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Deep-sea benthic foraminiferal response to the early Oligocene cooling: a study from the Southern Ocean ODP Hole 1138A

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Abstract

Ongoing rapid climate change has a major effect on marine fauna, and understanding these faunal changes analogous to future climatic periods is crucial. The Oligocene is commonly considered a critical transition period, linking the archaic world of the tropical Eocene and the more modern ecosystems of the Miocene. Here, we show the response of marine benthic foraminifera to the early Oligocene climatic changes at Ocean Drilling Program (ODP) Hole 1138A of the Southern Ocean (Indian Sector). We made use of the diversity parameters, the relative abundance of dominant benthic foraminifera, and isotopic data to understand past oceanographic changes. Our results suggest that the early Oligocene was an interval of unstable conditions dominated by the species of high oxygen, intermediate food supply, and well-ventilated, cold, corrosive bottom water conditions. The species richness abruptly decreases at the end of the studied interval, which shows the major Southern Hemisphere glaciation. During this time, species were characterized by relatively cold and carbonate-corrosive bottom water. Additionally, the present study of the benthic foraminiferal abundance and diversity indices reveals the cooling of the Southern Ocean at the early and late stages of the studied interval interrupted by a short-lived warming event. The study further enhances the understanding of paleo-marine ecology by evaluating the response of deep-sea benthic foraminifera to global climate change.

Introduction

The planet Earth has witnessed extreme climate variability in its geological past, especially during the Cenozoic, i.e., the last 65 Ma. Cenozoic climate history was marked by multiple climatic changes in which the transition from Greenhouse to Icehouse was major event. This transition was marked as the Eocene–Oligocene Transition (EOT) at ~ 34 Ma (Zachos et al. 2001; Coxall et al. 2005; Anagnostou et al. 2016; Tang et al. 2020). Additionally, the early Oligocene events (Oi-1) that are the peak timing of the Antarctic glaciation at the end of the EOT (DeConto and Pollard 2003) were subdivided into two positive excursions, Oi-1a and Oi-1b (Zachos et al. 1992). Although recent studies compile many small positive excursions in their high-resolution stable isotopic analysis, these previous studies record the long Oi-event from 33.6 to 25.2 Ma with small abrupt perturbations, namely,

Oi-1 (33.7 Ma and 33.4 Ma), Oi-1a (32.8 Ma), and Oi-1b (31.7 Ma) in the Southern Ocean (Miller et al. 1991; Pälike et al. 2006; Lee and Jo 2019; O'Brien et al. 2020). They suggest that a decrease in pCO_2 consumption caused the short-term recovery phase resulting from a decrease in the present ice sheet cover during the Oi-1a, also known as the earliest Oligocene Glacial Maxima (EOGM) (Coxall and Wilson 2011). Additionally, these events also coincide with low eccentricity. However, the high eccentricity level between these events suggests that total solar irradiance on the ground was slightly higher than the average (Lee and Jo 2019). Other studies explain that the observed isotopic excursions between Oi-1 (33.5 Ma) and Oi-1b (31.7 Ma) events are due to the release of a short-lived pulse of CO_2 at different phases due to leakage of fossil carbon (Coxall et al. 2018). These events are noticeable by observing the positive and negative excursions of oxygen isotope data ($\delta^{18}O$ values) that mark the periods of global cooling/increase in ice volume and warming, respectively. And the decrease in the oxygen isotopic values in the austral high latitude during the recovery phase could have been caused by regional sea ice melting.

These climatic/oceanographic changes affect the living hood of marine fauna heavily. Marine protists, especially

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benthic foraminifera, have proven to be good indicators of such climatic events. Benthic foraminifera occur in most marine environments, eutrophic to oligotrophic settings, flourishing in epifaunal and infaunal microhabitats, different oxygenated environments, and sustaining variable temperature and energy conditions; therefore, they are ideal for paleo-reconstruction of climatic variability and global ocean circulation (Gupta and Thomas 1999, 2003; Corliss et al. 2009; De and Gupta 2010; Singh et al. 2022). Previous studies indicate a significant relationship between deep-sea benthic foraminifera diversity and high latitudinal oceanic processes (Fischer 1960; Buzas and Gibson 1969; Thomas and Gooday 1996). The diversity in deep-sea benthic foraminifera depends on numerous attributes like heterogeneity in habitat, availability of food, temperature, and rate of predation (Kaiho 1994; Gooday et al. 2010). Several studies relate the significant and gradual change in the diversity of deep-sea benthic foraminifera to cooling deep water and an oxygenated environment ($CaCO_3$ corrosivity; Thomas 1992). Therefore, deep-sea benthic foraminifera witnessed significant oceanic and climatic turnover throughout the Cenozoic (Singh et al. 2012). Many recent and earlier studies provide critical information related to the distribution and ecological preferences of benthic foraminifera and the factors controlling it (Streeter 1973; Lohmann 1978; Corliss 1979; Thomas 1992; van der Zwaan et al. 1999; Gooday et al. 2000; Fentimen et al. 2020).

Deep-sea benthic foraminifera provide multiple ways to record climatic and oceanographic changes; however, isotopic records, faunal response, and diversity are the most distinct and reliable tools (Miller et al. 1991; Nomura1995; Singh and Gupta 2004; Zachos et al. 2001; Rai and Maurya 2009; Kumar et al. 2021). Deep-sea benthic foraminifera are also vital in deciphering oceanic environments due to their wide ecological adaptability (Schnitker 1974; Streeter 1973; Singh et al. 2021). The ecology of marine fauna gets severely affected due to the surface productivity and oxygenation of deep water throughout the Cenozoic (Rodrigues et al. 2018; Kender et al. 2019; Lu et al. 2020). During Cenozoic, the opening of the Drake Passage and the Tasman gateway caused a significant change in the oceanic circulation, triggering the initiation of ice sheet building over the Antarctic landmass, initiating the Antarctic Circumpolar Current (ACC) (Kennett 1977; Lawver and Gahagan 2003). The corresponding high thermal gradient between high and low latitudes and the decline in atmospheric $p\mathrm{CO}_2$ levels formed the continental ice sheet over Antarctica (DeConto and Pollard 2003; Katz et al. 2008; Bohaty et al. 2012; Anagnostou et al. 2016). The beginning of ACC and the growth of the ice sheet resulted in the Oligocene cooling more than the warmer Eocene, which affected the faunal abundance and diversity pattern at the high latitude (Pälike et al. 2012). Miller et al. (1991)

further represented Oligocene as an analog for the modern icehouse world with numerous episodes of the waxing and waning of ice sheets. Consequently, the early Oligocene marks a phase of noticeable change in the volume of deep water formation in the Southern Ocean (Takata et al. 2012).

The stable isotope analysis is an excellent indicator for observing and delineating the paleoclimate and paleoceanographic conditions of the deep marine (Armstrong McKay et al. 2016). Additionally, benthic foraminiferal carbon, as well as oxygen isotope records, forms a reliable chemostratigraphic tool for correlation and a proxy to constrain the past carbon cycle and the global climatic and oceanographic perturbations (Li et al. 2022). They have been used in many discussions of change in bottom water mass type (i.e., changeover from older bottom water to younger bottom water), global ice volume, deep-sea temperature, and local productivity (Zachos et al. 2001; Ravelo and Hillaire-Marcel 2007). Furthermore, the carbon isotopic values of deep-sea benthic foraminifera species and their microhabitat preferences also reveal the deep environmental condition. The δ^{13}C values of epifaunal taxa reflect the bottom water dissolved inorganic carbon and aging, and the infaunal taxa closely align with the more negative δ^{13}C values of pore waters (Ravelo and Hillaire-Marcel 2007). This correlation between isotopic composition and microhabitat preference indicates that the δ^{13}C values of deep-sea benthic foraminifera are directly/indirectly influenced by deep ambient environments and ecological preferences (Rathburn et al. 2000).

