Acta Oceanol. Sin., 2019, Vol. 38, No. 3, P. 124–137
https://doi.org/10.1007/s13131-019-1405-7
http://www.hyxb.org.cn
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Miocene paleoenvironmental evolution based on benthic foraminiferal assemblages in the Lufeng Sag, northern South China Sea

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Received 7 September 2018; accepted 24 December 2018

Abstract

The Miocene epoch marks the most crucial period during the Cenozoic cooling trend, characterized by the Middle Miocene Climatic Optimum (MMCO) and a series of short-lived cooling events (Miocene isotope events). To understand the paleoenvironmental evolution along the shallow water shelf in the South China Sea during the Miocene, the benthic foraminiferal assemblage and total organic carbon content (TOC) were analyzed at Hole LF 14 located in the Lufeng Sag, northern South China Sea. Three benthic foraminiferal assemblages (e.g., the *Uvigerina* spp. assemblage, the *Cibicides* spp. assemblage, and the *Cibicidoides* spp. assemblage), corresponding to different watermass conditions, were recognized based on Q-mode factor analysis. Early studies suggested that Hole LF14 was deposited under semienclosed bay, middle to outer shelf or even upper bathyal environment during ~18.7–4.53 Ma. The dominant *Uvigerina* spp. assemblage was characterized by low diversity and shallow infaunal to infaunal species, indicating a warm, low-oxygenation and eutrophic conditions since the Early Miocene to MMCO (~18.7–14.24 Ma). An abrupt sea level drop and significant faunal changes were recorded during 14.24–13.41 Ma, suggesting development of the East Antarctic Ice Sheets, which resulted in a drop of sea level and change in benthic foraminiferal assemblages along the shallow water shelf. Beyond the *Uvigerina* spp. assemblage, the *Cibicides* spp. assemblage became important during the middle-late Middle Miocene (14.24–11.54 Ma). This assemblage was dominated by epifaunal species with relative high diversity, suggesting high-energy, high-oxygenation and oligotrophic conditions with episodic supply of organic food. The dominant *Cibicidoides* spp. assemblage with high diversity, indicates a mesotrophic conditions with relative high-oxygen content during the Late Miocene to Pliocene (11.54–4.53 Ma). The appearance and continuous occurrence of *Ammonia* spp. and *Pseudorotalia* spp. since 10.02 Ma, may reflect the influence of the Kuroshio Current.

Key words: South China Sea, Lufeng Sag, Miocene, benthic foraminiferal assemblage, total organic carbon, shelf paleoenvironment

Citation: Xue Liyuan, Ding Xuan, Pei Renjie, Wan Xiaoqiao. 2019. Miocene paleoenvironmental evolution based on benthic foraminiferal assemblages in the Lufeng Sag, northern South China Sea. Acta Oceanologica Sinica, 38(3): 124–137, doi: 10.1007/s13131-019-1405-7

1 Introduction

From a global climatic and evolutionary point of view, the Miocene is an important time of a series of drastic climatic shifts during the Cenozoic cooling trend (Zachos et al., 2001). As inferred from the δ^{18}O values of planktic and benthic foraminifera, the global climate warmed again after Miocene-1 (Mi-1, ~23 Ma) and reached an optimum in the Middle Miocene (17–15 Ma), which is known as the middle Miocene climatic optimum (MMCO) (Miller et al., 1991; Wang et al., 2003; Abels et al., 2005; Smart et al., 2007; Brandano et al., 2017). During this interval, atmospheric CO_2 concentrations were similar to modern levels, and a significant positive carbon isotope shift was recorded that triggered the onset of the glacial-interglacial climatic mode (Woodruff and Savin, 1991; Holbourn et al., 2004, 2007; Tripati et al., 2009; Brandano et al., 2017). There is no agreement among researchers on the mechanism resulting in this warm period. After the MMCO, Mi-3 (14.2–13.6 Ma) through Mi-6 (~9.6 Ma) events carried on the pattern of stepwise cooling, especially during Mi-3 (Wang et al., 2003). This cooling event (Mi-3) indicates the major expansion of the Antarctic ice caps, leading to their permanent existence, cooling of the bottom water, and establishment of the modern bottom water circulation (Miller et al., 1991; Wright et al., 1992; Flower and Kennett, 1995; Wang et al., 2003). This major ice sheets growth on East Antarctica further resulted in variation of global sea level and invigoration of surface ocean circulation systems, which influenced the composition of planktic and benthic foraminiferal assemblages (Thunell and Belyea, 1982; Haq et al., 1987; Flower and Kennett, 1994). Gallagher et al. (2001) noted significant changes in paleoenvironmental conditions and benthic foraminifera corresponding to global cooling and major Antarctic Ice Sheets expansion in the Gippsland Basin, southeastern Australia. A distinct change in the foraminiferal assemblage in response to expansion of the East and West Antarctic Ice Sheets is also recorded in the Port Phillip Basin of southeast Australia during the early Middle Miocene (Gourley and Gallagher, 2004).

The South China Sea (SCS) is the largest marginal sea in the West Pacific Ocean. The marginal sea is more sensitive than the

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Foundation item: The National Natural Science Foundation of China under contract No. 91328201.

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open ocean in response to global changes and can often play an “enhancement” or “strengthening” role in paleoceanographic research (Wang et al., 1986). Recent studies in reconstructing paleoclimate and paleoenvironment in the SCS have been largely based on deep-sea basin records recovered by the Ocean Drilling Program (ODP) and International Ocean Discovery Program (IODP). The benthic foraminiferal δ^{18}O and δ^{13}C records from ODP Site 1148 (northern SCS, at a water depth of ~3 294 m) show evidence for a similar cooling trend with global climate evolution during the Late Cenozoic, including expansion of the East Antarctic Ice Sheets, Mi events, and global carbon excursions in the Miocene (Zhao et al., 2001a, b; Wang et al., 2003). Wang and Li (2009) documented the Miocene paleoenvironmental changes based on benthic foraminiferal records from the deep–sea basin of the SCS. Paleoceanographic research on the shallow marine sequence is sparse and the literature is old. Huang et al. (2012) documented changes in sedimentation and benthic foraminifera from the shallow marine sequences of the Western Foothills of Taiwan during the Miocene without interpreting the paleoenvironmental conditions. The Zhujiang (Pearl) River Mouth Basin (ZRMB) is the most developed and typical area of Neocene marine sediments in the SCS. Thus, the ZRMB is an ideal setting for studying the continental margin record of changes in the SCS during the Miocene.

Benthic foraminifera have long been recognized for their potential in marine paleoenvironmental settings, as their distribution depends on several physical, chemical, and biological factors of watermasses (Murray, 1991, 2006; den Dulk et al., 2000). Studies of dead and living benthic foraminifera have shown that they can be good indicators for oceanographic parameters, such as water depth, substrate, dissolved oxygen, and organic matter supply (Kaiho, 1994, 1999; Hohenegger, 2005; Jorissen et al., 2007). Moreover, the microhabitats and ecological preferences of benthic foraminifera have been widely used to interpret paleoenvironmental changes (Báldi, 2006; Singh et al., 2012; Deprez et al., 2015).

In this paper, Hole LF14 from the ZRMB, located on the continental shelf of the northern SCS (Fig. 1), was studied. The aims of this study are as follows: (1) to characterize the benthic foraminiferal assemblages along the hole; (2) to reconstruct the shallow–water shelf paleoenvironment in the northern SCS during the Early Miocene to the Pliocene; and (3) to improve our understanding of the paleoenvironmental changes in the continental shelf in relation to global climatic and paleoceanographic changes during the Miocene.

