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Northward Migration of Antarctic Polar Front during the Quaternary: Planktic Foraminiferal Record from Southeast Indian Ocean

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Abstract: The ODP Hole 763A is influenced by the northward-flowing cold West Australian Current (WAC) and Southward flowing warm Leeuwin Current (LC). LC is a branch of the South Equatorial Current (SEC), which brings relatively warmer waters from the tropical Pacific Ocean into the Indian Ocean via Indonesian Throughflow (ITF). The modern planktic foraminiferal fauna thrives along the western margin of Australia. It consists mainly of warm water assemblages brought by the LC. The present study provides planktic foraminiferal census data from ODP Hole 763A, influenced by the LC and WAC, to document the history of cold water influence at the site during the quaternary. The northward migration of the Antarctic Polar Front (APF) and resultant intensification of the cold West Australian Current have been inferred based on the dramatic increase in the relative abundance of temperate water species group *Globoconella* at Hole 763A situated in the low latitude region. The Quaternary planktic foraminiferal census data shows several episodes of invasion of *Globoconella*. These intervals of high abundance of *Globoconella* group have been attributed to the intensification of WAC, probably due to Antarctic ice volume expansion and resultant northward migration of the APF at 0.05 Ma, 0.2 Ma, 0.45 Ma, 0.7 Ma and 1.2 Ma. We have documented that the amplitude of fluctuations in cold/warm events has increased after the Mid-Pleistocene Transition (MPT). LC is a heat supplier to the higher latitudes, its weakening during such intervals might have contributed to the ice volume expansion over Antarctica. Thus, the study proposes that the Antarctic ice cap formation creates a positive feedback mechanism by lowering sea level, reduced strength of LC due to a decrease in ITF and less heat supply towards the South Pole. All these phenomena add to further cooling.

Keywords: Antarctic Polar Front; Planktic foraminifera; West Australian Current.

Introduction

The Antarctic Polar Front has shifted northwards as a response to the climatic cooling and expansion of the Antarctic ice sheet (Kemp et al., 2010; Taylor-Silva and Riesselman, 2018). The Antarctic polar frontal zone surrounds the icy continent of Antarctica, isolating its thick permanent ice sheets from the influence of warmer northerly waters (Barker and Thomas, 2004). Thermal isolation of Antarctica occurs with the development of Circum Antarctic Circulation due to the opening of the Tasmanian Seaway and the Drake Passage in the Early Cenozoic (Kennett, 1977). Mapping the distribution of diatomaceous sediments helped in tracing the northward extent of the APF. Laminated diatom mat deposits have preserved episodes of enormous diatom *Thalassiothrix antarctica* beneath the Antarctic Polar Front, which acts as a marker for tracking the

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migration of the APF through time (Kemp et al., 2010). Antarctica has a significant influence on the Southern Ocean surface temperatures and the APF has responded directly to glacial/interglacial stages by its northward and southward movements. These responses differ from basin to basin due to the position of the continents and local hydrography. The expansion of the Antarctic ice sheet influences the Benguela Current System in the South Atlantic (Little et al., 1997), it also results in the intensification of the cold West Australian Current in the southeast Indian Ocean (Sinha and Singh, 2007). Feldberg and Mix (2003) detected the invasion of cold water planktic foraminiferal species *Globorotalia* (*Globoconella) inflata* up to equatorial latitudes due to intensification of eastern boundary current in the southeast Pacific Ocean. However, very few studies have been made regarding the influence of Antarctic ice sheet expansion at low latitudes using faunal census data. It is generally understood that the intensification of the equatorward flowing cold currents and Polar Front migration will affect the low latitude oceans (McClymon et al., 2016). The expansion of the ice sheet and migration of the Polar Front toward low latitudes would also result in habitat migration, the cold water fauna is expected reach low latitudes and later get preserved in oceanic sediments (Feldberg and Mix, 2003; Sinha et al., 2006). Planktic foraminifera, which shows latitudinal provincialism, provides one of the best proxies for tracing such habitat migration. Since they are passive surface dwellers, their distribution in the oceanic sediments mimics the overlying surface water mass distribution. We have also tried to examine our data in the light of Mid-Pleistocene Transition (MPT) characterised by a shift from obliquity-driven climate cycles (~ 41 000 years, 41 kyr) to the ~ 100 kyr cycles typical for the late Pleistocene. In the present study, the sampling interval is too coarse to precisely detect the Milankovitch cycles. Thus, we tried to find the other aspect of the MPT, which is an increase in the amplitude of glacial-interglacial signals (Ruddiman et al., 1986), expected to be reflected in the amplitude of variation in the relative abundance of cold water fauna. Thus, the study points on the following two critical aspects: the timings of expansion of the Antarctic ice sheet and related northward migration of Polar Front and how does the present data set reveal a change in the amplitude of glacial-interglacial stages after Mid-Pleistocene? Lastly, we discuss the probability of the role of strengthening/weakening of LC in the feedback mechanism related to Antarctic Cooling.

The present study has been conducted on ODP Hole 763A from the Eastern Indian Ocean (EIO) situated at the Western margin of Australia (Figure 1). This is a unique eastern boundary where though equatorward winds predominate, there is no continuous upwelling. Due to the dominance of the southward flowing Leeuwin Current and the northward transport of waters nullified by southward flowing warm Leeuwin Current, there is no continuous equatorward flow within 1000 km of the coast of Western Australia (Smith, 1992; Veeh et al., 2000). The West Australian Current is a northward diverted part of Circum Antarctic circulation (Figure 1), and its intensification is related to an increase in the Antarctic ice volume. The northward migration of the Polar Front has been manifested in the strengthening of the WAC, which brings cold waters in the tropical eastern Indian Ocean. WAC influences the area and we presume that its intensification would have been caused by northward migration of the Antarctic Polar Front during glacial stages.