The Southern Ocean plays a crucial role in controlling the global climate due to its unique oceanography, which is a primary source of surface and deep cold water currents. The current oceanographic setting of the Southern Ocean is established after many tectonic and oceanographic changes in the past. It changed over time and became a primary source of cold deep water mass (Lawver and Gahagan 2003; Haumann et al. 2020). It behaves like a buffer zone of all the water masses; here, all the primary ocean water gets mixed and distributed throughout the world ocean by the water circulation process (thermohaline circulation). The mixing of water leads to a change in the behavior of water masses. So, the deep ocean currents play a vital role in maintaining the ocean's heat budget, while the surface water currents and the organisms control the atmospheric carbon dioxide level (Pascual et al. 2020). To understand paleoceanography, we can analyze the deep-sea sediments, elemental analysis (stable isotope analysis) of faunas, and morphological characteristics of fossils. Also, the quantitative study, i.e., census data, factor analysis, statistics, and time series analysis of fauna abundance, can be essential for studying paleoceanography and simple climatology. Thus, the combined study of micropaleontological and paleoceanographic data can predict future biotic and climatic advancements.

The present study focuses on understanding the diversity index pattern and the relative abundance of the early Oligocene deep-sea benthic Foraminifera at the ODP hole 1138A, the Southern Ocean (Indian Sector). Due to proto-ACC initiation, the influence of cold water profoundly affected the present study site, and its implications are recorded in the deep-sea benthic foraminifera. The mainstay of this paper remains to explore benthic foraminiferal response with the help of diversity patterns and stable isotope records in the Southern Ocean and its relative abundance in response to the ocean-driven diversification during the early Oligocene.

Physiology of the study area

The Kerguelen Plateau is a large igneous province in the Indian Sector of the Southern Ocean which extends from ~2300 km southeast between 46°S and 64°S toward Antarctica. The shallow submarine Kerguelen Plateau is divided into Northern Kerguelen Plateau (NKP), Central Kerguelen Plateau (CKP), and Southern Kerguelen Plateau (SKP) (Fig. 1a). The estimated age of SKP is ~80 to 100 Ma, whereas NKP has formed from ~65 Ma to recent (Frey et al. 2003). It is surrounded by Australian-Antarctic, Prince Elizabeth Trough, Enderby, and Crozet basins in the northeast, south, southwest, and north, respectively (Wang et al. 2016).

The Kerguelen Plateau creates an obstacle for the ACC, therefore diverting its route (Wang et al. 2016; Wright et al. 2018). ACC is the world's largest and most influential ocean current system driven eastward around Antarctica by prevailing westerly winds (Rintoul and Da Silva 2019). The main component of ACC is Circumpolar Deep Water (CDW). CDW is considered the highest volume water mass in the Southern Ocean and is a mixture of North Atlantic Deep Water (NADW) mass and Antarctic Bottom Water (AABW) mass, as well as some ocean fronts, i.e., Polar Front (PF), Subantarctic Front (SAF), and Southern Antarctic Circumpolar Current Front (SACCF) (Wright et al. 2018; Rintoul and Da Silva 2019) (Fig. 1a). The Kerguelen Plateau is influenced by the deep water components of the ACC that flow northward through the central part of the Kerguelen Plateau and then turn eastward toward the Australian-Antarctic Basin (Park et al. 2009). It accounts for two-thirds of the water masses driven by the ACC in all regions around Antarctica. The exact path of these water masses and fronts around the Kerguelen Plateau is still in debate (Park et al. 2009); however, the central Kerguelen Plateau is dominated by the CDW irrespective of the slight differences in PF and SACCF locations. The ODP Hole 1138A is directly under the influence of Circumpolar Deep Water (CDW) masses, and fronts are located south of the PF and north of the SACCF zones (Fig. 1a).
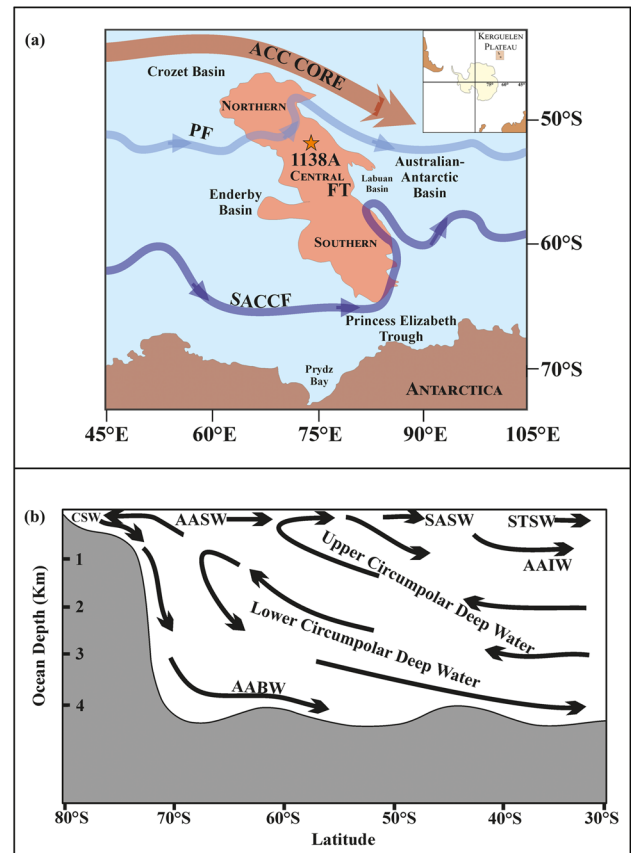

Fig. 1 **a** Outline map of Kerguelen plateau with the location of hole 1138A (star). The continuous dark and light lines with arrow directions show different oceanic currents on this site. The inset map shows a broad area view of the Southern Ocean with the location of the Kerguelen Plateau. **b** A general schematic section of meridional ocean water circulation of the Southern Ocean illustrates modern water circulation. Acronyms: SACCF, Southern Antarctic Circumpolar Current Front; PF, Polar Front; ACC, Antarctic Circumpolar Current; FT, Fawn Trough; AABW, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; CSW, Continental Shelf Water; AASW, Antarctic Surface Water; SASW, Subantarctic Surface Water; STSW, Subtropical Surface Water. Modified after Speer et al. (2000)

The modern Southern Ocean water circulation is governed by the cold deep and surface water masses (Fig. 1b). The Antarctic Bottom Water (AABW) dominates the bottom part of the Southern Ocean, while the middle water column is dominated by the Lower Circumpolar Deep Water (LCDW) and the Upper Circumpolar Deep Water (UCDW). The LCDW is colder than the UCDW, while AABW is the coldest water mass among them. Above the UCDW, a water mass known as Antarctic Intermediate Water (AAIW) dominates the Southern Ocean (Fig. 1b). In contrast, the surface regions are dominated by the different water masses, i.e., Continental Shelf Water (CSW) around the self-regions, then Antarctic Surface Water (AASW), then Subantarctic Surface Water (SASW), and the distal water mass known as Subtropical Surface Water (STSW). These water masses

are also cold water mass but differ by the properties of their temperature and density (Speer et al. 2000) (Fig. 1b).