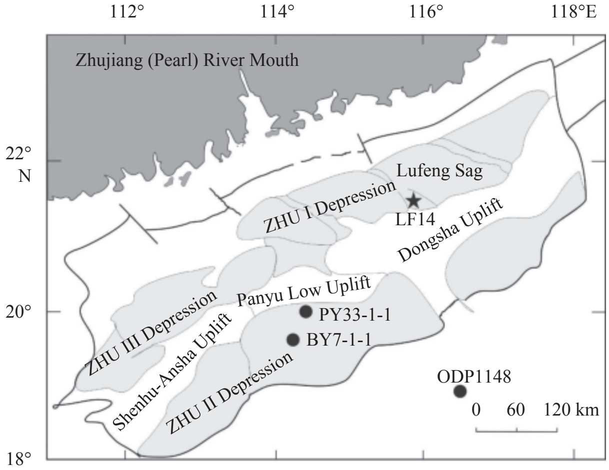

Fig. 1. Location of the Hole LF14 in the ZRMB (solid black line, modified after Gong et al. (1989)).

2 Study area

2.1 *Geological settings and stratigraphy*

Hole LF14 studied here is located in the Lufeng Sag of the ZRMB in the northern SCS at a water depth of ~145 m (Fig. 1). The ZRMB was developed by normal faulting during the Late Mesozoic–Early Cenozoic on the passive southern Asian continental margin (Yao et al., 1994). The Paleogene syn–rifting basin was filled by lacustrine–lake deposits and finally covered unconformably by Neogene post–rifting strata (Huang et al., 2012). Six major structural units exist in the basin: Zhu I, Zhu II, and Zhu III depressions and Dongsha, Shenhu–ansha, and Panyu Low Uplifts (Gong et al., 1989; Chen, 2000). The Lufeng Sag is one of the five sags in the Zhu I Depression (Fig. 1).

After the Middle Oligocene, rapid subsidence caused a rise in local sea level and marine transgressions from south to north in the ZRMB. Seawater entered the Zhu I Depression after 21 Ma (Qin, 1996). Since then, the Zhu I Depression was considered as a restricted semienclosed bay (Qin, 1996). This restricted environment ended at 16 Ma as the Dongsha Uplift was submerged under sea level (Qin, 1996).

The Neogene sediment sequence in the ZRMB has been divided into four units formally described as formations. The lowermost unit is the Zhujiang Formation (Wang, 1985; Jiang et al., 1994). The Zhujiang Formation accumulated at delta to shelf settings in slightly deeper water, prograding to carbonate platform reef facies on the Dongsha Uplift (Wang and Li, 2009; Zeng et al., 2015). The overlying Hanjiang Formation contains mudstone and sandstone similar to the Zhujiang Formation, probably deposited also in an overall transgressive environment (Chen et al., 1994; Jiang et al., 1994). The Yuehai Formation and Wanshan Formation were interpreted as shelf deposits (Wang and Li, 2009).

2.2 *Modern surface circulation*

In the SCS, the modern upper water is mostly controlled by the underlying morphology of the enclosed basin and the overlying atmospheric circulation, especially the East Asian Monsoon (Wang and Li, 2009). The surface circulation pattern in the SCS exhibits a general cyclonic gyre in winter and an anticyclonic gyre in summer (Wyrtki, 1961), accompanied by a “Summer Southeast Vietnam Offshore Current” (Fang et al., 2002) (Fig. 2). This unique surface circulation pattern is the result of seasonal changes in the East Asian Monsoon. Qu (2000) suggested that the upper-layer circulation pattern is also influenced by the Kuroshio Current in its northern part.

3 Materials and methods

3.1 *Materials and sampling*

In this paper, an interval of 1 724 m, from 676 to 2 400 m depth at Hole LF14, was studied. In total, 171 drill cutting samples were collected. The samples were taken at 10–m intervals with a span of 3–5 m.

Samples were first crushed into small fragments (about 5–10 mm in diameter), oven dried (<60°C), and weighed. Then the indurated marlstones were soaked in 10% hydrogen peroxide solution for at least 24 h, until the samples were completely disaggregated. Finally, the samples were washed over a 63 μm sieve

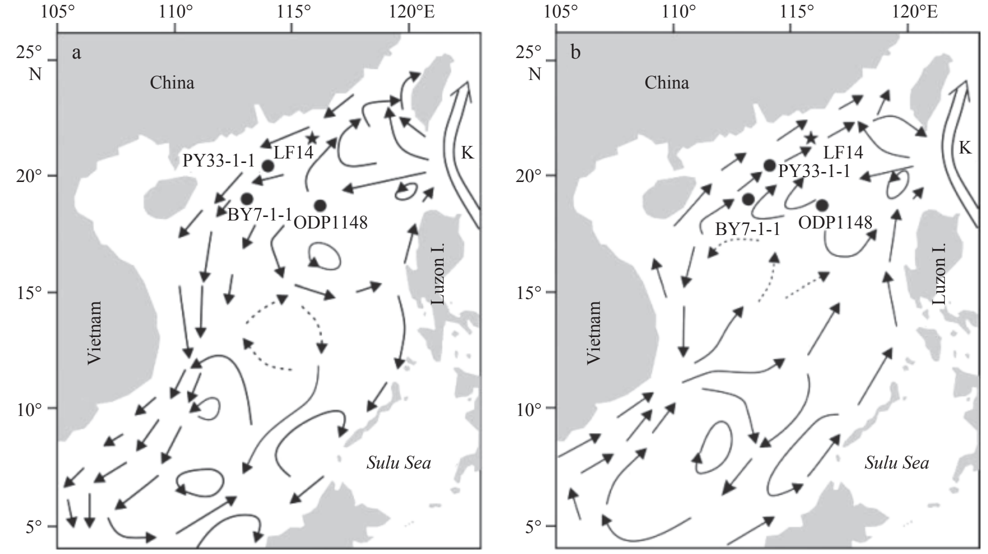

Fig. 2. Main surface circulation patterns of the modern SCS. a. Winter, and b. summer. ★ is the location of the Hole LF14, and K the Kuroshio Current (modified from Fang et al. 1998).

and dried.

3.2 *Data processing and analyses of benthic foraminifera*

For faunal analysis, the >125 μm fraction of the residues was divided into equal aliquots with a microsplitter to obtain subsamples containing at least 100 benthic foraminiferal specimens. Generally ~150 specimens were picked from each sample. The foraminifera were identified to the species level wherever possible and counted under a binocular microscope. Taxonomic identification of benthic foraminifera was based on Hubei Institute of Geosciences (1978), Hao et al. (1980), Wang et al. (1981), Zheng (1988), Loeblich and Tappan (1994), and Holbourn et al. (2013). The benthic foraminiferal numbers per gram of dry sediment was calculated.

The diversity of fauna is generally expressed as (1) number of species (S); (2) the Shannon diversity (H, assessed diversity of the benthic foraminiferal assemblage), given by

$$H = -\sum_{i=1}^{S} p_i \ln p_i,$$

where S is the number of species, p_i is the proportion of the ith species, and ln is the natural logarithm; (3) Buzas and Gilson's evenness (E, where 0 represents completely dominated assemblages and high values indicate even assemblages), given by

$$E = \mathrm{e}^{H}/S,$$

where e is the base of the natural logarithm, H is the Shannon index, and S is the number of species; and (4) dominance (D) (Levin and Gage, 1998), the percentage of the most frequent species. This analysis was based on PAST2.0 software (Hammer et al., 2001).

The percentage of planktic foraminifera (P=100%×P/(P+B)) in the total number of foraminifera (P+B) was calculated in Xue et al. (2017). The paleowater depths were quantitatively calculated based on depth ranges of benthic foraminifera using the transfer function developed by Hohenegger (2005) and later modified by Báldi and Hohenegger (2008) and Hohenegger et al. (2008). The paleowater depths of Hole LF14 fluctuated frequently between 68 and 299 m during ~18.7–4.53 Ma, suggesting a middle–outer shelf or even upper bathyal environment (Xue et al., 2018).