It is envisaged here that such expansion would result in the shifting of the habitat of cool water planktic foraminifera towards the tropical EIO region. At present, the studied area is mainly influenced by warm LC, which is a branch of SEC. Our studies show that the modern planktic foraminiferal fauna consists primarily of warm water assemblages in the EIO region. However, the down core variation during Quaternary indicates that the Period witnessed the weakening and strengthening of the warm LC in concert with the interglacials and glacials. Contrasting generalisations were made regarding the weakening (Wilson et al., 1987) and strengthening (Kendrick et al., 1991) of the LC during the Quaternary to explain changes in the biogeographic pattern of planktic foraminifera at the southern Australian margin. Based on planktic foraminiferal census data from the studied ODP Hole 763A from Exmouth Plateau, EIO, we have attempted to identify the timing of several cooling events during the Quaternary when the cold WAC intensified. Planktic foraminifera is an excellent indicator of overlying surface water masses that has been used to infer past surface ocean circulation changes (Kennett et al., 1985). The relative abundance of temperature-sensitive species groups has been exploited to infer surface water paleoceanography (Wei, 1998; Srinivasan and Sinha, 2000). In the present climatic condition, warm water planktic foraminiferal assemblages such as *Globigerinoides trilobus, Gs. sacculifer, Gs. quadrilobatus, Gs. ruber, Gs. conglobatus, Pulleniatina*

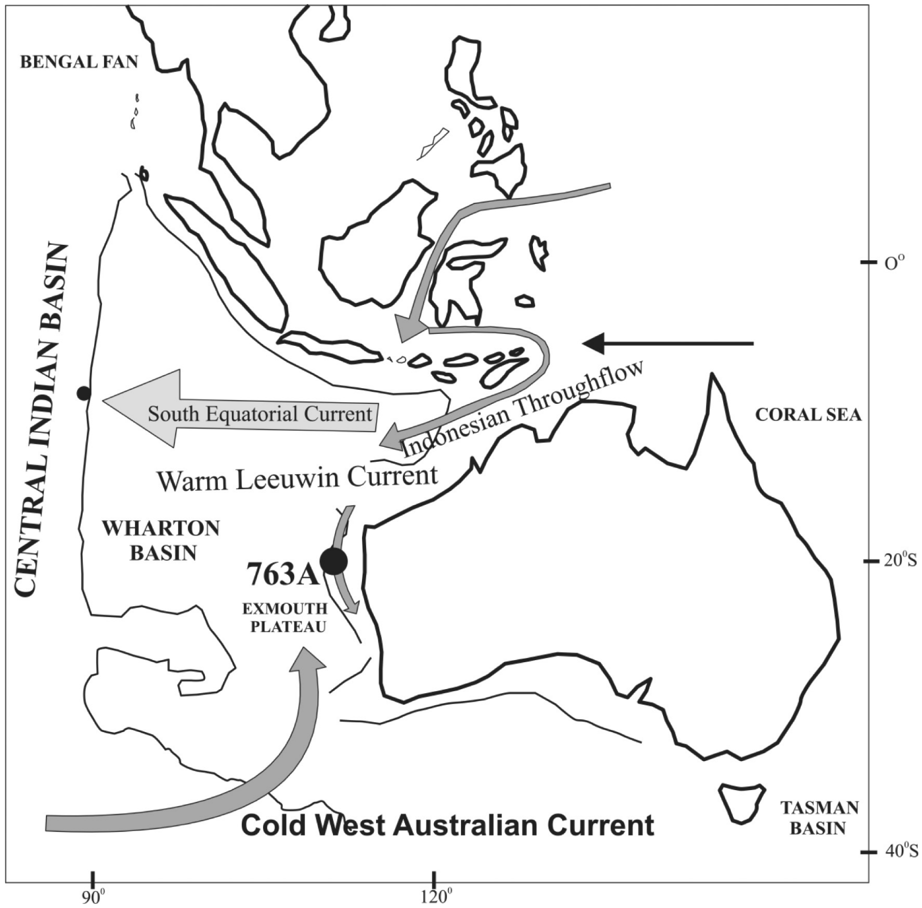

Figure 1: Location and oceanographic set up of ODP Hole 763A, Eastern Indian Ocean.

obliquiloculata groups dominate the surface waters of EIO region.

Material and Methodology

Age Model

Detailed planktic foraminiferal investigations were carried out for ODP Hole 763A. Sample resolution at the ODP Hole was at 1.5 m intervals spanning the quaternary. The ages of the samples were taken from the detailed biostratigraphy integrated with magnetostratigraphy from Sinha and Singh (2008). Their work was based on determining the sequential order of planktic foraminiferal events and their numerical age estimation. Our biostratigraphic record shows that the studied interval lies within the Pleistocene. Gradstein (2012) revised the base of the Pleistocene, which coincide with the base of the Gelasian Stage at 2.56 Ma. The paleomagnetic stratigraphy (Tang, 1992) for the core shows the top of the Olduvai Event (1.77 Ma) at the same level as our recorded LA of *Globigerinoides fistulosus* and thus age at 32 m can be safely taken as 1.77 Ma. The integrated planktic foraminiferal biostratigraphy with paleomagnetic stratigraphy (Sinha and Singh, 2008) give the age of each sample at ODP Hole 763A (Figure 2).

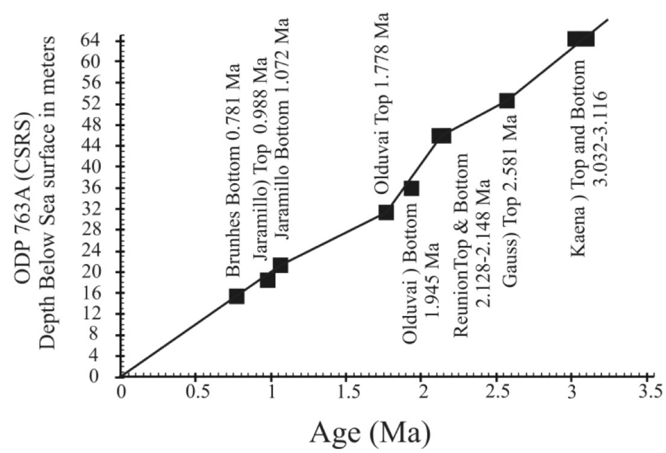

Figure 2: Age-Depth plot of ODP Hole 763A. Paleomagnetic stratigraphy after Tang (1992) and revised ages of paleomagnetic events after Gradstein et al. (2012).