Site location, materials, and methodology

ODP site 1138 (53° 33.100′S, 75° 58.490′E; water depth, 1141 m) was drilled in the middle of the Kerguelen Plateau during the ODP leg 183 (Fig. 1a). A total of 145 samples were used from sediment cores of 35R (1–5) to 36R (1–6) of 10 cm³ volume from Ocean Drilling Program (ODP), site 1138, Hole A, located in the middle of the central Kerguelen Plateau. The studied sample belongs to calcareous nanno-fossil zones NP21 to NP23, planktic foraminifera zones P18 and P19, and abyssal and bathyal benthic foraminifera zones AB8 and BB5. The calcareous nannofossil zones NP21 are defined by the last occurrences (LO) of *Discoaster saipanensis* and *Coccolithus formosus*, NP22 as determined by the disappearance of *Coccolithus formosus* and *Reticulofenestra umbilicus*, and zone NP23 is defined by LO of *Reticulofenestra umbilicus* and first occurrences of (FO) of *Sphenolithus ciperoensis* (Pälike et al. 2010; Gradstein et al. 2012). The planktic foraminifera zone P18 is demarcated by the LO of *Hantkenina alabamensis* and *Pseudohastigerina naguewichiensis*, and zone P19 is defined by the LO of *Pseudohastigerina naguewichiensis* and *Turborotalia ampliapertura* (Wade et al. 2011; Gradstein et al. 2012). The bathyal benthic foraminifera zone BB5 is demarcated by the LO of *Cibicidoides truncanus* and *Plectofrondicularia paucicostata* and/or *Bulimina jacksonensis*, while the abyssal benthic foraminifera zone AB8 is defined by the LO of *Nuttallides truempyi* and *Cibicidoides micrus* (Berggren and Miller 1989). The 16.8 m of this early Oligocene foraminifera bearing well-preserved nannofossil chalk deposited at a water depth of ~1141 m (Apel et al. 2002) is used for this study. The samples cover the early Oligocene age ranging from ~34 to ~31 Ma. Apel et al. (2002) reported that ~80 m of the Oligocene epoch occurs in the core from 183-1138A-23R to the base of core 183-1138A-36R. The laboratory work was followed per the standard protocol used by Gupta and Thomas (1999) and Rai and Maurya (2007). The sediment samples were wet-sieved at > 125 μm and dried overnight at 50 °C. After drying, a microsplitter was used to subdivide the sample to contain ~300 specimens of benthic foraminifera. All benthic foraminifera have been picked from the split fraction and mounted on an assemblage slide of 48 chambers. All the specimens were identified to species level using standard literature and catalog (e.g., Nomura 1995; Holbourn et al. 2013).

The picked specimens were further computed for Shannon–Weaver ($H(S)$), Hurlbert's (S_m), Fisher's alpha (α), and equitability (E') diversity indices (for more details, see Rai and Maurya 2009) and were plotted to study the relative abundance and the diversity pattern of the benthic foraminifera on the Kerguelen Plateau. The Shannon–Weaver diversity index explains how community individuals are distributed among existing species. So, it can also be called entropy rather than diversity. Instead of the number of species present in the community, the entropy provides the average level of uncertainty regarding the identity of a single species chosen from it (Bouchet et al. 2012). The Shannon–Weaver index defines each species dependent on its pi proportion, so the rare species make a small contribution, and Hurlbert's diversity index contributes to reducing different size samples to a standard size so that we make them comparable in terms of the number of species. Fisher's alpha (α) index explains the richness of the particular species in a sample, and equitability (i.e., evenness) describes high diversity when only a few species show higher abundance. It defines as the dependence of an individual on a species. Finally, species richness (S) has been used to understand the variation pattern in the species throughout the study interval. However, a variety of food resources may cause enhanced diversity. So, using the different diversity indices, we can explain the ecological preferences of the deep-sea benthic foraminifera. We have also calculated the sedimentation rate using depth and age data which remains constant (~20 m/Ma) at the study hole throughout the early Oligocene (Fig. 2).

The stable isotopic analysis was performed on benthic foraminifera species (*Cibicidoides* spp.). The carbon and oxygen isotope analyses of all the 140 samples from ODP Hole 1138A have been performed at the Stable Isotope Laboratory (SIL), Department of Earth Sciences, Indian Institute of Technology Roorkee, in India. Samples were ultrasonically washed using millipore water and dried in an oven at 50 °C. After drying, the samples were reacted with 104% H_3PO_4 at 70 °C in an automated ThermoFisher Kiel carbonate reaction device (Kiel IV) connected to MAT 253 plus mass spectrometer. Analytical accuracy and precision of measurements were observed by repeat analyses of laboratory standards calibrated by assigning $\delta^{18}O$ values of -28.23‰ to in-house standard (MERCK) and -23.19‰ to NBS18 and $\delta^{13}C$ values of -13.88‰ to in-house standard (MERCK) and -5.016‰ to NBS18. The internal and external measurement precision was 0.07‰ or better for both $\delta^{13}C$ and $\delta^{18}O$ in samples.

Results

Diversity indices are a well-established indicator of environmental changes and their possible effect on faunal abundance and diversity (Klootwijk and Alve 2022). The Shannon–Weaver ($H(S)$) index, Hurlbert's (S_{100}) diversity index, Fisher's alpha (α) index, and species richness (S) vary repeatedly with significantly high values at ~33.7, ~33.4, ~32.8,
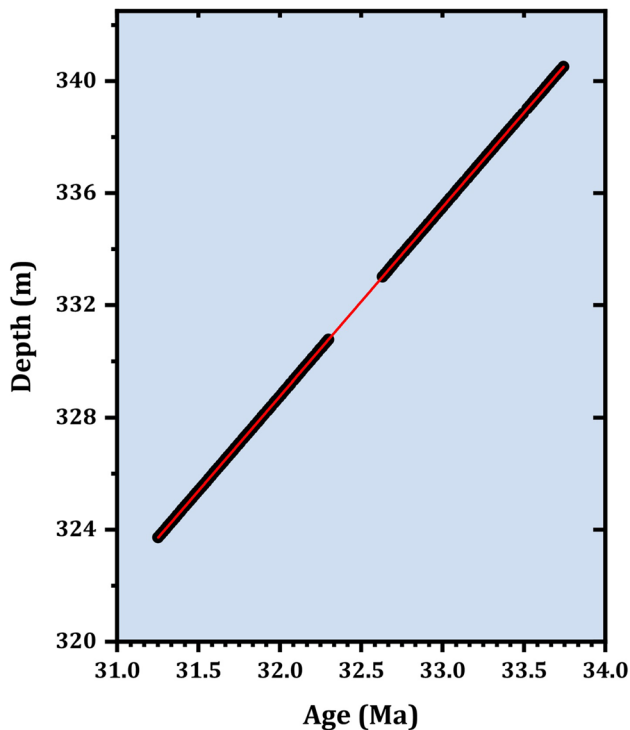
Fig. 2 An age-depth plot of hole 1138A and numerical ages after GTS 2012. The straight line (red) is the age vs. depth plot trend