Q-mode factor analysis was performed to determine the benthic foraminiferal assemblages using the program developed by Klovan and Imbrie (1971). This method involves Principal Component Analysis (PCA) followed by varimax rotation. Only the genera and species whose relative abundances were >2% and presented at least in three samples were taken into the calculation.

Reconstruction of the dissolved oxygen conditions at the seafloor is based on the relative abundance of oxic species in the benthic foraminiferal assemblage. In this study, the simplified method in Báldi (2006) was followed. The oxic species were composed of "oxic indicators" defined as having >1.5 mL/L oxygen content in Kaiho (1994) or classified as "Group 5" in Kouwenhoven and van der Zwaan (2005). In this study, *Cibicides* spp., *Cibicidoides* spp., *Globocassidulina subglobosa*, *Hanzawaia* spp., *Quinqueloculina* spp., and *Triloculina* spp. were considered as the oxic species after the study by Rosoff and Corliss (1992), Kaiho(1994, 1999), Kouwenhoven and van der Zwaan (2006), and Singh et al. (2015).

The relative abundance of infaunal species was calculated to understand more about the trophic conditions (Báldi, 2006). According to Corliss (1991), the infaunal species are generally characterized by elongate, smooth, and serial shape. In this study, these species are *Amphicoryna scalaris*, *Bolivina* spp., *Brizalina* spp., *Bulimina* spp., *Florilus* spp., *Melonis* spp., *Nonionella* spp., *Pullenia bulloides*, *Rectobolivina* spp., *Stilostomella* spp., *Trifarina bradyi*, and *Uvigerina* spp. (Jorissen, 1987; de Stigter et al., 1998; den Dulk et al., 2000; Fontanier et al., 2002; Murray, 2006).

3.3 *Analyses of total organic carbon content*

A total of 171 samples were selected for the analyses of total organic carbon content (TOC). Samples were dried at 105°C for 2 h, and then grinded (<74 μm). Dried sediment was weighed. About 200 mg of sediment was decalcified with 10% H_3PO_4, and dried. The TOC was determined using a CS-580A carbon–sulfur analyzer (Eltra). The TOC measurements were taken at the Beijing Research Institute of Uranium Geology (BRIUG).

4 Biostratigraphy

A detailed overview of the biostratigraphy of Hole LF14 was reported based on planktic foraminiferal events and assemblages in Xue et al. (2017). As the studied samples are drill cutting samples, only the last appearance datum (LAD) of planktic foraminiferal event was applied to avoid the influence of falling samples. The most important planktic foraminiferal events are displayed here (Table 1). Because most planktic foraminiferal events identified in the studied interval are recognized in the Miocene, the planktic foraminiferal standard global tropical/subtropical zonation of Berggren et al. (1995) is applied here. Ages in this paper are based on the Geologic Time Scale of the Neogene (Gradstein et al., 2012). The LAD of *Sphaeroidinellopsis kochi* is identified at 685–690 m. So the age of the top of the studied interval is 4.53 Ma. The age of the bottom (2 400 m) of the studied interval is estimated at ~18.7 Ma by using average sedimentation rate method.

5 Results

5.1 *Faunal and paleoenvironmental indices*

Foraminifera occurred in all samples in the studied interval from 676 to 2 400 m. At the base of the interval, foraminiferal tests were filled in by sediment and some of them were recrystallized, but they exhibit a good appearance, allowing identification at the species level. For the upper part of the interval, the preservation of the foraminiferal tests was good. The species of *Bolivina* spp., *Cibicides* spp., *Cibicidoides* spp., *Hanzawaia* spp., *Heterolepa* spp., *Lenticulina* spp., *Planulina* spp., *Rectobolivina* spp., *Trifarina bradyi*, and *Uvigerina* spp. are all abundant, with the peak abundances of >20%. The distributions of quantitatively important species are shown in Fig. 3.

Benthic foraminiferal numbers per gram of dry sediment (BFN) of the studied interval vary between 11 and 426 g^{-1} (87 samples) with a mean value of 102 g^{-1} before ~14.24 Ma. However, the values are generally high (10–790 g^{-1}, being 275 g^{-1} on average for 84 samples) from ~14.24 to 4.53 Ma (Fig. 4). On the contrary, percentage of planktic foraminifera (*P*) is generally high before ~14.24 Ma (36%–91%, being 68% on average for 82 samples) whereas the *P* values vary widely between ~14.24 and 4.53 Ma, from 15% to 81%, with an average of 49% (Fig. 4).

Benthic foraminiferal diversity, *S*, *H*, *E* and *D* in the studied interval of Hole LF14 show significant variability (Fig. 4). The number of species (*S*) varies between 14 and 35 though the stud-

Table 1. The biostratigraphic events identified in the Hole LF14

Depth/m	Zone	Marker events	Age/Ma
685±5	PL1	LAD *Sphaeroidinellopsis kochi*	4.53
785±5	PL1	LAD *Globigerinoides seiglei*	4.72
975±5	M13a/M12	LAD *Globoquadrina dehiscens*	9.83
1 135±5	M12/M11	LAD *Globorotalia siakensis*	10.46
1 265±5	M11/M10	LAD *Globigerinoides subquadratus*	11.54
1 345±5	M10/M9	LAD *Globorotalia foshi*	11.79
1 425±5	M9/M8	LAD *Globorotalia peripheroacuta*	13.41
1 485±5	M8/M7	LAD *Globorotalia peripheroronda*	13.80
1 555±5	M7/M6	LAD *Globigerinoides sicanus*	14.24
1 755±5	M6	LAD *Globigerinatella insueta*	14.66
1 885±5	M5b	LAD *Globorotalia birnageae*	16.00
1 905±5	M4b	LAD *Globigerinoides parawoodi*	16.50
2 005±5	M4/M3	LAD *Catapsydrax dissimilis*	17.54

Note: LAD represents last appearance datum.

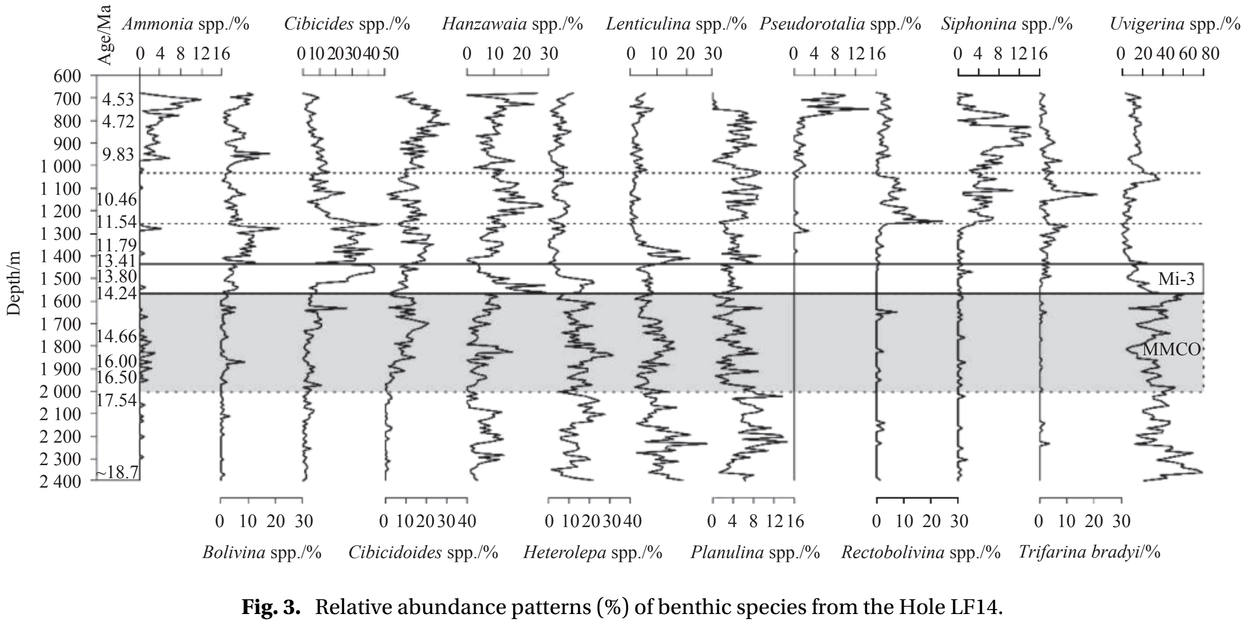

Fig. 3. Relative abundance patterns (%) of benthic species from the Hole LF14.