Planktic Foraminiferal Census Counts

All the deep-sea core samples from Hole 763A (Leg 122; Haq et al., 1990), spanning 2.6 million years, were studied for planktic foraminiferal census counts. A fraction of >150 micron was chosen for census counting as it gives maximum climatic information in the least time (Imbrie and Kipp, 1971) and is the size fraction now adopted by many major paleoclimatic studies (Wells et al., 1994). A microsplitter was used to separate an aliquot of 300 or more planktic foraminiferal individuals. Each individual was identified up to the species level following the taxonomic studies by Kennett and Srinivasan (1983) and Bolli and Saunders (1985) mounted on assemblage slides. SEM micrograph of crucial species from ODP Hole 763A and adjacent site 762B has been provided in Plates 1-3 for the taxonomic concept. The percentage of each species was calculated and relative abundance curves were plotted for key species discussed later. Based on the water mass distribution of the planktic foraminiferal species (Kennett and Srinivasan, 1983; Schiebel and Hemleben, 2017), several groups were made for creating percentage frequency plots used for paleoceanographic interpretation.

Species Groups for Paleoceanographic Interpretation

Based on the ecological preference of planktic foraminiferal species, three groups were made for paleoceanographic interpretations. Group 1 (Warm mixed layer, oligotrophic) included *Globigerinoides ruber*, *Globigerinoides sacculifer* and *Globigerinoides fistulous* (Plate 1). Group 2 (tropical thermocline dweller) included *Pulleniatina primalis, Pulleniatina praecursor* and *Pulleniatina obliquiloculata* (Plate 2). Group 3 (temperate and subpolar) included *Globorotalia (Globoconella) puncticulata* and *Globorotalia (Globoconella) inflata* (Plate 3). Detailed taxonomic notes and ecological preferences of each species have been provided.

Taxonomy and Ecological Preferences of the Species Groups

Group 1: Warm Mixed Layer Oligotrophic Group

***Globigerinoides sacculifer* (Brady)**

Plate 1, Figures: 1-7	
1877	*Globigerina sacculifer* Brady; Geol. Mag., NS, decade 2, 4 (12) 535 (Figures in Brady, 1884; Rep. voy. challenger, Zool.,9: 604, Plate 80, Figures 11. 11-17; Plate 81, Figure 2, Plate 82, Figure 4).
1960	*Globigerina sacculifer*; Banner and Blow, Contr, Cushman Found. Foram. Res., 11: 21, Plate 1, Figures 1a-b, 2a-b; in plate caption given as Globigerinoides quadrilobatus sacculifer
1983	*Globigerinoides sacculifer*; Kennett and Srinivasan, Hutchinson. Ross Publ.Co.U.S.A., p.66, Plate 14, Figures 4-6.

Remarks: *Globigerinoides sacculifer* derives its name from a sac-like final chamber and is distinguished by this character from *Gs. trilobus and Gs. quadrilobatus.* There have been frequent uses of the terms like "*Globigerinoides sacculifer* with or without sac" while referring to specimens picked up for isotopic analyses. The original concept of the species incorporates a sac-like chamber and the specimens without sac should be considered as *Globigerinoides quadrilobatus*. The surface is highly porous and the circular pores (Plate 1; Figure 7) are situated in hexagonal pore pits (Plate 1; Figures 5 and 7). By developing finger (fistules) like projections *Gs. Sacculifer* gives rise to an important age marker species *Gs. fistulosus* near the base of the Olduvai Normal Event. Hilbrecht (1997) also came out with the conclusion that there are no significant differences in the ecology of both forms, i.e., non-saccate forms (here considered *Gs. quadrilobatus*) and saccate forms (*Gs. sacculifer*) in agreement with culture experiments (Hemleben et al., 1987). *Globigerinoides sacculifer* is an abundant species in tropical to subtropical surface waters (Be 1977; Schmuker and Schiebel, 2002). This species bears dinoflagellate symbionts, feeds mostly on calanoid copepods and reproduces on a synodic lunar cycle (Hemleben et al., 1989; Bijma et al., 1990; Erez et al., 1991). This is a euryhaline species. This species is abundant in Oliotrophic surface waters (Conan and Brummer, 2000; Schiebel et al., 2004).

***Globigerinoides fistulosus* (Schubert)**

Plate 1, Figures: 8-11	
1910	*Globigerinoides fistulosus* Schubert; Geol. Reichsanst., Verh., Wien, p. 323, Text Figure 1.
1967	*Globigerinoides fistulosus;* Parker, Bull. Am. Paleont., 52 (235), 154, Plate 21, Figures 3-6; Text Figure 4.
1983	*Globigerinoides fistulosus*; Kennett and Srinivasan, Hutchinson. Ross Publ. Co. USA, p. 68, Plate 14, Figures 7-9.

Remarks: *Gs. fistulosus* is characterised by its multiple digitate extensions of the last few chambers. *Gs. fistulosus* is differentiated from *Gs. sacculifer* by having a number of attachments in its last chamber. Its last appearance datum corresponds to the top of the Olduvai Normal Event (Srinivasan and Sinha, 1991, 1992; Sinha and Singh, 2008; Berggren et al., 1995a). *Gs. fistulosus* evolved from *Gs. sacculifer* by developing multiple digitate extensions on the last few chambers in the final whorl. The ecological preference of *Gs. fistulosus* is presumed to be the same as its ancestor *Gs. sacculifer.*

***Globigerinoides ruber* (d'Orbigny)**

Plate 1, Figures: 12-15	
1839	*Globigerina ruber* (d'Orbigny); *In:* De La Sagra, Histoire physique, politique et naturelle de L'blle de cuba, 8: 82, Plate 4, Figures 12-14.
1960	*Globigerina ruber* d'Orbigny; Banner and Blow, Contr. Cushman Found. Foram. Res., 11: 19, Plate 3, Figure 8 (lectotype)
1983	*Globigerina ruber*; Kennett and Srinivasan, Hutchinson. Ross Publ. Co. U.S.A., p.78, Plate 17, Figures 1-3.