and ~ 31.7 Ma (see Supplementary Materials (S1) for details and Fig. 3). Furthermore, the equitability (E′) shows comparatively less variability than the other diversity indices, and the values vary repeatedly (Fig. 3). The stable isotope values of *Cibicidoides* spp. provide quantitative estimation of the past climatic changes. Stable oxygen isotope data show a long-term decreasing trend from ~ 33.7 to ~ 33.1 Ma. The high values at ~ 33.7 Ma and ~ 33.4 Ma relate to the Oi-1 events (EOGM); furthermore, increasing trends in $\delta^{18}O$ at ~ 32.8 Ma and ~ 31.7 Ma coincide with Oi-1a and Oi-1b events, respectively, during the early Oligocene. The oxygen isotope ($\delta^{18}O$) shows positive and negative excursion from time to time; it shows 0.92‰ at ~ 33.7 Ma and increases up to 1.55‰ at ~ 33.7 Ma; again, it drops to 0.48‰ at ~ 33.8 Ma and increases up to 1.89‰ at ~ 33.4 Ma. This abrupt positive excursion at ~ 33.7 Ma and ~ 33.4 Ma correlates with the Oi-1 events. At the same time, the carbon isotope increased from 0.61 to 1.63‰ at ~ 33.6 Ma and ~ 33.4 Ma, respectively, while a positive excursion of 1.29‰ also has been noted at 33.7 Ma. The decreasing trend in $\delta^{18}O$ values from ~ 33.7 to ~ 33.6 Ma and ~ 33.4 to ~ 32.8 Ma is considered a recovery phase. Another positive excursion of $\delta^{18}O$ is recorded at ~ 32.6 Ma and ~ 31.6 Ma with isotopic values of 1.81‰ and 2.58‰, respectively. These positive excursions are closely related to the Oi-1a and Oi-1b events

during the early Oligocene. The carbon isotopic values also fluctuated from a minimum value of 0.20‰ to the highest value of 1.54‰ at ~ 32.1 Ma and ~ 31.6 Ma, respectively (Fig. 3; see S1 for details).

We also made use of the relative abundance of seven different species of deep-sea benthic foraminifera within the studied time interval. Here, we have selected high abundance species (> 5% at least in 3 samples) to describe the deep ocean environments. The benthic foraminifera species *Oridorsalis umbonatus* is abundant throughout the early Oligocene but attained a maximum at ~ 31.8 Ma, ~ 32.7 Ma, and from ~ 33.4 to ~ 33.7 Ma (Table 1, Fig. 4). The second species, *Nuttallides umbonifer*, is also present throughout the earliest Oligocene interval; however, it is dominant from ~ 33.4 Ma, ~ 32.8 Ma, and ~ 31.6 Ma (Fig. 4, Table 1). The third species, *Cibicidoides kullenbergi*, exhibits a significant high from ~ 33.4 to ~ 32.6 Ma and from ~ 32.0 to ~ 31.7 Ma; the latter peak is not perpetual (Table 1; Fig. 4). The fourth species, *Pullenia bulloides*, occurs throughout the studied interval with a significant increase from 33.3 Ma, which attains the maximum at ~ 32.8 Ma (Fig. 4). The fifth species, *Globocassidulina subglobosa*, increases upward throughout the interval; however, it is abundant at ~ 33.4 Ma and ~ 32.8 Ma and attains the maximum from ~ 31.5 to ~ 31.3 Ma (Table 1, Fig. 4). The sixth species, *Astrononion echolsi*, exhibits a decreasing trend from ~ 33.7 to ~ 33.4 Ma and has maximum abundances recorded at ~ 31.9 Ma (Fig. 4; Table 1). The last species, *Uvigerina peregrina*, showed maximum abundance at ~ 32.2 Ma and ~ 31.6 Ma (Fig. 4, Table 1; for details, see S1).

Discussion

Paleoceanography and paleoenvironmental reconstructions based on fossil record profoundly rely on new proxies and their correlation. Geochemical data (e.g., stable isotope data and trace element data), faunal species diversity, and abundance are essential to understanding past deep marine environmental conditions. Our deep-sea benthic foraminifera records at ODP Hole 1138A showed significant variation, coinciding with the changes in marine temperature, ocean productivity, global ice volume, and global ocean circulation. The initiation of proto-ACC and the influence of cold water profoundly affected our study site. These changes are observed at this site, captured by the deep-sea fauna (benthic foraminifera). A correlative study between benthic foraminiferal species diversity and the relative abundance of dominant species helps us understand the ocean-driven
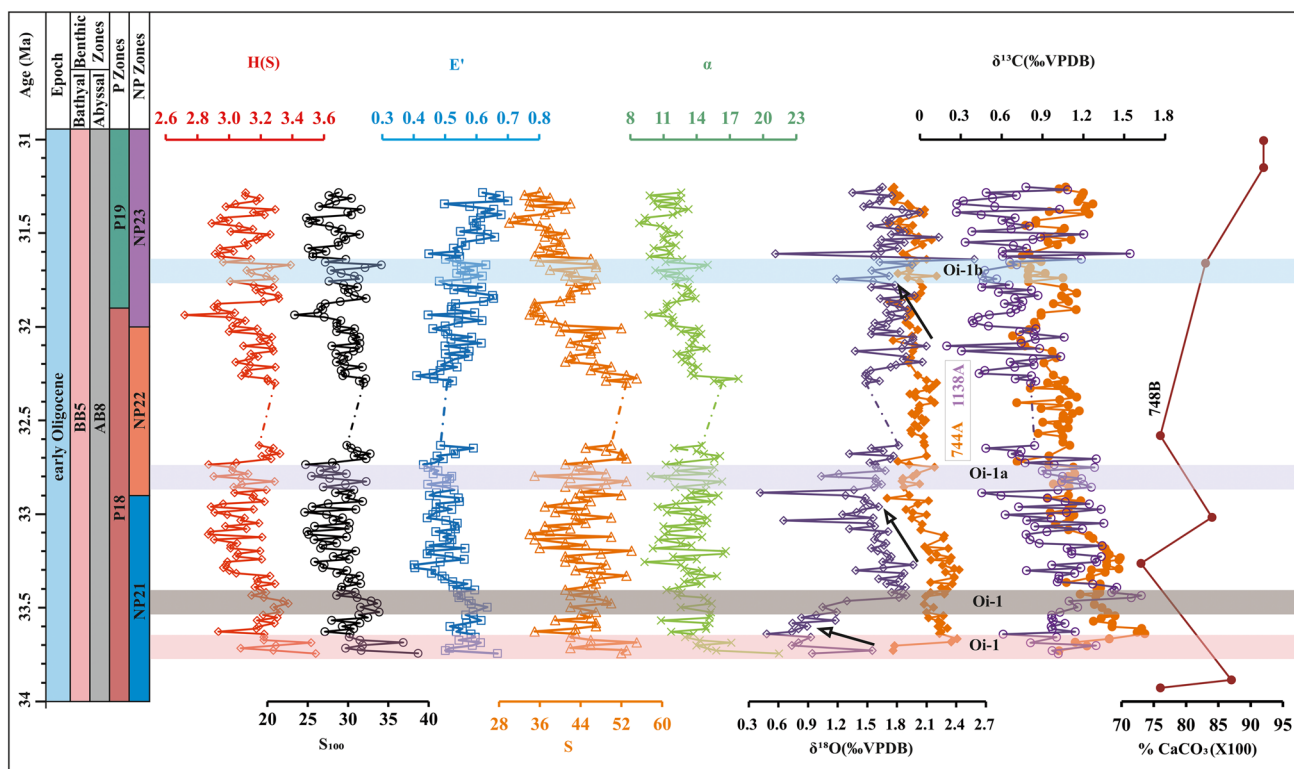
Fig. 3 Time series plot of species diversity at ODP hole 1138A of Shannon–Weaver ($H(S)$) index, Hurlbert's (S_{100}) diversity, equitability (E'), species richness (S), and Fisher's alpha (α) index with stable isotope data. Highlighted portion in the figure shows early Oligocene cooling events Oi-1 (pink and brown color), Oi-1a (violet color), and Oi-1b (blue color). The black arrow shows the recovery phase. Abyssal (AB) and bathyal (BB) benthic foraminiferal zones of Berggren and Miller (1989) are correlated with planktic (P) foraminiferal zones after Wade et al. (2011) and calcareous nannofossil (NN) zones after Pälike et al. (2010). Isotope data is from ODP site 744A (Salamy and Zachos 1999) with Bulk $CaCO_3$ contents from ODP site 748B (Zachos et al. 1992). Numerical ages after GTS 2012