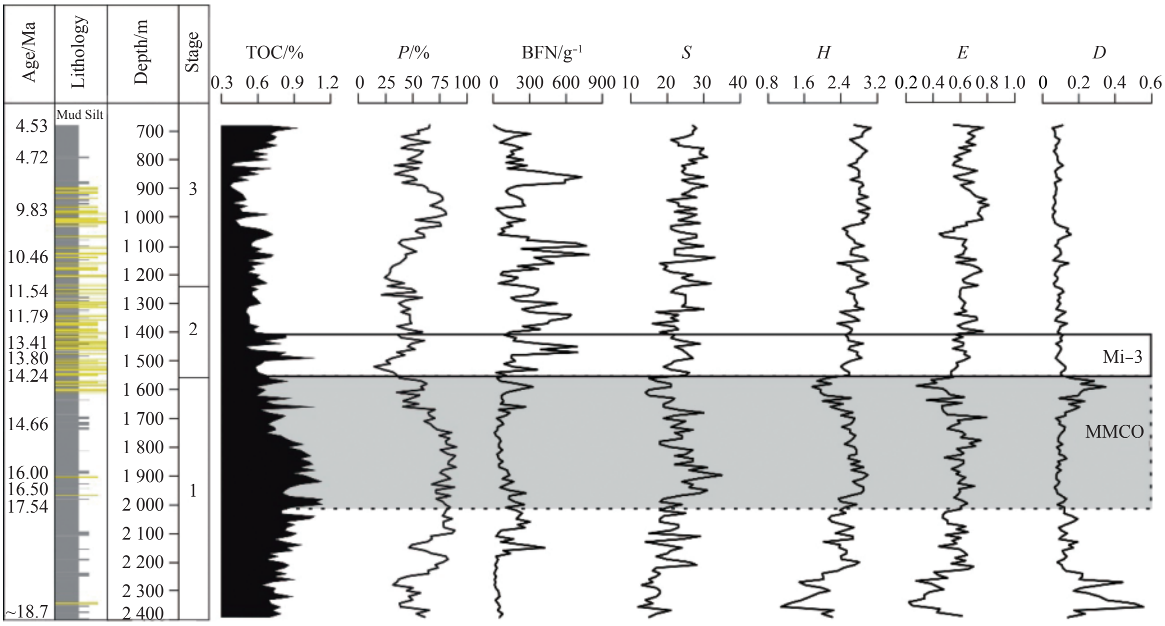

Fig. 4. Overview of lithology, TOC, percentage of planktic foraminifera (*P*), number of benthic foraminifera (BFN), *S* (number of species), *H* (Shannon diversity), *E* (Buzas and Gilson's evenness) and *D* (dominance).

ied interval with an average value of 23. The values of *H* are generally low (1.09–2.89, with 2.39 on average for 87 samples) with large fluctuations before ~14.24 Ma. However, the values of *H* are higher (2.34–3.07, being 2.75 on average for 84 samples) from ~14.24 to 4.53 Ma. The Shannon index (*H*) combines information on the number of species present with the evenness (*E*). However, fluctuations in the evenness are more noticeable. The values of *H* exhibit low values between 14.66 and 14.24 Ma with a minimum value of 1.8. The dominance (*D*) shows an opposite trend to those shown by *H* and *E* (Fig. 4).

The TOC is high (0.64%–1.14%, being 0.88% on average for 62 samples) and show a trend similar to that of *P* before 14.66 Ma, whereas the TOC is low (0.38%–1.08%, being 0.63% on average for 109 samples) from 14.66 to 4.53 Ma (Fig. 4).

5.2 *Benthic foraminiferal assemblages and ecological interpretation*

5.2.1 *Benthic foraminiferal assemblages*

The Q-mode factor analysis was performed for 171 samples and 39 benthic foraminiferal genera and species. On the basis of Q-mode factor analysis, three benthic foraminiferal assemblages were recognized in the studied interval (Fig. 5); these account for 84.65% of the total variance (Table 2). The benthic foraminiferal assemblage is named based on the highest Varimax score of the species (Table 3). The principal factors show higher positive loadings at different layers, thus reflecting paleoenvironmental changes. The paleoenvironmental significant of the benthic foraminiferal assemblages is interpreted based on the ecological preferences and microhabitat preferences of the benthic foraminiferal species presenting (Báldi, 2006; Székely and Filipescu, 2016). The ecological and microhabitat preferences of benthic foraminiferal species are listed in Table 4.

***Uvigerina* spp. assemblage**

Factor 1 accounting for 62.87% of the total variance is the most significant factor in the studied interval (Table 2). *Uvigerina* spp. assemblage indicated by Factor 1 is dominated by *Uvigerina* spp. with *Heterolepa* spp. (mainly *Heterolepa dutemplei*), *Lenticulina* spp., and *Planulina* spp. as accompanying species (Table 3). The infaunal *Uvigerina* spp. are typical in the upper slope and outer shelf environment with high food availability and moderate oxygen depletion in fine-grained sediments (Lutze and Coulbourn, 1984; Debenay and Redois, 1997; Schmiedl and Mackensen, 1997, Schmiedl et al., 2000, 2010; Fontanier et al., 2002; Koho et al., 2008; Pérez-Asensio et al., 2012). *Heterolepa* spp. are epifaunal to shallow infaunal species and typical indicator of organic-rich substrate and warm water (Wang et al., 1988; Debenay and Redois, 1997). Coincidently, *Lenticulina* spp. are shallow infaunal species and common in high-food-flux and/or low-oxygenation environment at the seafloor (Youssef and Taha, 2013). Thus, the *Uvigerina* spp. assemblage probably represents a warm, low-oxygen-concentrations and eutrophic conditions.

***Cibicides* spp. assemblage**

Factor 2 accounts for 16.97% of the total variance (Table 2). This factor is correlated with the *Cibicides* spp. assemblage. *Cibicides* spp. are the major contributor in this assemblage comprising *Bolivina* spp., *Cibicidoides* spp., and *Trifarina bradyi* as secondary species (Table 3). *Cibicides* spp. are epifaunal species living on hard substrate in high-energy conditions with strongly pulsed food supply (Gupta, 1997; Murray, 2006; Gupta and Das, 2007; Singh et al., 2012). Besides, some species of this genera (e.g., *Cibicides wuellerstorfi*) have also been considered as an indicator of a high seasonal food supply in oligotrophic environment (Loubere and Fariduddin, 1999). *Bolivina* genera, such as *Bolivina robusta* and *Bolivina dilatata*, are shallow to deep infaunal species, which usually occur in a wide range of mesotrophic to eutrophic environments, and are especially resistant to low-oxygen conditions (Melki et al., 2010; Sgarrella et al., 2012). Kuhnt et al. (1999) earlier noted that the *Bolivina* spp. could be used as indicators of enhanced C-flux rates in the SCS, as pointed out by Hess and Kuhnt (1996). As a consequence, the *Cibicides* spp. assemblage is indicative of a high-energy, high-oxygen-content and oligotrophic environment with episodic organic matter input.