Remarks: *Gs. ruber* is characterised by its symmetrically placed primary aperture above the suture between earlier two chambers. Some of *Gs. ruber* species are pink in colour and some are high spired.

Gs. ruber is considered as the shallowest dwelling planktic foraminiferal species (Hemleben et al., 1989) and is most suitable for isotopic analyses for sea surface temperature and salinity estimation. It is distinguished from other *Globigerinoides* by its symmetrically situated aperture above the suture between the early two chambers (Plate 1, Figures 12-14). It shows a wide range of variation in the height of the spire. This species occurs in two varieties. One produces white tests and occurs in all oceans, while the other slightly larger variety having a pink test, pigmented by reddish colour (Hemleben et al., 1989). Pink forms are rare in the assemblages. White forms belong to the dominating species in tropical and subtropical planktic foraminifera. Pink variants prefer warmer habitats than white variants (Bé and Hamlin, 1967; Hemleben et al., 1989). *Gs. ruber* together with its ancestor *Gs. obliquus* and *Gs. extremus* form a dominant species group characterizing well stratified oligotrophic conditions in the upper water column.

Plate 1

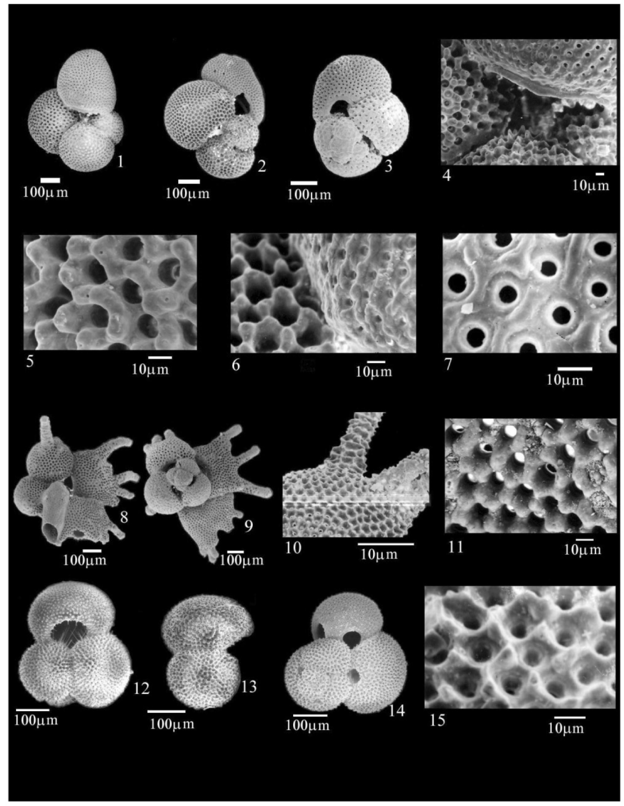

Plate 1: 1. *Globigerinoides sacculifer* Brady; apertural view showing sac like final chamber and open aperture. Sample No. 122-763A, 2H-5, 75-77 cm. 2. Spiral view, showing secondary aperture. Sample No. 122, 762B, 12H-7, 50-52 cm. 3. Spiral view. Sample No. 122-763A, 2H-5, 75-77 cm. 4. Ultrastructure showing enlarged apertural rim. Sample No. 122-762B, 1H-1, 6-8 cm. 5. Ultrastructure of penultimate chamber showing pore details. Sample No. 122-763A, 2H-5, 75-77 cm. 6. Ultrastructure of the junction of final and penultimate chamber. 7. Ultrastructure of final chamber of Figure 1. Sample No. 122-763A, 2H-5, 75-77 cm; 8. *Globigerinoides fistulosus* (Schubert) Apertural view showing finger like projection in the final chamber. 9. Spiral view. 10. Showing diameter of fistules. Sample No. 122-763A, 7H-1, 75-77 cm. 11. Ultrastructure of showing pore details. Sample No. 122-763A, 5H-1, 75-77 cm; 12. *Globigerinoides ruber* (d'Orbigny), apertural view showing symmetrically placed primary aperture above the junction of two earlier chambers. Sample No. 122-763A, 1H-1, 76-78 cm. 13. Side view. Sample No. 122-762B, 1H-1, 6-8 cm. 14. Spiral view showing symmetrically placed secondary aperture above the junction of two earlier chambers. 15. Ultrastructure of chamber in Figure 12 showing funnel shaped pores, tapering towards the centre of the test. Sample No. 122-763A, 1H-1, 76-78 cm.

Group 2: Tropical thermocline dweller

***Pullaniatina primalis* Banner and Blow**

Plate 2, Figures: 1-4, 13	
1967	*Pullaniatina primalis* Banner and Blow; Micropal.13 (2), p. 142, Plate 1, Figures 3-8; Plate 3, Figures 2a-c.
1975	*Pullaniatina primalis*; Srinivasan and Srivastava, Late Neogene Epoch boundaries, Micropal., Spec. Publ., no. 1, p. 146.
1983	*Pullaniatina primalis*; Kennett and Srinivasan, Hutchinson Ross Publ. Co. USA, p. 201, Plate 49, Figures 1-3, 5.

Remarks: *Pu. primalis* can be distinguished from its ancestor *N. acostaensis* by the absence of apertural lip and streptospiral arrangement of the last chamber of the final whorl. It is distinguished from its descendent *Pu. praecursor* by its aperture restricted to the umbilical side and does not reach the periphery of the previous whorl. The first evolutionary appearance marks the base of Zone N17 B in a study by Srinivasan and Kennett (1981a,b). Bolli and Saunders (1985) stated that the origin of *Pulleniatina* from *N. acostaensis* has yet to be proved, however, we have observed a sufficient number of intergrades between *N. acostaensis* and *Pu. primalis*, which agrees with the study by Kennett and Srinivasan (1983) regarding the ancestry of *Pulleniatina.* Its ecological preference and paleoceanographic significance are the same as that of its descendent *Pu. Obliquiloculata. Pulleniatina* minimum events have been used to indicate the deepening of thermocline in the Indian Ocean. Srinivasan and Sinha (2000) provided the isotopic depth ranking of *Pulleniatina* and indicated the closing of Indonesian seaway to thermocline waters during the Early Pliocene.