Table 1 Dominant species of deep-sea benthic foraminifera (species with ≥ 10% abundance) at ODP hole 1138A with their environment preferences during correlative ages

| Species	Microhabitat	Environmental preferences	Age of abundance
Oridorsalis umbonatus	Shallow infaunal	Low temperature, high oxygen, variable food supply	~ 33.7 to ~ 33.4 Ma, ~ 32.7 Ma, and ~ 31.8 Ma
Nuttallides umbonifer	Epifaunal	Low temperature, high oxygen, low food supply, corrosive bottom water	~ 33.4 Ma, ~ 32.8 Ma, and ~ 31.6 Ma
Cibicidoides kullenbergi	Epifaunal	High temperature, less oxygen, intermediate food supply	~ 33.3 to ~ 32.6 Ma and ~ 32.0 to ~ 31.4 Ma
Pullenia bulloides	Shallow infaunal	Low temperature, high oxygen, variable food supply	~ 33.3 to ~ 32.8 Ma
Globocassidulina subglobosa	Shallow infaunal	High temperature, oxic conditions, low to the intermediate food supply	~ 33.4 to ~ 32.8 Ma and ~ 31.5 to ~ 31.3 Ma
Uvigerina peregrina	Infaunal	High temperature, OMZ species, irrespective of food supply	~ 32.2 Ma and ~ 31.6 Ma
Astrononion echolsi	Shallow infaunal	Low temperature, intermediate oxygen, low organic carbon	~ 33.6 Ma and ~ 31.9 Ma
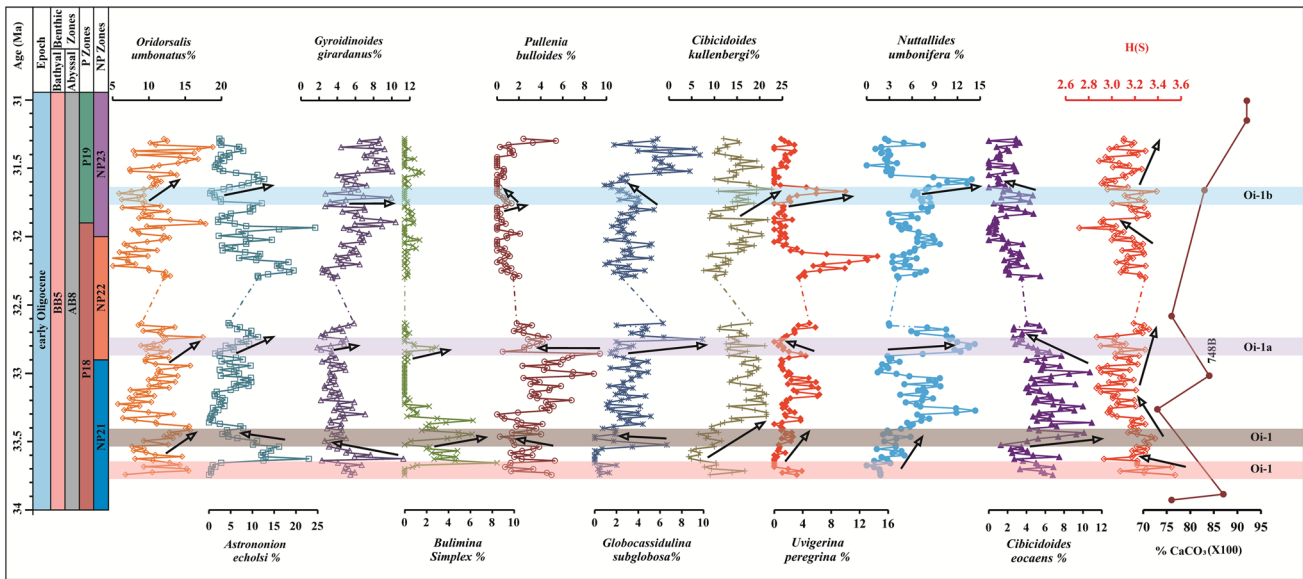
Fig. 4 Time series plots of the relative abundance of dominated benthic foraminifera at ODP hole 1138A with Bulk CaCO$_3$ contents from ODP site 748B (Zachos et al. 1992). Highlighted portion in the figure shows early Oligocene cooling events Oi-1 (pink and brown color), Oi-1a (violet color), and Oi-1b (blue color). The black arrow shows increasing and decreasing trends of the Shannon–Weaver diversity index and species abundance. Abyssal (AB) and bathyal (BB) benthic foraminiferal zones of Berggren and Miller (1989) are correlated with planktic (P) foraminiferal zones after Wade et al. (2011) and calcareous nannofossil (NN) zones after Pälike et al. (2010). Numerical ages after GTS 2012

diversification in this faunal group in the Southern Ocean (Indian Sector) of the early Oligocene.

Environmental preferences of deep-sea benthic foraminifera in the Southern Ocean

Oridorsalis umbonatus is an opportunistic, shallow infaunal dweller species that can live in various marine environments (Fig. 4). This taxon prefers both eutrophic and oligotrophic settings, and the depth preference is known from lower bathyal to abyssal in the Antarctic Ocean (Uchio 1960), the Atlantic Ocean (Lohmann 1978; Streeter and Shackleton 1979), the Indian Ocean (Corliss 1979; Gupta 1994), and the Sulu and South China Sea (Miao and Thunell 1993). *O. umbonatus* dominates above the carbonate lysocline around Antarctica, which may point toward the presence of AABW or similar water mass environments (Mackensen et al. 1990). Some researchers mentioned it as an indicator of oligotrophic settings with carbonate-corrosive bottom currents found in lower temperatures and intermediate oxygen conditions (Bremer and Lohmann 1982; Nomura 1991). The association of *O. umbonatus* with high carbonate levels and low carbon is also reported from the deep bottom water of the Sulu Sea (Miao and Thunell 1993). *O. umbonatus* choose well-oxygenated, low organic carbon environments associated with regions of low surface productivity (Burke et al. 1993), whereas Woodruff (1985) noticed that *O. umbonatus*

is more related to regions with high productivity in the surface area, and Kaiho (1999) reported suboxic bottom waters. The abundance of this species is higher at the studied site 1138A during the early Oligocene time (~ 33.7 to ~ 33.4 Ma; Table 1 and Fig. 4), reflecting a colder water mass than the Eocene. Additionally, a higher abundance of this species was also observed at DSDP sites 516 and 522 in the South Atlantic; ODP sites 744 and 689 in the Southern Ocean; and ODP sites 1218, 1219, and U1334 in the eastern equatorial Pacific Ocean during the early Oligocene interval (Tjalsma 1983; Coxall and Wilson 2011; Takata et al. 2012). During the early stage of the Oligocene, the dominance of the species was slightly higher than the other species as the nutrient condition was possibly high and well-oxygenated conditions have been reflected by this species.