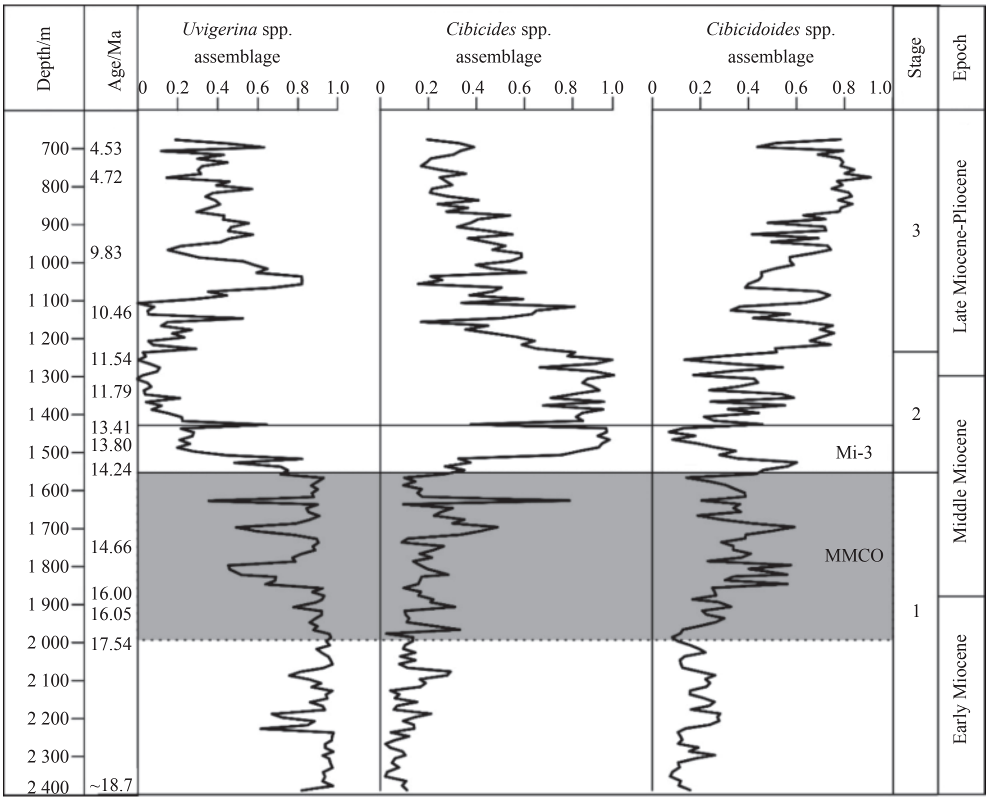

Fig. 5. Curves of the varimax loadings for the three principal factors against the hole depth.

Table 2. Factors, total variance and cumulative total variance

Q-mode assemblages	Total variance/%	Cumulative total variance/%
Uvigerina spp. assemblage (Factor 1)	62.87	62.87
Cibicides spp. assemblage (Factor 2)	16.97	79.84
Cibicidoides spp. assemblage (Factor 3)	4.81	84.65

***Cibicidoides* spp. assemblage**

Factor 3 correlated with the *Cibicidoides* spp. assemblage accounts for 4.81% of the total variance (Table 2). *Cibicidoides* spp. are important in this assemblage. Some of the associated species of this assemblage are *Ammonia* spp., *Bolivina* spp., *Hanzawaia* spp., *Planulina* spp., *Pseudorotalia* spp., *Rectobolivina* spp., and *Siphonina* spp. (Table 3). *Cibicidoides* spp. are usually described as epifaunal to infaunal in oligo-mesotrophic environments with well-oxygenated and unstable conditions (Kaiho, 1994; Murray, 2006; Melki et al., 2009; Takata et al., 2010; Sgarrella et al., 2012), although some authors argue that this genera/species can tolerate low oxygen concentrations (Rathburn and Corliss, 1994; Szarek et al., 2007). The presence of *Hanzawaia* spp. with a clinging mode life indicates a high-energy, food-limited environment (Kitazato, 1994; Schönfeld, 1997; Murray, 2006), for example, on the Sunda Shelf in the southern SCS (Szarek et al., 2007). *Pseudorotalia* spp. have been reported to be typical warm member of the Indo-Pacific shelf assemblage in tropical water characterized by coarse substrate and being less sensitive to water depth (Murray, 1991; Gallagher et al., 2009; Minhat et al., 2016). *Ammonia* spp., such as *Ammonia beccarii*, is a shallow infaunal and low salinity tolerant species occurring in the inner-middle shelf. This species is quite often found in association with mesotrophic and hypoxic environments (Murray, 1991, 2006; Báldi, 2006; Pérez-Asensio et al., 2012; Minhat et al., 2016). In the Zhujiang (Pearl) River Estuary (water depth less than 10 m), the relative abundance of this species is particularly high as it can tolerate a wide range of salinity (Li et al., 2011). *Siphonina* spp. are epifaunal to shallow infaunal species and are related to oligotrophic and oxic environments (Jones, 1994; Szarek et al., 2007). It is thus inferred that this faunal assemblage broadly indicates a relatively high-oxygen-content and mesotrophic environment.

5.2.2 *Changes in benthic foraminiferal assemblages*

During the Early Miocene–early Middle Miocene (~18.7–14.24 Ma), the high-food-exploiting *Uvigerina* spp. assemblage develops significantly along with higher relative abundances of *Uvigerina* spp., *Heterolepa dutemplei*, and *Lenticulina* spp. (Figs 3 and 5). Moreover, the *Cibicidoides* spp. assemblage also shows relatively high loadings during 16–14.24 Ma. The typical low-food-exploiting *Cibicides* spp. assemblage becomes important and remained dominant during the middle–late Middle Miocene (14.24–11.54 Ma) (Fig. 5). The *Cibicidoides* spp. assemblage becomes dominant during the Late Miocene to Pliocene (11.54–4.53 Ma) (Fig. 5). The relative abundances of *Rectobolivina* spp. and *Siphonina* spp. exhibit a rapid rise at 11.54 Ma, meanwhile *Cibicides* spp. decrease significantly (Fig. 3). Besides, the relative abundances of *Ammonia* spp. and *Pseudorotalia* spp. increase rapidly after 10.02 Ma and appear continuously during the Late Miocene and Pliocene interval (Fig. 3).

Table 3. Varimax factor score matrix for 39 benthic genera/species in 3 principal factors

Genera/species	Factor 1	Factor 2	Factor 3
Ammonia spp.	–0.017	–0.045	0.131
Amphicoryna scalaris	0.01	0.01	0.005
Amphistegina radiata	–0.023	0.008	0.06
Bammina minima	0.035	–0.008	–0.002
Barbourinella teretis	–0.002	–0.002	0.012
Bolivina spp.	–0.052	0.147	0.186
Brizalina spp.	0.002	0.003	0.018
Bulimina spp.	–0.003	–0.008	0.026
Cibicides spp.	–0.028	0.953	–0.169
Cibicidoides spp.	–0.089	0.105	0.713
Epistominella pulchra	0.044	0.078	0.035
Eponides spp.	–0.004	0.007	0.032
Florilus spp.	0.041	0.02	–0.018
Gaudryina spp.	0.007	0.011	–0.008
Globocassidulina subglobosa	0.01	–0.003	0.008
Gyroidina soldanii	0.092	0.073	0.031
Hanzawaia spp.	–0.017	0.099	0.514
Heterolepa spp.	0.332	0.055	0.093
Lenticulina spp.	0.214	0.099	–0.007
Martinottiella communis	0.014	–0.002	–0.001
Melonis spp.	0.004	0.005	0.015
Migros flintii	0.019	–0.001	–0.008
Nonionella coarseperforta	0.005	0.008	0.029
Planularia spp.	–0.005	0.021	0.008
Planulina spp.	0.1	0.079	0.103
Poroeponides cribrorepandus	–0.003	–0.011	0.028
Pseudorotalia spp.	–0.017	–0.034	0.102
Pullenia bulloides	0.012	0	0.008
Quinqueloculina spp.	–0.004	0.006	0.01
Rectobolivina spp.	–0.037	0.036	0.146
Sigmoidella spp.	0.011	0.005	–0.002
Siphonina spp.	–0.049	–0.033	0.257
Sphaeroidina bulloides	0.035	–0.035	0.099
Spirorutilis spp.	0.018	0.005	–0.01
Stilostomella spp.	0.011	–0.004	0.007
Textularia spp.	0.021	0.009	0.032
Trifarina bradyi	–0.023	0.103	0.047
Uvigerina spp.	0.894	–0.013	0.06
Vaginulina margaritifera	0.007	–0.001	–0.002