Pullaniatina precursor *Banner and Blow*

Plate 2, Figures: 5-8, 14	
1967	*Pullaniatina obliquiloculata praecursor* Banner and Blow; Micropal. 13(2): 139, Plate 3, Figure 3a-c.
1983	*Pullaniatina praecursor*; Kennett and Srinivasan, Hutchinson Ross Publ. Co. USA, p. 200, Plate 49, Figures 6-8.

Remarks: *Pullaniatina praecursor* represents an intermediate evolutionary stage between *Pu. primalis* and *Pu. obliquloculata*. It differs from *Pu. primalis* in possessing an aperture that extends further up to the periphery. Parker (1967) included this species in *Pu. primalis.*

***Pullaniatina obliquiloculata* (Parker and Jones)**

Plate 2, Figures: 9-12, 15	
1865	*Pullenia sphaeroides* (d' Orbigny) *var. obliquiloculata* Parker and Jones; in Carpenter, Roy. Soc. Lond. Philos. Trans. 155: 365, 368, Plate 19, Figure 4a-b. p. 183 (nomen nudum)
1967	*Pullaniatina obliquiloculata* Banner and Blow; Micropal. 23/13 (1/2): 137, Plate 3, Figure 4, Plate 4, Figure 9.
1983	*Pullaniatina obliquloculata*; Kennett and Srinivasan, Hutchinson Ross Publ. Co. U.S.A., p. 202, Plate 49, Figure 2; Plate 50, Figures 6-9.

Remarks: This species is characterised by streptospiral coiling and a low arched aperture extending from the umbilical area to the periphery and onto the spiral side. *Pu. obliquloculata* evolved from *Pu. primalis* via *Pu. praecursor* in the Early Pliocene. Although, this species is cosmopolitan, it is abundant in warm tropical waters. Maximum standing stocks of *Pulleniatina obliquiloculta* occur in the thermocline (Watkins et al., 1996). The species feeds on chrysophytes and diatoms.

Group 3: Temperate and subpolar group

***Globorotalia (Globoconella) puncticulata* (Deshayes)**

Plate 3, Figures: 1-5	
1932	*Globigerina puncticulata* Deshayes*,* Encyclopedie Methodique: Hist. Nat. des versa., Paris, Mme. V. Agasse, 2(2): 170.
1983	*Globorotalia (Globoconella) puncticulata*; Kennett and Srinivasan, Hutchinson Ross Publ. Co. U.S.A., p. 116, Plate 27, Figures 4-6.
1989	*Globorotalia puncticulata*; Hornibrook, Brazier and Strong, NZ. Geol. Surv. Paleont. Bull. 56: 134, Figure 29: 3a, b.

Remarks: *Globorotalia puncticulata* is characterised by its flattened to slightly convex spiral side and moderately arched aperture (Plate 3; Figures 1-3, 5). It has four chambers in its final whorl, increasing slowly in size (Plate 3; Figure 1). *Globorotalia puncticulata* is distinguished from *Gr. inflata* by having not less than four chambers and less inflation with a smaller aperture.

***Globorotalia (Globoconella) inflata* d'Orbigny**

Plate 3, Figures: 6-11	
1939	*Globorotalia inflata* d'Orbigny 1839; Foraminiferes des Iles Canaries In: Barker-Webb, P. and Berthelot, 2, Plate 2, Zool. p. 134, Plate 12, Figures 7-9.