Nuttallides umbonifer is an epifaunal species that live in various environments and is associated with AABW (Fig. 4; Streeter 1973; Lohmann 1978; Bremer and Lohmann 1982; Mackensen et al. 1995). The presence of this species in the ocean indicates a cold, carbonate-corrosive oligotrophic environment between CCD and calcite lysocline deep water mass (e.g., AABW or its near equivalents) (Bremer and Lohmann 1982; Woodruff 1985; Mackensen et al. 1990, 1995; Nomura 1995; Bordiga et al. 2015). A close association between relatively high oxygenated, low temperature, and low food supply in the deep bottom water of this species is reported in the Indian Ocean (De and Gupta 2010; Singh et al. 2012). It is observed that *N. umbonifer* is an indicator

of a low-productivity oceanic regime, while, Woodruff and Savin (1989) reported it as a high-productivity surface area species. It is a characteristic benthic fauna of all the major ocean abyssal zone of the Pacific Ocean, the Atlantic (Schnitker 1974; Streeter 1973; Lohmann 1978; Streeter and Shackleton 1979), and the Indian Oceans (Corliss 1983). The high abundance of this species dominated during the early Oligocene at ~ 33.4 Ma, ~ 32.8 Ma, and ~ 31.6 Ma at the studied site 1138A, indicating a cold, carbonate-corrosive, relatively high oxygenated, and low food supply environment at the studied site in the Southern Ocean. However, this species achieved dominance during Oligocene in the South Atlantic Ocean at DSDP sites 522 and 516 and became an important taxon (Tjalsma 1983). Other than that, higher abundance of this species was also observed at ODP sites 744 and 689 in the Southern Ocean and 1218, 1219, and U1334 in the eastern equatorial Pacific Ocean (Nomura 1995; Takata et al. 2012).

Cibicidoides kullenbergi species have preferred a substrate with low organic carbon content below the low surface productivity area (Burke et al. 1993). The Cape region also reported that this species has low carbonate contents suggesting higher carbonate dissolution rates (Eberwein and Mackensen 2006). This species is associated with the high $\delta^{13}C$ suggesting a low carbon influx to the seafloor (Nomura 1995). The stratigraphic distribution of *C. kullenbergi* is confined to oxygen-rich and nutrient-poor North Atlantic Deep Water (NADW) (Lohmann 1978; Mackensen et al. 1995). The warm water association of this species is noted in the Pacific Ocean (Woodruff 1985), the Atlantic Ocean (Lutze 1979), and the Indian Ocean (Maurya and Rai 2006). These species got their higher abundance during the middle age of the early Oligocene at ~ 33.3 to ~ 32.6 Ma and ~ 32.0 to ~ 31.4 Ma as the deep water condition changed to warmer for a brief interval possibly due to the release of a short-lived pulse of CO_2 at different phases due to the leakage of fossil carbon (Coxall et al. 2018). This species indicates an oxygen-rich but nutrient-poor marine environment. The abundance of this species dominated during the early Oligocene at the studied site 1138A, indicating a short interval of relatively high temperature, less oxygenated, and intermediate food supply environment at the studied site in the Southern Ocean. However, this species achieved dominance during the late Oligocene but was less or absent during the early Oligocene in the South Atlantic Ocean at DSDP sites 522 and 516 and became a vital taxon (Tjalsma 1983). Additionally, a higher abundance of this species was also observed during the late Oligocene, while a low abundance of this species was recorded during the early Oligocene at ODP sites 747, 757, and 758 in the eastern Indian Ocean (Nomura 1995).

Pullenia bulloides is a shallow infaunal species that have well-established environmental preferences. It has shown the association with low temperature and highly oxygenated deep water with a top to the moderate influx of nutrient supply (Maurya and Rai 2006). Gupta and Thomas (1999) observed this species as an indicator of the average flux of organic in poorly ventilated bottom water conditions. This species allied with low oxygen conditions with intermediate to the high flux of organic matter in the Indian Ocean (Gupta et al. 2006). *P. bulloides* may be associated with areas of low surface productivity and, therefore, a small flux of organic matter to the seafloor (Burke et al. 1993), and observed the abundant occurrence of this species in postglacial sediments on the Ontong Java Plateau. *P. bulloides* is a representative species associated with high-salinity NADW in the southwest Indian Ocean (Corliss 1983). It has also been associated with assemblages that indicate the cold, low to intermediate organic flux, strongly pulsed, and high seasonality in the Indian Ocean (Gupta and Thomas 2003). In contrast, Bhaumik et al. (2007) found that this species was associated with NADW-like water mass with high oxygen and carbon at northeastern Indian Ocean DSDP site 216. This species is observed with glacial/interglacial intervals, which indicates the species can survive in low dissolved oxygen in the northwestern Atlantic Ocean. At the studied site, a higher abundance of *P. bulloides* was recorded during the earliest Oligocene at ~ 33.3 to ~ 32.8 Ma. The abundance of this species shows the cold with a highly oxygenated deep-sea environment. Additionally, this species commonly occurred during the early Oligocene in the South Atlantic Ocean at DSDP sites 522 and 516 but not as a vital taxon (Tjalsma 1983).

Globocassidulina subglobosa is an opportunistic cosmopolitan infaunal species associated with several different water masses with a wide bathymetry and long stratigraphic distributions. Species feeds on a fresh phytodetritus (Giusberti et al. 2016). It is reported from ODP site 758 in the eastern Indian Ocean as cold water dwelling and high food exploiting taxa (Nomura 1995). A high abundance of this species is linked to the strengthening of ocean bottom currents (Nagai et al. 2009). Takata et al. (2012) reported it as indicator of well-oxygenated bottom water with high organic carbon influx to the bottom of ocean. Fariduddin and Loubere (1997) reported that the association of *G. subglobosa* with NADW indicates low-productivity species in the Atlantic Ocean. As mentioned above, the association of this species with high seasonal food pulses is the characteristic feature this taxon (Eberwein and Mackensen 2006). High abundance of this taxon was also reported from submarine ridges and hills of the South Atlantic with an oligotrophic water mass of Circumpolar Deep Water (Mackensen et al. 1995). Gupta and Thomas (2003) have suggested that *G. subglobosa* may flourish in oligotrophic condition of the northeastern and southeastern Indian Ocean. It has also been reported that warm water condition is unfavorable to this species, and it has been observed to prefer cold water

masses (Miao and Thunell 1993). Corliss (1979) reported it in close association with AABW. In this study, the abundance of *G. subglobosa* is high at ~ 33.4 to ~ 32.8 Ma in the early and ~ 31.5 to ~ 31.8 Ma of later stages of the studied interval (Table 1; Fig. 4) which indicates relatively colder bottom water. Additionally, a common abundance of this species was also observed at DSDP sites 516 and 522 in the South Atlantic; ODP sites 1218, 1219, and U1334 in the eastern equatorial Pacific Ocean; and ODP sites 747, 757, and 758 in the eastern Indian Ocean during the early Oligocene interval marked presence of cold bottom water (Tjalsma 1983; Nomura 1995; Takata et al. 2012).

