glacial Maximum (LGM) time and only *G. ruber* was highly abundant species in north part during the LGM time's then decreases at the south.

In present study, 20 planktonic foraminifera species were recognized through plankton net samples at the 200 m depth, the similar number of species also reported from the Andaman Sea ([Mohan et al., 2013](#)) and 26 species were reported from the Bay of Bengal ([Chowdhury et al., 2003](#)). The present study found eight additional genera: *D. anfracta*, *H. pelagica*, *S. globigerus*, *G. calida*, *G. adamsi*, *O. reideli*, *T. parkerae* and *T. compressa*, which are useful for updating plankton checklists in the research area. The identified taxa are the tropical and subtropical species including groups Canderinidae, Heterohelicoidae, Histigerinoidae, Hedbergellidae, Globigerinoidae, and Globorotaloidae. Among them, Globigerinoidae and Globorotaloidae were known previously from the south of Australia and the West Pacific Ocean. Other tropical species were overlooked by these regions but were reported from the tropical latitudes of Arabian Sea and Atlantic waters as shown in [Table 3](#). Particularly, these are cosmopolitan species within their preferred bioprovince and paleoenvironmental indicator species of tropical and temperate region ([Schiebel and Hemleben, 2017](#)). Current study of the depth zones, 200 m in the eastern Indian Ocean experienced with various species are reported new which were not reported from surface. *Globigerinina glutinata* is cryptic species of tropical and temperate areas ([André et al., 2013, 2014; Table 3](#)), recently recorded from nine stations in the eastern Indian Ocean and abundant in equatorial zone (present study). This species was reported earlier from the West Pacific Ocean ([Martinez et al., 1998](#)). Other tropical-temperate water species, such as *T. parkerae* and *T. compressa* although has appeared for the first time from the eastern Indian Ocean area and often distinguished from the North Arabian Sea, Caribbean and North Atlantic species ([Hemleben et al., 1989](#)). Though it is found rare in the tropical areas ([Saito et al., 1981; Schumuker, 2000](#)).

*Streptochilius globigerus* ([Fig. 2a](#)) is planktonic species identified for the first time from equatorial zone of the eastern Indian Ocean (present study). This species was previously reported from the Arabian Sea ([Schumuker, 2000](#)). Two species are *Hastigerina pelagica* and *Orcadia riedeli* were recorded for the first time from the eastern Indian Ocean. *Orcadia riedeli* was found abundantly in the equatorial zones of this area. These species has been re-

ported from other oceans ([Table 3](#)) and previously distinguished from the Red Sea ([Hemleben et al., 1989](#)) and the West Pacific Ocean ([Schiebel and Hemleben, 2017](#)).

Compare to previous studies on Globigerinidae ([Thompson et al., 1979; Martinez et al., 1998; Cushing, 2000; Schiebel and Hemleben, 2005, 2017](#)) two species *G. calida* and *G. adamsi* are the first reported species in the eastern Indian Ocean. These species are recorded with low abundance compare to other species such as *G. bulloides*, *G. siphonospheara* and *G. ruber*. *Globigerina bulloides*, *G. siphonospheara* and *G. ruber* are common species in this region ([Martinez et al., 1998](#)). *Orbulina universa* ([Figs 6a, b](#)) was collected from nine stations around the eastern Indian Ocean. *Orbulina universa* ([Figs 6a, b](#)) is abundant in tropical, subtropical, and even the subantarctic areas but has low diversity in this area. This species originally described from the Atlantic Ocean and West Pacific Ocean ([Weiner et al., 2014](#)). Other, species are *T. humilis* and *T. quinqueloba* were collected from 11 stations in the eastern Indian Ocean. Previously these species were reported from tropical and subtropical areas ([Table 3](#)) and distributed widely from the equatorial and north-south Atlantic Ocean ([Darling et al., 2000; Darling and Wade, 2008](#)).

*Dentigloborotalia anfracta* ([Figs 8a, b](#)) recorded for the first time from this area, and previously known from the Arabian and Somalian coast ([Conan et al., 2002; Schiebel et al., 2004](#)).

Planktonic foraminifera at the depth of 200 m shows decreased percentage values as 0.86 to increased percentage values 41% to total foraminifera recorded in spring time. The previous studies in the eastern Indian Ocean have shown that planktonic diversity of planktonic foraminifera was high (1 000 m<sup>3</sup>) in summer season around the south of Java upwell area and others area was comparatively low species diversity ([Ujiie and Nagase 1971; Bé and Hutson 1977](#)). The Indo-Pacific species are *G. adamsi*, *G. conglomerata*, *G. hexagonus*, *N. duterteri*, *P. obliquiloculata* and one Atlantic tropical species, *G. ruber* pink are endemic species ([Martinez et al., 1998](#)). The shallow-water species (*H. pelagica*, *G. sacculifer*, *G. bulloides*, *G. ruber*) were also observed which are important for regulating the carbonate in the tropical oceans ([Schiebel and Hemleben, 1997](#)).