Plate 2

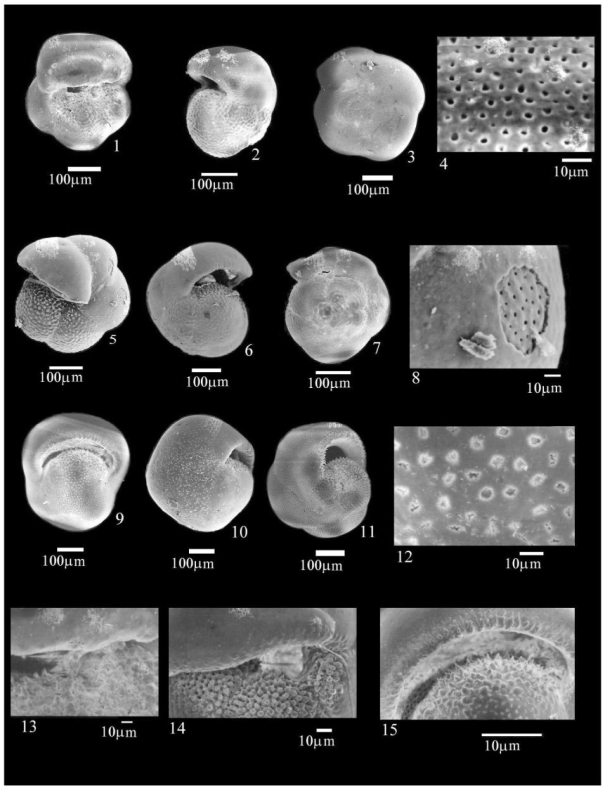

Plate 2: 1. *Pulleniatina primalis* Banner and Blow; apertural view, showing trochospiral to slightly streptospiral coiling and final chamber covering the umbilical area, Sample No. 122-762B, 11H-7, 28-30 cm. 2. Side view, Sample No. 122-763A, 9H-1, 75-77 cm. 3. Spiral view, showing smooth flat surface, Sample No. 122-762B, 11H-7, 28-30 cm. 4. Ultrastructure of side view, Sample No. 122-762B, 9H-1, 75-77 cm. 13. Ultrastructure of apertural view showing apertural details, 122-762B, 11H-7, 28-30 cm; 5. *Pulleniatina praecursor* Banner and Blow; apertural view, showing trochospiral to streptospiral coiling and last chamber covering the umbilicus. 6. Side view, showing the umbilical-extraumbilical aperture extending up to the periphery of the preceding whorl, Sample No. 122-762B, 7H-1, 75-77 cm. 7. Spiral view, Sample No. 122- 762B, 9H-7, 60-62 cm. 8. Ultrastructure of apertural view showing the development of cortex. 14. Ultrastructure of apertural view showing apertural details and pitted earlier chambers, Sample No. 122-762B, 7H-1, 75-77 cm. 9. *Pulleniatina obliquiloculata* (Parker and Jones); apertural view, showing streptospiral coiling and arched aperture extending from umbilical area to periphery and onto the spiral side, Sample No. 122-762B, 1H-1, 6-8 cm. 10. Side view. 11. Spiral view, showing smooth surface and pitted apertural area, Sample No. 122-763A, 1H-1, 0-2 cm. 12. Ultrastructure of apertural view. 15. Ultrastructure of apertural view showing apertural details, Sample No. 122-762B, 1H-1, 6-8 cm.

1971 *Globorotalia inflata*; Jenkins, N.Z. Geol. Surv. Paleont. Bull. 42: 116, Plate ll, Figures 282-287.

1983 *Globorotalia (Globoconella) inflata*; Kennett and Srinivasan, Hutchinson Ross Publ. Co. U.S.A., p. 118, Plate 27, Figures 7-9.

1989 *Globorotalia (Globoconella) inflata*; Hornibrook, Brazier and Strong, N.Z. Geol. Surv. Paleont. Bull. 56: 130-131, Figure 29: 4a, b.

Remarks: *Gr. (G.) inflata* evolved from its ancestor *Gr. puncticulata* by an increase in inflation of the test and a reduction in the number of chambers. *Gr. inflata* is characterised by three and half chambers and an

Plate 3

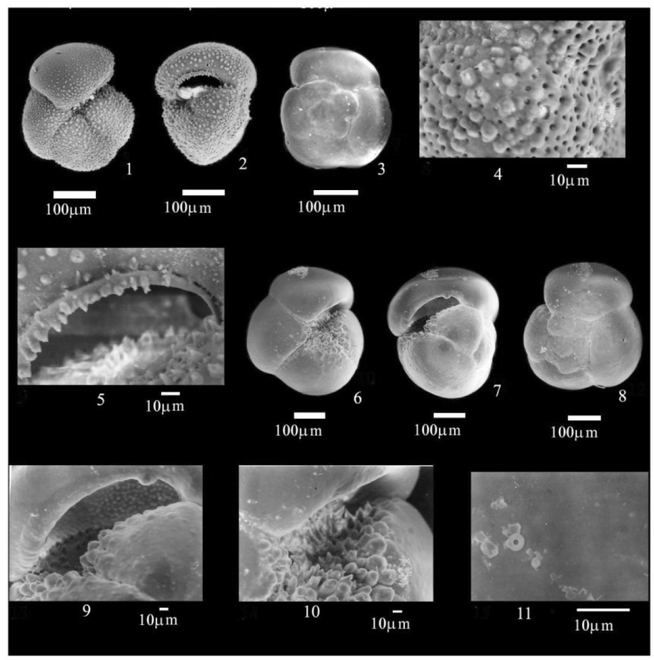

Plate 3: 1. *Globorotalia puncticulata* Deshayes apertural view, showing the chambers covered by dense pustules. 2. Side view, showing arched aperture bordered by a thick rim. 3. Spiral view, showing smooth hyaline surface. 4. Ultrastructure of apertural view showing pore and pustules details. Sample No. 122-763A, 1H-1, 76-78 cm. 5. Detailed ultrastructure of apertural view showing high arched aperture bordered by a thick lip, Sample No. 122-763A, 1H-1, 76-78 cm. 6. *Globorotalia inflata* d'Orbigny; apertural view showing inflated chambers with smooth surface ultrastructure and pustules over apertural area. 11. Side view, showing high arched aperture. 7. Spiral view, showing rounded periphery. 8. Ultrastructure showing the details of arched aperture, side view. 9. Surface ultrastructure of apertural view showing pustules. 10. Ultrastructure of apertural view showing the smooth surface. Sample No. 122-763A, 1H-1, 76-78 cm.

open arched aperture and rounded periphery with a hyaline test. This is a temperate species and abundant in subpolar oceans (Schiebel and Hemleben, 2017). *Globorotalia inflata* has often been found to occur in the vicinity of the hydrographic fronts (Chapman, 2010; Retailleau et al., 2011). In the present study, its abundance combined with *Globoconnela puncticulata* its ancestor, has been used to infer northward migration of Antarctic Polar Front during Quaternary.

Results

ODP Hole 763A in EIO contains a mixture of tropical and temperate planktic foraminifera. Tropical planktic foraminiferal assemblage (e.g., *Globigerinoides sacculifer, Gs. ruber, Gs. triloba*) dominates during the Quaternary. Climatically sensitive planktic foraminiferal assemblage shows a remarkable degree of down core variation in the relative abundances in the section. Almost 60 to 70 percent of the population was represented by 4-5 planktic foraminiferal species. The variation in the relative abundance of these species was used for paleoclimatic interpretation due to their importance as proxy indicators of paleo-latitudinal passive migration, paleo-water masses, past upwelling conditions and trophic levels in the ocean water column. *Gs. ruber* indicates that warm well-stratified water is exploited best by oligotrophic species (high abundance of *Gs. ruber*). The critical group used here to identify the northward migration of APF is temperate species group *Globoconella* consisting mainly of *Globorotalia* (*Globoconella) puncticulata* and *Globorotalia* (*Globoconella) inflata.* At ODP Hole 763A, the abundance curves of *Globoconella and Globigerinoides group* show opposite trends (Figure 3). The relative abundance of *Globigerinoides* shows a gradually decreasing trend from the beginning of Pleistocene. On the contrary, the temperate-subpolar group shows a gradual increase during the same interval (Figure 3). The relative abundance of *Globocobella* (temperate-subpolar group) shows a significant trend. Before 1.3 Ma, the species abundance is sporadic, however, after 1.3 Ma, the species show a gradually increasing amplitude of abundance, reaching maximum after the Mid-Pleistocene transition (Figure 3). The relative abundance of Mixed Layer Oligotrophic species groups shows a gradual decline in abundance from Early to Mid-Pleistocene. After Mid-Pleistocene, this group also shows a higher degree of fluctuation but remains low as compared to the Early Pleistocene (Figure 3).