6 Discussion

Benthic foraminiferal assemblage, species diversity, and TOC have been widely applied to paleoenvironmental reconstruction. Shifts in these factors indicate changing environmental conditions such as food supply and oxygenation, which may be linked to water depth (Gebhardt et al., 2004; Gupta and Kawahata, 2006; Jorissen et al., 2007). There is a causal relationship between changes in the trophic conditions and variations in the diversity and microhabitat preferences (Pérez-Asensio et al., 2012). Generally, oligotrophic environments are dominated by epifaunal species and have rather low diversity; mesotrophic environments show highest diversity and all microhabitats are represented; and finally, eutrophic environments are characterized by low diversity and dominance of (deep) infaunal species (Jorissen et al., 1995; Pérez-Asensio et al., 2012). Therefore, benthic foraminifera provide a useful tool for understanding the environmental variations in response to various paleoclimatic and paleoceanographic changes.

According to the three principal factors, diversity indices and percentage of planktic foraminifera (P), the studied interval was divided into three stages from the bottom up (Fig. 5). We compare the data of Hole LF14 with the records of $\delta^{18}O$ and $\delta^{13}C$ from ODP Site 1148 (Wang et al., 2003), to discuss the shallow-water environment changes in the SCS during the Miocene. The depositional environment related to water depth has been distinguished after Katz et al. (2003): inner shelf (0–50 m), middle shelf (50–100 m), and outer shelf (100–200 m).

6.1 *Eutrophic conditions in the Early Miocene to early Middle Miocene, 2 400–1 550 m (~18.7–14.24 Ma)*

According to the variations of the species diversity indices, paleowater depths, and loadings of the *Cibicidoides* spp. assemblage, the Stage 1 can be subdivided into two parts: the Early Miocene (~18.7–17.54 Ma) and the MMCO (17.54–14.24 Ma).

6.1.1 *Early Miocene (~18.7–17.54 Ma)*

This period is dominated by the *Uvigerina* spp. assemblage, suggesting warm, low-oxygen-concentrations and eutrophic conditions during ~18.7–17.54 Ma. This is supported by the relative high values of TOC (0.64%–1.08%, being 0.81% on average) and low percentage of oxic species (Figs 4 and 6).

Species diversity patterns (S, H and E) are generally low and characterized by significant fluctuation during this period (Fig. 4). In modern benthic foraminiferal assemblages, decreased diversity is associated with unstable and eutrophic environments (Sanders, 1969; Bollmann et al., 1993; Wade and Bown, 2006). Further, Jorissen et al. (1995) suggested that a eutrophic environment is commonly characterized by low diversity and dominance of (deep) infaunal species.

The paleowater depths vary between 122 and 299 m, being 173 m on average (Fig. 6), which should indicate outer shelf or even upper bathyal environment (Xue et al., 2018). Li et al. (2004a) suggested that the percentage of planktic foraminifera in the modern shelf (water depth of 100–200 m) of the northern SCS varies between 49% and 98%, being 81% on average. The percentage of planktic foraminifera (63%) of Hole LF14 (Fig. 4) is coincident with the result of paleowater depths. Qin (1996) also suggested that this period is characterized by a high sea level in the ZRMB.

However, the Zhu I Depression was considered as a restricted semienclosed bay (Qin, 1996), rather than an outer shelf environment indicated by paleowater depths of Hole LF14 during this period, which may result in poor water exchange in the Lufeng Sag. In an environment with high organic input, the remineralization of organic matter decreases the oxygen concentrations on the seafloor (Jorissen et al., 1995; Mojtahid et al., 2009). Thus, the study area is interpreted as a warm, low-oxygenation and eutrophic semiclosed bay during ~18.7–17.54 Ma.

6.1.2 *Middle Miocene climatic optimum (17.54–14.24 Ma)*

Uvigerina spp. assemblage is still dominant during 17.54–14.24 Ma, accompanied by the distinct development of the *Cibicidoides* spp. assemblage, indicating warm, relatively low-oxygenation and eutrophic conditions. A gradual increase in oxic species suggests increasing seafloor oxygenation, especially after 16 Ma (Fig. 6). Warm water benthic indicators, such as *Heterolepa* spp., show high relative abundance in this part suggesting that the oceanic conditions were warm during 17.54–14.24 Ma. At Hole BY7-1-1, the warm water species *Sphenolithus* and *Discoaster* show high values (e.g., 25%–35% and 16%–18%, respect-

Table 4. Summary of known ecological preferences and tolerances for selected benthic foraminiferal genera/species

Factors	Genera/species	Microhabitat	Food	Bottom oxygen	Substrate	References
1	*Uvigerina* spp.	infaunal	eutrophic	hypoxic	muddy	1), 2), 3), 4)
	Heterolepa spp.	epi-shallow infaunal	eutrophic	hypoxic-oxic	hard	1), 4), 5)
	Lenticulina spp.	shallow infaunal	eutrophic	hypoxic-oxic	mud	1), 6)
	Planulina spp.	epifaunal	oligotrophic	oxic	hard	1), 7), 8)
2	*Cibicides* spp.	epifaunal	oligo-mesotrophic	oxic	hard	1), 9), 10)
	Trifarina bradyi	infaunal	eutrophic	hypoxic-oxic	mud-sand	1), 11), 12), 13), 14)
	Bolivina spp.	epifaunal or infaunal	meso-eutrophic	hypoxic-oxic	muddy	1), 15), 16), 17)
3	*Cibicidoides* spp.	epifaunal or infaunal	oligo-mesotrophic	oxic	hard	1), 2), 18), 19), 20)
	Ammonia spp.	shallow infaunal	mesotrophic	hypoxic	muddy sand	1), 21), 22)
	Pseudorotalia spp.	epifaunal	meso-eutrophic	–	muddy sand	1), 23), 24)
	Siphonina spp.	epi-shallow infaunal	oligotrophic	oxic	mud	1), 20), 25)
	Hanzawaia spp.	epifaunal	oligotrophic	oxic	hard	1), 26), 27)
	Rectobolivina spp.	infaunal	eutrophic	–	–	21), 28), 29)

Note: 1) Murray (2006), 2) Schmiedl et al. (2000), 3) Lutze and Colbourn (1984), 4) Debenay and Redois (1997), 5) Wang et al. (1988), 6) Speijer and Schmitz (1998), 7) Vieira et al. (2015), 8) Pérez-Asensio et al. (2012), 9) Singh et al. (2012), 10) Loubere and Fariduddin (1999), 11) Gupta et al. (1997), 12) Rasmussen and Thomsen (2017), 13) Corliss (1991), 14) Fiorini (2015), 15) Douglas (1981), 16) Melki et al. (2010), 17) Sgarrella et al. (2012), 18) Ernst et al. (2006), 19) Kaiho (1994), 20) Szarek et al. (2007), 21) Báldi and Hohenegger (2008), 22) Li et al. (2011), 23) Minhat et al. (2016), 24) Gallagher et al. (2009), 25) Jones (1994), 26) Kitazato (1994), 27) Schönfeld (2002), 28) Fontanier et al. (2003), 29) Mojtahid et al. (2010).