Astrononion echolsi (synonymous with *Astrononion umbilicatulum*, also close ally with *Astrononion pusillum* Hornibrook) is a shallow infaunal benthic foraminifera, whose ecological information is minimal. *A. echolsi* is reported as a common species at ODP site 748 (Kerguelen Plateau) throughout the early Oligocene (Mackensen and Berggren 1992), and the first occurrences are recorded in the lower Oligocene by Nomura (1995). This species prefers a low-productivity zone on the Ontong Java Plateau (Burke et al. 1993). The association of this species with the lowest primary productivity and well-ventilated water is also reported in the Gulf of Aden (Almogi-Labin et al. 2000). This species prefers high-saline waters in the Red Sea (Gupta 1994). Singh and Gupta (2004) have mentioned that this species is associated with low organic influx and the well-ventilated deep marine environment in the southeastern Indian Ocean. *A. echolsi* is a representative taxon associated with hot and high-salinity NADW in the southwest Indian Ocean (Corliss 1983). ODP sites in the Indian Ocean reported that the occurrence of *A. echolsi* is widespread and influenced by the AABW (Corliss 1983; Nomura 1995). It is also reported from the Polar Front region of the southwest Atlantic Ocean (Mead and Kennett 1987). Miao and Thunell (1993) described its close association with oxygenated bottom water with low organic carbon influx of the South China Sea. The peak abundance of this species recorded at ~ 33.6 Ma and ~ 31.9 Ma at the studied site indicates higher production of the cold bottom water in the Southern Ocean. Additionally, this species was reported as common faunal element at ODP sites 1218, 1219, and U1334 in the eastern equatorial Pacific Ocean and ODP sites 747, 757, and 758 in the eastern Indian Ocean during the Oligocene at marked intervals (Nomura 1995; Takata et al. 2012).

Uvigerina peregrina is an infaunal species commonly described as a high-productivity taxon. The occurrence of *U. peregrina* in the Southeast Indian Ocean suggests the existence of Circumpolar Deep Water (Corliss 1983). The environmental preferences of this species are high organic carbon and low oxygen, commonly occurring below the upwelling zone, including the area of high concentration with bacteria, meiofauna, and exoenzymes (Altenbach and

Sarnthein 1989). Jannink et al. (1998) proposed that this taxon can survive in low food supply and organic areas without any relation to oxygen paucity. Geslin et al. (2004) reported that the responses of this species vary with the oxygen condition of the deep-sea environment. A close relation of *U. peregrina* with the continuous organic carbon flux irrespective of the oxygen level was also reported southern Atlantic Ocean (Mackensen et al. 1995). The dominance of this species is higher at the Oxygen Minimum Zones (OMZ) reported from the northwestern Indian Ocean (Hermelin and Shimmield 1990), the northeastern Indian Ocean (Arabian Sea) with high organic flux (Jannink et al. 1998). De and Gupta (2010) reveals that the species *U. peregrina* is associated with warm bottom water, intermediate to high organic carbon, high surface productivity and low oxygen level in the northwest Arabian Sea. At ODP Hole 1138A, the *U. peregrina* encountered the warm water interruptions at ~ 32.2 Ma and ~ 31.6 Ma (Table 1; Fig. 4). In comparison, this species is reported to be less common or absent at ODP sites 747, 757, and 758 in the eastern Indian Ocean during the Oligocene interval (Nomura 1995).

The relative abundance of species has been also correlated with diversity indices which change their abundance as the temperature fluctuation occurs at the bottom of the ocean (Shimadzu et al. 2013). The successive peaks of *P. bulloides* and *N. umbonifer* (Fig. 4) indicate a change in the environment from the well-ventilated low organic flux to the dominance of carbonate-corrosive AABW (Nomura 1995; Bordiga et al. 2015). The ups and down in the diversity parameters from ~ 33.7 Ma to ~ 33.1 Ma suggests that conditions were unstable during this interval. This event coincides with one of the most abrupt changes during the earliest Oligocene between ~ 33.7 to ~ 33.4 Ma, known as the EOGM (Oi-1, Zachos et al. 1993). The oxygen isotope ($\delta^{18}O$) values also show an abrupt increase from 0.48 to 1.89‰ during this interval (Fig. 3). The change in isotopic values during this interval demonstrates that the continental ice suddenly appeared or increased on the Antarctic continent with a decrease in regional sea surface temperature (Kennett and Shackleton 1976; Zachos et al. 2001; Coxall et al. 2005; Lee and Jo 2019). This glaciation event was a result of the establishment of strong thermal isolation between the high (Antarctic continent) to the low latitudes and followed by opening of the Drake Passage and the establishment of the Antarctic Circumpolar Current (ACC) (Mackensen and Ehrmann 1992; Zachos et al. 2001; Lawver and Gahagan 2003; Livermore et al. 2007; Sijp et al. 2009), and hopefully polar front around Antarctica was more stronger at ~ 33.4 Ma. The cooling of the Antarctica as well as surrounding area by diverting warm western boundary currents away from the high southern latitudes (Salamy and Zachos 1999) further facilitated the ice buildup in the southern pole. The first appearance of species *A. echolsi* is

recorded at this interval (Fig. 4), which showed significant abundance during the Oi-1, and a similar faunal event was also noted by Nomura (1995). This event occurred just after the EOT indicating a profound global change from a warm Eocene greenhouse to an icehouse Oligocene. The carbon isotopic (δ^{13}C) record also shows an abrupt increase from 0.61 to 1.63‰. The increment in δ^{13}C during this interval demonstrates as increased regional productivity. *O. umbonatus* showed a significant peak with a higher diversity index during the Oi-1 and Oi-1a interval (Fig. 4). This species also indicates the increased influence of AABW, intermediate to the high food supply, and presence of cold deep water in the Southern Ocean of the Indian sector. However, Oi-1 and Oi-1a were a phase change environment of the deep-sea benthic foraminifera, which maximizes surface water productivity in the Southern Ocean (Salamy and Zachos 1999; Diester-Haass and Zahn 2001).

The Shannon–weaver index [H(S)], Hurlbert's diversity index (S_{100}), species richness (S), equitability ($E\prime$), and fisher's alpha index (α) showed high values at ~ 33.7, ~ 33.4, ~ 32.8 and ~ 31.7 Ma. Also, a decreasing trend of species richness and fisher's alpha index have been observed after ~ 31.7 Ma. The variability in diversity indices express the change in the bottom water conditions from warm to cold and vice versa. This time interval coincides with the progressive influence of ACC, AABW, and AAIW due to opening Drake Passage which is responsible thermal isolation of Antarctic landmass from rest of the world. The ACC intensified, and AAIW flow increased during this interval, which enhanced erosional strength (Pagani et al. 2000) and was marked by numerous hiatuses that appeared on Kerguelen Plateau (Barker and Burrell 1977). The dotted line marks hiatus at the study site (Fig. 3) are indicative of intense circulation due production of AABW. Again, the parameters H(S), S_{100}, S, E′, and α decrease up to ~ 33.1 Ma after that, showing a gradual increase from ~ 33.1 Ma to 32.8 Ma. After 32.8 Ma, all the diversity indices showed a constant increase up to 32.0 Ma, and after that, a sharp decrease in the parameters followed by a high peak at ~ 31.7 Ma and an increasing pattern up to ~ 33.1 Ma, coinciding with the Early Oligocene Postglacial Maximum (EOPM; 33.1 Ma to ~ 32.6 Ma) (Coxall and Wilson 2011). These positive excursions of the different diversity indices indicate the opening of Drake Passage and the abrupt formation of the Antarctic ice sheet, while the negative peaks show the deglaciation period (Miller et al. 1991; Pälike et al. 2006; Lee and Jo 2019) that correlated with short warming intervals.