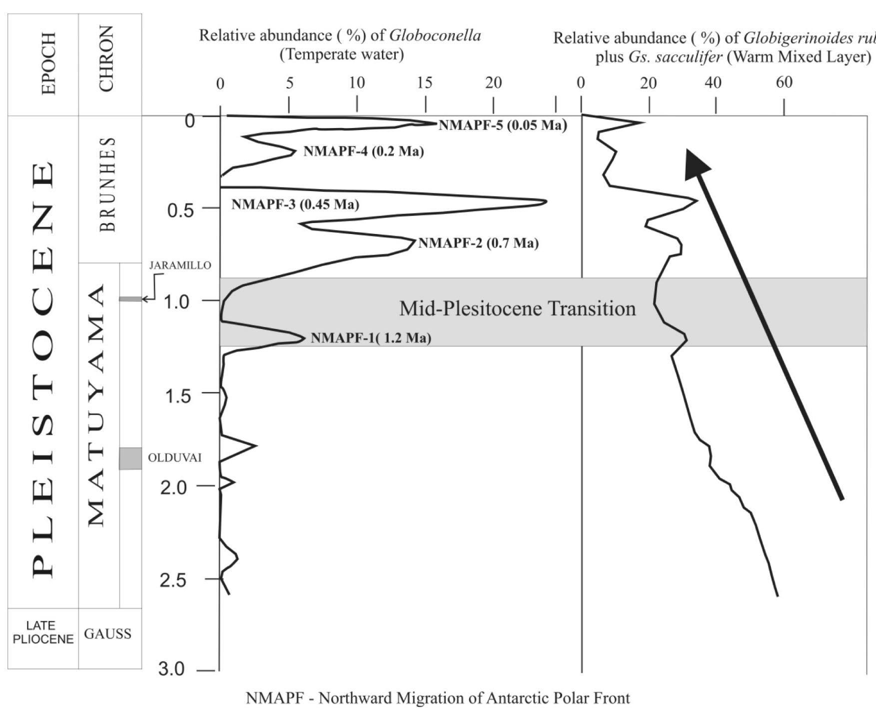

Figure 3: Relative abundance (%) of *Globoconella group* Vs. *Globigerinoides* group (*Gs. ruber* + *Gs. Sacculifer*) – Warm Mixed Layer Oligotropic species. Paleomagnetic stratigraphy after Tang (1992) and revised ages of the paleomagnetic events after Gradstein et al. (2012).

The comparison of the temperate group *Globoconella* with the tropical thermocline dweller *Pulleniatina* group shows significant trends (Figure 4). In general, the intervals of higher abundance of the temperate group are coincident with the low abundance of *Pulleniatina* and vice-versa. *Pulleniatina* also shows a higher amplitude of variation throughout the section. *Pulleniatina* is a typical thermocline dweller and is abundant in tropical waters. Its high abundance also indicates a well-developed thermocline and well-stratified water column. During the invasion of temperate group *Globoconella,* the *Pulleniatina group* shows decreased abundance indicating a loss of stratification of the water column. In general, the high abundance of *Pulleniatina* indicates increased strength of LC.

Discussion

Our record shows five intervals during the Quaternary when there is an increase in the abundance of temperate species *Globorotalia inflata* (Figures 3 and 4) at Hole 763A. These intervals occur at 0.05 Ma, 0.2 Ma, 0.45 Ma, 0.7 Ma and 1.2 Ma. The only plausible explanation for the increase in abundance of cool water species *Globorotalia inflata* is the expansion of the Antarctic Polar Front northward, causing the intensification of the West Australian Current. These intervals have been marked as NMAPF-1 to NMAPF-5 in ascending stratigraphic order (from oldest to youngest). Thus, in modern ocean waters, *Globorotalia inflata* is confined to cool subtropical and subpolar latitudes, was brought to the region of Hole763A (20ºS latitude) by the movement of cool water habitat towards low latitudes as a result of northward migration of APF. Cooling of the surface waters due to ice volume increase must have resulted in the lowering of sea-level and weakening of the Leeuwin Current leading to a decrease in the population of warm water species, which is very well reflected by a gradual decrease in the abundance of warm mixed layer oligotrophic species groups (Figure 3). The strength of the LC is controlled by the volume of ITF (Sinha et al., 2006; Spooner et al., 2011). Sinha