### 4.2 Species characterization among similar congenera

Planktonic foraminifera are calcifer shell forming species. The shell morphology, chamber arrays and ornamentation of umbilical plates are the key characters ([Schiebel et al., 2004](#)).

The recent taxonomic grouping of planktonic foraminifera species are followed by the references ([Kennett and Srinivasan, 1983; Schiebel and Hemleben, 2005, 2017; Aze et al., 2011](#)). The taxonomic classification of several species was erected from *Globigerina* which was synonymous to *G. bulliodies*, e.g., *G. quadrilateral*, *G. megastoma*, *G. bermudezi*, *G. cariacensis*, *G. riveroae* ([Kennett and Srinivasan, 1983](#)). In Hastigerinidae, *Hastigerina pelagica* and *Orcadia riedeli* was characterised by the 5.5 chambers, spines bases at the chamber tips, ovate to ampullate umbilical aperture ([Figs 2b–f](#)). In general, morphologically both species are closely similar but has been differentiated on the trochospiral coiling and umbilical cord chambers ([Cushing, 2000](#)).

In Globigerinidae, *G. calida*, and *G. adamsi* ([Figs 3a–d](#)) were characterized due to their lowtrochospiral development and radial oblong chambers are the key characteristics distinguishing it from *G. bulliodies*, *G. siphonospheara* ([Figs 4a–d](#)) and *G. ruber* ([Figs 5a, b](#)). *Globigerina bulloides* and *G. siphonospheara* are closely similar species, with large sizes and 4 chambers. *Globigerinoides ruber* ([Figs 5a, b](#)) differs slightly by its three chambers in globular

form and position of the primary and complementary sutural openings, which are always placed symmetrically above the suture between two chambers. *Orbulina universa* (Figs 6a, b) is spherical shape test contained single chamber with longitudinal spines compare to *G. bulloides* (4 chambers) and *G. siphosphaera* (5 to 6 chambers). *Turborotalita humilis* (Figs 6e, f) and *T. quinqueloba* (Figs 6c, d) has more than 6 chambers. *Turborotalita humilis* differs from *T. quinqueloba* (Figs 6c, d) by its small test with micro-perforated wall with larger pores.

*Globigerinita glutinita*, *T. paraker* and *T. compressum* are grouped in family Canidaide, where the subspherical chambers plates are divided into 4 or 5 compartments, and have microperforated cell texture. Only secondary aperture, bulla with extra-umbilical plate in *G. glutinita* differentiate it to other species. *Tenuitella compressa* (Figs 7d, e) and *D. anfracta* (Fig. 8b) have similar chamber pattern in umbilical view. *Dentigloborotalia anfracta* can be differentiated by microperforation pores and tooth-pustules with the umbilical area. *Globorotalia scitula* (Figs 8c, d) having discoid-shaped shells with 4.5 to 5.5 chamber arrays, small, more elongated umbilical side and smooth surface perforated with circular pores.

*Globorotalia menderi*, *G. unguulate* and *G. tumida* were characterized on the basis of 4.5 to 5.5 chambers, discoid shell, with extra umbilical aperture, keel-like test wall (Figs 8 and 9). *Globorotalia menderi*, *G. unguulate* and *G. tumida* (Fig. 6f) have similar shell structure. The difference can be based on the chamber plates, e.g. elongated chamber in *G. menderi* and compressed and smooth chamber in *G. unguulate* and *G. tumida*. Umbilicus narrow and interiomarginal have low arch covered by lip which are same in these species (Kennett and Srinivasan, 1983).

On the basis of recent taxonomic reviews, classification has been significantly changed after genetic analysis. The genotypic variation has led to some new taxonomic visions that may cause a major revision in the future (Kennett and Srinivasan, 1983; Darling et al., 1996a, 2000; De Vargas et al., 2002; Kucera and Darling, 2002; Pawlowski and Holzmann, 2002; Smart and Thomas, 2007; Aurahs et al., 2009, 2011; Aze et al., 2011; Spezzaferri et al., 2015). In the case of *G. sacculifer*, it is now the junior synonym for *T. sacculifer*, which was recently revised by Spezzaferri et al. (2015). However, *T. sacculifer*, *G. ruber* (pink and white) and *N. pachyderma* are genotype species without any specific variation (Aurahs et al., 2009; Kucera and Darling, 2002). *Hastigerina pelagica* due to their monolocular chamber array was separated to new genera (Hemleben et al., 1989; Alldredge and Jones, 1973). *Streptochilis globigerus* can be confused with *B. variabilis* of Bovilinidea in general, which added later in the planktonic foraminifera group of the low Miocene of Atlantic Ocean and Indian Ocean (Smart and Tomas, 2007; Darling et al., 2009).

These foraminifera are widely used for climatic and geological studies in many oceanic areas; the taxonomic studies of planktonic foraminifera from the eastern Indian Ocean will be beneficial for scientist from the microbiology and geology research institutes. Further recommendations can be useful if DNA analysis can be used to reconstruct the systematic relationships from past geological time and to understand the recent paleoceanographic linkage.

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