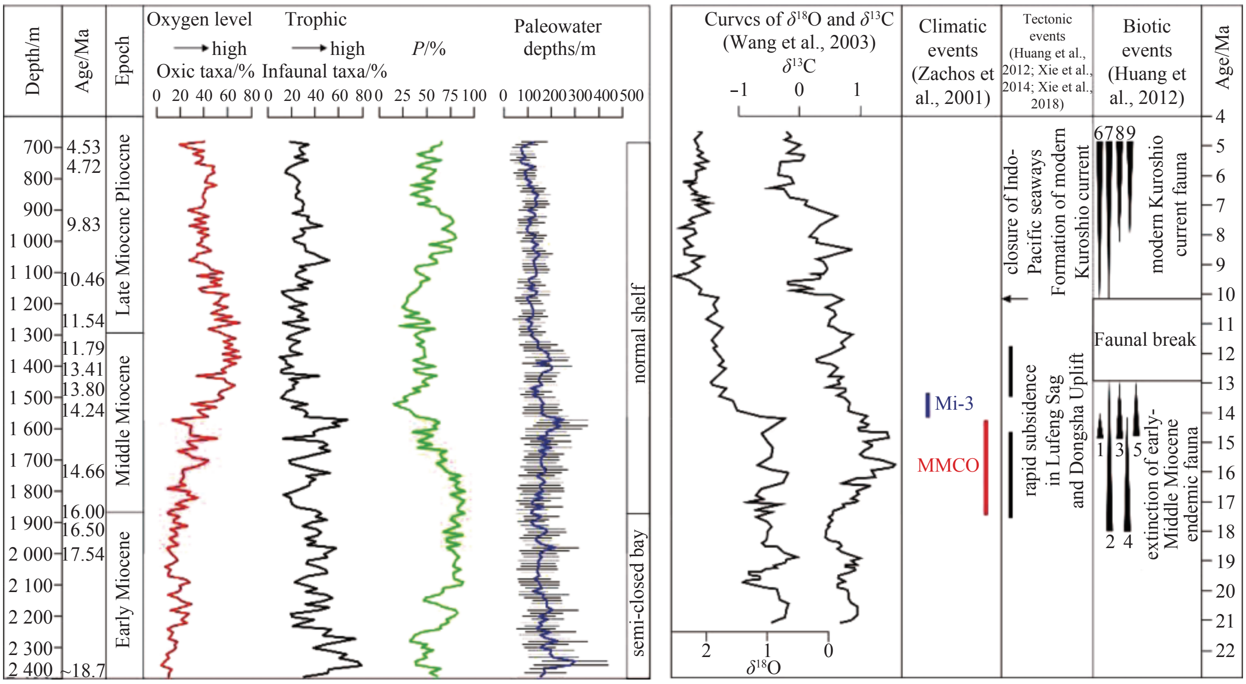

Fig. 6. Interpretation of results in relationship to benthic foraminiferal records of $\delta^{18}O$ and $\delta^{13}C$ at ODP Site 1148, climatic, tectonic and biotic events. Left, oxygen level based on the percentage of oxic taxa, trophic condition based on the percentage of infaunal taxa, percentage of planktic foraminifera (P), and paleo-water depths; Right, benthic foraminiferal isotopic records are after Wang et al. (2003); climatic events are after Zachos et al. (2001); tectonic events are after Huang et al. (2012), Xie et al. (2014) and Xue et al. (2018); biotic events are after Huang et al. (2012): 1. *Textularia kansaiensis*; 2. *Heterolepa praecincta*; 3. *Textularia akaminei*; 4. *Bigenerina shihtiensis*; 5. *Uvigerina nitidula*; 6. *Ammonia cf. japonica*; 7. *Ammonia altispira*; 8. *Asterorotalia yabei*; 9. *Pseudorotalia tikutoensis*.

ively), implying that a warm surface water during 17.54–14.24 Ma (Xu, 1996). Zhao et al. (2001a) also noted a warm bottom water condition in the SCS based on the light values of $\delta^{18}O$ of ODP Site 1148 during this period. The above analysis allows us to infer that the northern SCS is characterized by a warm water condition during 17.54–14.24 Ma.

The paleowater depths of Hole LF14 are high in the stage. The paleowater depths vary between 115 and 252 m, being 163 m on average (Fig. 6) (Xue et al., 2018), which is further supported by the high percentage of planktic foraminifera (71%) (Fig. 4). A high sea level, based on the abundances of planktic foraminifera and calcareous nannofossils, has been reported in the ZRMB during 17.54–14.24 Ma (Qin, 1996; Xu, 1996). The Dongsha Uplift is characterized by high subsidence rate during this period (Xie et al., 2014). This may provide an explanation for the submersion of the Dongsha Uplift at 16 Ma (Qin, 1996), to result in open shelf environment.

According to Jorissen et al. (1995), the low species diversity patterns (*S*, *H* and *E*) also suggest eutrophic conditions during 17.54–14.24 Ma. The TOC shows high values during 17.54–14.66 Ma, indicating a high sea surface productivity and high organic flux to the seafloor (Fig. 4). Based on the high values of planktic foraminiferal abundance, δ^{13}C, percentages of *Uvigerina* and *Bulimina* (*U*+*B*), and ratios of infaunal/epifaunal (*I*/*E*), Dong and Wan (1996) suggested that the ZRMB is characterized by a high sea surface productivity during 17.54–14.24 Ma. This is a period of MMCO, characterized by low mean δ^{18}O, high mean δ^{13}C, and burial of organically preferred ^{12}C–rich carbon in the world oceans (Vincent et al., 1985; Zachos et al., 2001; Singh et al., 2012). Wang et al. (2003) have identified the MMCO in the SCS based on the decrease of benthic foraminiferal δ^{18}O of ODP Site 1148 during 17.8–13.2 Ma (Fig. 6). Besides, the carbon isotope records of the world oceans are characterized by the high δ^{13}C values of planktic and benthic foraminifera between 17.5 and 13.5 Ma, which is also known as the Monterey Carbon Isotope Excursion (Vincent and Berger, 1985; Banerjee et al., 2017). Wang et al. (2003) suggested that the Monterey excursion is also prominently displayed at ODP Site 1148, reflecting accumulation of diatom–rich deposits in the Pacific Rim. The decline of species diversity patterns (*S*, *H* and *E*), TOC and *P* between ~14.66 and 14.24 Ma may be explained by the drastic fluctuation in paleowater depths (Fig. 6), possibly caused by a short–lived tectonic uplift in the Lufeng Sag and Dongsha Uplift (Xie et al., 2014; Xue et al., 2018). It is inferred that rising sea level results in open sea environment and gradually increases seafloor oxygenation, however, the high primary productivity and organic carbon storage make a eutrophic outer shelf or even upper bathyal environment. Consequently, the dominance of the *Uvigerina* spp. assemblage and high TOC show a good correlation with the MMCO.

6.2 *Oligotrophic conditions in the middle to late Middle Miocene, 1 550–1 240 m (14.24–11.54 Ma)*

The *Cibicides* spp. assemblage becomes important, suggesting a high–energy, high–oxygenation, and oligotrophic environment with pulsed organic matter input during the middle–late Middle Miocene (Fig. 5). The high percentage of oxic species of Hole LF14 also indicates a high seafloor oxygenation (Fig. 6). The paleowater depths fluctuate between 94 and 198 m, being 149 m on average, suggesting a middle to outer shelf environment (Fig. 6) (Xue et al., 2018). The shift in lithology from mud to silt–mud alternating layer at ~14.24 Ma is accompanied by decreasing paleowater depths (Figs 4 and 6). This suggests frequent alternations of dark and light sediments upward may be caused by frequent fluctuations of paleowater depths.