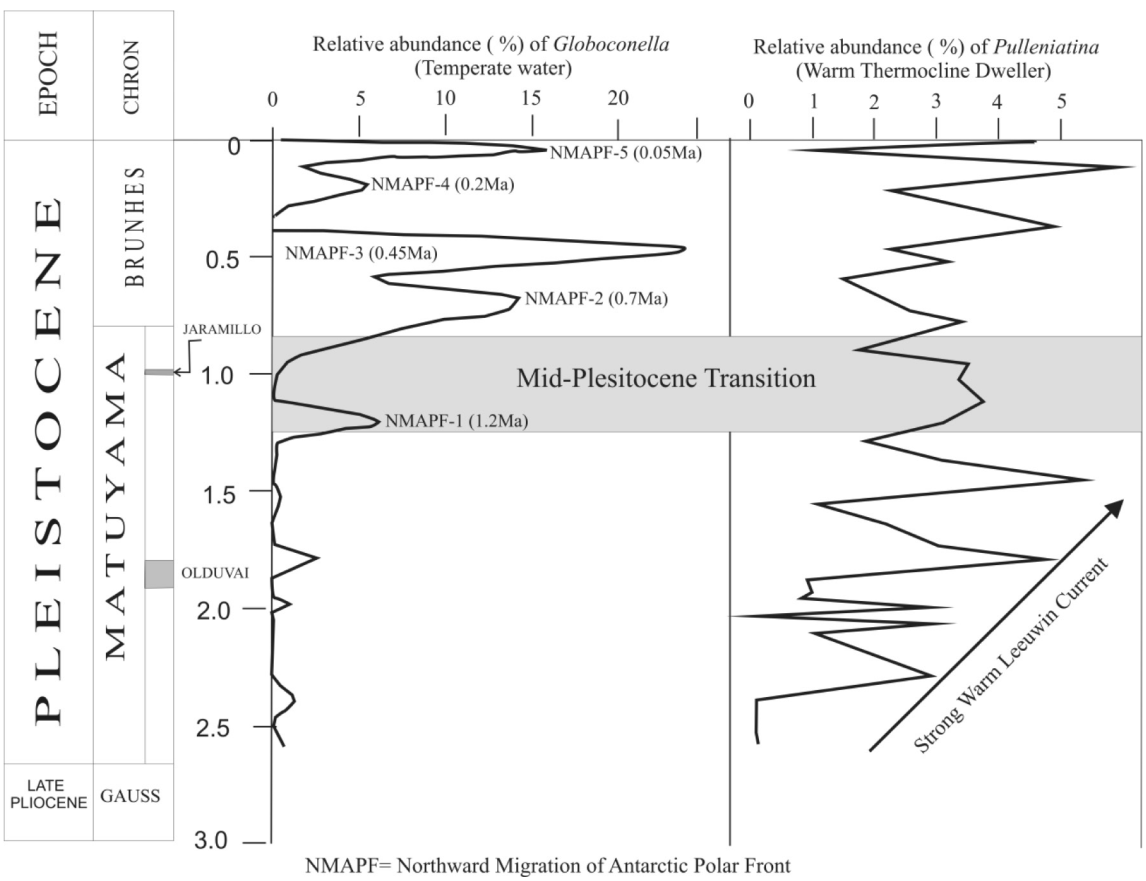

Figure 4: Relative abundance (%) of Globoconella group Vs. Pulleniatina (Indicator of the strength of warm Leeuwin Current). Paleomagnetic stratigraphy after Cheng Tang (1992) and revised ages of the paleomagnetic events after Gradstein et al. (2012).

et al. (2006) identified episodes of a reduction in ITF during quaternary and attributed the same to either lowering of sea level or a strong El Nino. Considering the modern oceanographic setup, the cooling of the surface waters at the region of ODP site 763A can occur by a northward shifting of the isotherms (Thiede et al., 1992) (subtropical convergence) due to episodic expansion in the Antarctic ice sheet and the resulting increase in the influence of the WAC.

The Five events show a substantial increase in the percentage frequency of temperate species *Globorotalia inflata* (reaching 15-20% of the total population). The increase in abundance has been remarkable after the Mid-Pleistocene transition. Thus, we agree with Ruddiman et al. (1986) that the shift in the fourfold increase of the amplitude of glacial/interglacial cycles was not abrupt but gradual. The high abundance events of *Globoconella* are here considered to represent ice volume increase when sea levels must have been considerably lower, reducing the strength of the LC, also indicated by the reduced abundance of *Pulleniatiina* (Figure 4) as a result of a reduction in Indonesian throughflow (Srinivasan and Sinha 1998, 2003; Sinha et al., 2006; Spooner et al., 2011) accompanied by equatorward wind-driven circulation and offshore Ekman transport. All these intervals of weak Leeuwin Current are also marked by a reduction in the total percentage of typical warm water species *Globigerinoides sacculifer* and *Globigerinoides ruber* besides *Pulleniatina* (Figure 4) usually brought by the LC at ODP Hole 763 (Figures 3 and 4). The weakening of the Leeuwin current would also affect the Sea surface temperature in the Indian Ocean as the Indonesian throughflow generally warms the Indian Ocean (Prell et al., 1979). Thus these cold intervals could probably be the intervals of considerable lowering of SST in the Indian Ocean and would have influenced Indian Monsoonal intensity. The weakening of the Leeuwin Current is also linked to the reduction in Western Pacific Warm Pool due to El Nino Events (Sinha et al., 2006). At this juncture, it can be concluded that during the weak Leeuwin Current, there is a possibility of the reduced intensity of winter Indian Monsoon (Sinha et al., 2006) due to a reduction in net heat input to the Indian Ocean through Indonesian throughflow. We also propose that the weakening of the warm LC is a member of the long feedback mechanism and adds to the climatic cooling of Antarctica by reducing the poleward heat supply. Snooper et al. (2011) believed that LC provides a conduit from the warmest oceanographic feature on Earth, the Warm Pool, to the Southern Ocean and may potentially aid in the reduction of Antarctic polar ice during intervals of its strengthening. We thus propose that the weakening of the Leeuwin Current would enhance Antarctic Ice Sheet expansion and create a positive feedback to further cooling.

Thus our study provides an understanding of the possible links between El Nino, Western Pacific Warm Pool, Indonesian throughflow, ocean circulation off Western Australia, Antarctic ice volume expansion resulting in northward migration of APF during Quaternary based on planktic foraminiferal population variation from Eastern Indian Ocean.

Conclusions

1. Five intervals in northward migration of APF has been detected during Quaternary in the Southeast Indian Ocean. These intervals at 0.05Ma, 0.2 Ma, 0.45 Ma, 0.7 Ma and 1.2 Ma represent increased strength of WAC and Antarctic Ice Cap expansion. These intervals also represent weak Leeuwin Current due to lowered sea level and the resultant reduction in ITF.
2. The weakening of the Leeuwin current would affect the sea surface temperature in the Indian Ocean as the Indonesian throughflow generally warms the Indian Ocean; thus, these cold intervals could probably be the intervals of considerable lowering of SST in the Indian Ocean and would have influenced Indian Monsoonal intensity.
3. The amplitude of glacial-interglacial intervals after the Mid-Pleistocene transition shows a gradual increase.
4. We propose that the weakening of the Leeuwin Current would enhance Antarctic Ice Sheet expansion and create positive feedback to further cooling by reducing the poleward heat supply.

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