During EOGM, the marine environment gradually changed, and conditions became more stable as the species diversity also showed increased values (Fig. 3), coinciding with decreased productivity. δ^{18}O values of *Cibicidoides*

spp. at ~ 33.0 Ma, a recovery phase may be triggered by a deglaciation event, causing a rising sea level. The carbon isotopic values also show decreasing δ^{13}C values (Fig. 3). This event also marks the high abundance of *C. kullenbergi,* with an increase in the number of species as well as species diversity parameters. However, a brief interval of increased abundance of *N. umbonifer* at ~ 32.8 Ma was noticed (Fig. 4). This sudden increased abundance of *N. umbonifer* indicates the presence of more corrosive bottom waters or less arrival of food at the seafloor or both after the second step of cooling (Fig. 4). At the same time interval (~ 32.8 Ma), the species *O. umbonatus* shows a high abundance (~ 18%), representing the cold and corrosive environments with high oxygen bottom conditions due. The low occurrence of *G. subglobosa* from ~ 32.2 Ma to ~ 31.5 Ma indicates the expansion of the Oxygen Minimum Zone (OMZ), eutrophic, anoxic, and stagnant (Fig. 4). *U. peregrina* (Fig. 4) is inferred to indicate the warm deep water and intermediate to high organic carbon, high surface productivity, and low oxygen level associated with OMZ. It was shown in high abundance from 32.2 to 31.5 Ma. Simultaneously, higher occurrence of these species indicates a mixed type of deep environment. After ~ 32.2 Ma, it is observed that the species diversity index drastically decreases with an increase in δ^{13}C values indicating higher productivity (Fig. 3). This event is recorded in the species *A. echolsi* and *O. umbonatus* (Fig. 4). This event at ~ 31.7 Ma was also known as Oi-1b (Lee and Jo 2019) in Oligocene. The high abundance of *G. subglobosa* from ~ 31.5 to ~ 31.2 Ma indicates a well-oxygenated, warmer temperature with a low to intermediate food supply (Fig. 4). This interval was recognized as the increasing δ^{13}C with diversity indices. We have also correlated our diversity index data to the bulk calcium carbonate ($CaCO_3$) content data of ODP site 748B (Zachos et al. 1992) and the stable isotopic data of ODP Hole 744A (Salamy and Zachos 1999) of the Southern Kerguelen Plateau (Figs. 3 and 4). The stable isotope data of ODP Hole 1138A and 744A reveals a decreasing trend in δ^{18}O, whereas δ^{13}C values exhibit a decreasing trend up to ~ 32 Ma, followed by an increasing trend (Fig. 3). These data show a decreasing trend from ~ 33.7 to ~ 33.1 Ma to a gradual increase in productivity, confirmed by the increase of stable carbon isotopic values. The peak at ~ 33.7 Ma and ~ 33.4 Ma relates to the Oi-1 event, whereas ~ 32.8 Ma and ~ 31.7 Ma coincide with Oi-1a and Oi-1b events, respectively, of early Oligocene (Fig. 3). In contrast, the carbonate contents of whole-rock samples from ODP site 748B reveals the decreasing trend from ~ 33.7 Ma followed by an increasing trend which attains maximum peak at ~ 33.2 Ma (Fig. 3); it starts decreasing again and got minimum value at ~ 32.7 Ma followed by increasing trend up to the end of the studied interval. These fluctuations in bulk calcium carbonate content in whole rock data also suggest
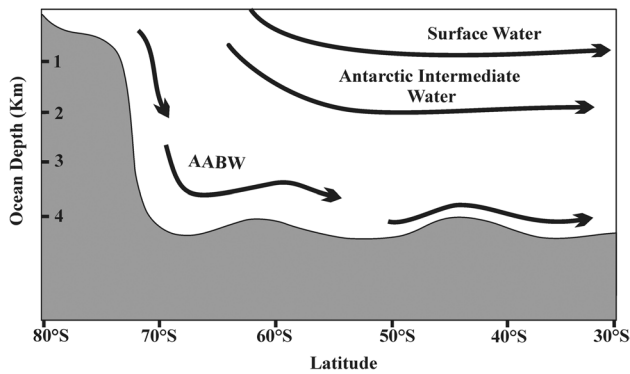
Fig. 5 A general schematic section of meridional ocean water circulation of the Southern Ocean illustrates surface and deep water circulation patterns during early Oligocene. Acronyms: AABW, Antarctic Bottom Water (modified after Kennett and Stott 1990)

that the influence of substantially warm water bathed the area for a brief periods during the studied interval (Fig. 3).

Ocean circulation during early Oligocene

We interpreted that the Oligocene oceanographic setting of the Southern Ocean was very different to the modern ocean. The deep water mass was dominated by AABW, intermediate water mass was dominated by AAIW, and the upper part of the Southern Ocean was dominated by surface water mass (Fig. 5). Kennett and Stott (1990) reveal the strong influence of the proto-AABW and Antarctic Intermediate Water (AAIW) on the Southern Ocean during this time; however, this study reveals that at this interval, AABW came in to full existence (Figs. 3, 4, and 5). The cooling climate initiated the formation of cold and dense bottom water (AABW), followed by sea and continental ice formation in the early Oligocene. These water masses led to the bathing of the Kerguelen Plateau and its surroundings in a stepwise manner during the earliest Oligocene and predominantly influenced the deep-sea benthic foraminifera as shown in Figs. 3 and 4. Our findings suggested that diversity-based indices and isotopic data derived from the benthic foraminifera quickly responded to the deep water mass variation during the early Oligocene and leads to production and dominance of AABW in Southern Ocean.

Conclusions

By most standards, the rapid cooling of the sub-polar seas and the appearance of a full-scale continental ice sheet on Antarctica was a major climate event that should have had a significant impact on Southern Ocean ecology and global climate. The isotopic records and the diversity parameters

of early Oligocene benthic foraminiferal species such as Shannon–Weaver ($H(S)$) index, Hurlbert's (S_{100}) diversity index, Fisher's alpha (α) index, equitability (E'), and species richness (S) combined with population abundance of dominating benthic foraminifera at ODP Hole 1138A are correlated with the increased glaciation on the Antarctic and related ocean wide productivity. Species diversity decreased during the glaciation and increased during interglacial intervals in the Southern Ocean. The decrease in the species diversity parameters of the Southern Ocean is also related to the occurrences of low oxygen species and high seasonality as observed in the North Atlantic and Southeastern Indian Oceans (Corliss et al. 2009; Singh et al. 2012). The increase in the species diversity was observed between Oi-1 (33.4 Ma) and Oi-1b (31.7 Ma) events due to the release of the short-lived pulse of CO_2 at different phases due to leakage of fossil carbon (Coxall et al. 2018) or release of trap gas hydrates (i.e., methane, ethane, or carbon dioxide) or short-lived volcanic eruptions, which release CO_2 and warm the deep ocean. The low values of species diversity amplified by high seasonality and relatively cold, strong bottom water currents after the Eocene–Oligocene Transition (33.9 Ma) and after the Oi-1b (31.7 Ma) event correspond to the substantial buildup of the Southern Hemisphere glaciation and intensification of ACC and AABW, and early Oligocene have also noticed marked intervals of warming.

Declarations

Ethics approval Not applicable.

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