The TOC values were high from 13.80 to 13.41 Ma (Fig. 4). A high TOC, caused by prevailing of upwelling in the Pacific Rim due to global cooling, has also been reported from Hole PY33–1–1 during 14.24–13.41 Ma (Wan et al., 1996). Besides, the relative abundances of *Uvigerina* spp. and *Heterolepa dutemplei* show significant decreases at Hole LF14 during 14.24–13.41 Ma (Fig. 3). A similar faunal change is also observed from shallow marine sequences of the Western Foothills in Taiwan (Huang et al., 2012). Huang et al. (2012) suggested that the decline of benthic foraminifera (e.g., *Heterolepa praecincta* and *Uvigerina nitidula*) during 14.5–12.9 Ma and extinction of the endemic benthic species (e.g., *Textularia kansaiensis*, *Textularia akaminei*, and *Bigenerina shihtiensis*) could partly be attributed to sea level drop due to the expansion of the Antarctic Ice Sheets. Our records are consistent with the study of Huang et al. (2012). However, we assume that this faunal change is caused by the sea level drop and decreased food supply and the improved seafloor oxygenation in response to the expansion of the Antarctic Ice Sheets (Fig. 6). A noticeable shoaling in paleowater depths and declining *P* were recorded at Hole LF14 from 14.24 to 13.41 Ma (Fig. 6). At Hole BY7–1–1, this is a period of regression, characterized by low sea level and cool water condition (Xu, 1996). However, the low tectonic subsidence rate (~50 m/Ma) indicates that tectonic subsidence should not be the main factor resulting in this sea level drop (Xue et al., 2018). Qin (1996) assumed that this remarkable sea level drop in the ZRMB resulted from global cooling and expansion of the Antarctic Ice Sheets. At ODP Site 1148, the Middle Miocene δ^{18}O level increases during 14.5–13.6 Ma with a 0.9‰ enrichment (Zhao et al., 2001a). The variation in the amplitude of the Cenozoic deep sea δ^{18}O signal largely reflects changes in continental ice volume and temperature (Miller et al., 1991; Zachos et al., 2001). Flower and Kennett (1994) suggested that Mi–3 indicates major ice sheets growth on East Antarctica, resulting in high–amplitude variations of global sea level, invigoration of surface ocean circulation systems, and changes in planktic and benthic foraminiferal assemblages. Therefore, the changes in paleowater depths, benthic species and TOC at Hole LF14 in the period correspond with the key time of global cooling (Mi–3) and changes in global sea level and benthic foraminiferal assemblages.

6.3 *Mesotrophic conditions in the Late Miocene to Pliocene, 1 240–676 m (11.54–4.53 Ma)*

The *Cibicidoides* spp. assemblage, suggesting a high oxygenation and mesotrophic environment, is important during 11.54–4.53 Ma (Fig. 5). The species diversity (*S*, *H* and *E*) is the highest throughout the hole. Both epifaunal and (shallow) infaunal species, e.g., *Bolivina* spp., *Cibicidoides* spp., and *Hanzawaia* spp., are important in the *Cibicidoides* spp. assemblage, indicating a mesotrophic environment during 11.54–4.53 Ma (Jorissen et al., 1995; Sgarrella et al., 2012; Pérez-Asensio et al., 2012).

The percentage of oxic species decreases slightly, but remains high during this period (Fig. 6). The paleowater depths are shallow and relatively stable, varying between 68 and 151 m, being 116 m on average (Fig. 6) (Xue et al., 2018). The global climate cooling trend continues, but show no large fluctuations during the Late Miocene to Pliocene (11.54–4.53 Ma), as inferred by the mean δ^{18}O values (Zachos et al., 2001; Wang et al., 2003). The TOC is low during 11.54–4.53 Ma, especially samples between 1 030 m and 880 m (0.38%–0.71%, being 0.47% on average) (Fig. 4). Benthic foraminiferal abundance interferes with oxygen and food levels at the seafloor affecting the *P* (van Hinsbergen et al., 2005; Milker, 2010). The values of *P* (53%–81%, being 72% on average) between 1 030 m and 880 m are relatively high compared to the paleowater depths (96–144 m, being 118 m on average). This may be explained by the low benthic foraminifera number due to lack of organic food. Therefore, the study area is middle–outer shelf environment characterized by relative high oxygenation and mesotrophic conditions during the Late Miocene to Pliocene.

The rapid increase of *Rectobolivina* spp. and *Siphonina* spp. at 11.54 Ma may be related to the increased food supply and slightly decreased oxygenation (Figs 3 and 6). The *Cibicidoides* spp. assemblage is also highlighted by the appearance and continuous occurrence of *Ammonia* spp. and *Pseudorotalia* spp. since 10.02 Ma (Fig. 3). Huang et al. (2012) documented that the benthic foraminifera of euryhaline species (e.g., *Ammonia* cf. *japonica* and *Ammonia altispira*) appear first, then the normal marine species (e.g., *Asterorotalia yabei* and *Pseudorotalia tikutoensis*) appear in the shallow water sequence of the Western Foothills of Taiwan since the transgression started at 10.2 Ma (Fig. 6). However, *Ammonia* spp. and *Pseudorotalia* spp. appear nearly at the same time at Hole LF14 (Fig. 3), which is located in the relatively deep environment in the Lufeng Sag. Huang et al. (2012) also suggested that the appearance of the new fauna at 10.2 Ma may represent an initiation of the modern Kuroshio Current by an intensification of the Western Boundary Current of the North Pacific. Tectonically, the Indo–Pacific seaway begins to close as a result of the subduction–collision between the Australia continent and the Indonesia Banda Arc in the Late Miocene (12–8 Ma) (Kennett et al., 1985; Huang, 1989; Li and Jian, 2001; Kuhnt et al., 2004; Li et al., 2004b; Kamikuri et al., 2009; Hall, 2012; Kamikuri and Moore, 2017). This event may account for an initiation of modern Kuroshio Current by an intensification of the Western Boundary Current of the North Pacific, leading to a distinct faunal change in the continental shelf of Taiwan (Huang et al., 2012). Therefore, the continuous occurrence of *Ammonia* spp. and *Pseudorotalia* spp. species may suggest that the study area is influenced by the Kuroshio Current since ~10.02 Ma.

7 Conclusions

Benthic foraminifera from 171 samples of Hole LF14 have been studied. Three distinct benthic assemblages are defined by Q–mode factor analysis. These assemblages, together with their corresponding ecological and microhabitat preferences, *P*, diversity indices and TOC are used in reconstructing the Lufeng Sag paleoenvironmental changes through the Miocene to Pliocene.

The dominance of the *Uvigerina* spp. assemblage and low diversity suggest warm, low–oxygen concentrations and eutrophic conditions during ~18.7–14.24 Ma. High values of TOC suggests an increased food flux to the seafloor. The low oxygen concentrations may be associated with a semiclosed bay with poor water exchanges and the MMCO, causing high food flux to the seafloor. High diversity and dominance of the *Cibicides* spp. assemblage suggest high–energy, high–oxygenation and oligotrophic conditions with episodic terrestrial matter input during the middle–late Middle Miocene. The sea level drop and changes in benthic foraminifera (e.g., *Uvigerina* spp., *Heterolepa dutemplei*, and *Cibicides* spp.) reflect a global cooling and major expansion of the Antarctic ice sheets. The *Cibicidoides* spp. assemblage, indicating relative high–oxygen content and mesotrophic conditions, becomes important during the Late Miocene–Pliocene. The appearance and continuous occurrence of *Ammonia* spp. and *Pseudorotalia* spp. after 10.02 Ma is possibly caused by the intensified Western Boundary Current of the North Pacific.

Acknowledgements

We thank the China National Offshore Oil Corporation for providing samples used in this study.

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