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Neogene oxygen isotopic stratigraphy, ODP Site 1148, northern South China Sea

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Abstract A detailed stable isotopic study based on benthic foraminifera from 1165 samples of ODP Site 1148 (18° 50.17.3′N, 116° 33.93′E, water depth 3308.3 m), northern South China Sea, provides an excellent oxygen isotopic record with an average resolution of 30 ka. It contains the most continuous $\delta^{18}O$ data with highest resolution for the whole Neogene sequence in the world. The $\delta^{18}O$ curve shows a step-like increasing upwards and records 5 increases, 3 decreases and 2 stable stages during the Neogene, reflecting the general trend of global cooling. Among these events the $\delta^{18}O$ decrease at 17.2—14.5 Ma, and two $\delta^{18}O$ increases at 14.5—13.6 and 3.0—2.4 Ma are most marked and globally comparable. The intervals at 13.6—10.2 and 6.0—3.0 Ma with the lowest-amplitude and least fluctuation in $\delta^{18}O$ represent the most stable bottom water periods for the South China Sea.

Keywords: oxygen stable isotope, benthic foraminifera, stratigraphy, paleoceanography, Neogene, South China Sea.

The transition of the Earth surface system from the early Cenozoic “greenhouse world” without polar ice into the late Cenozoic “ice house world” with both the Antarctic and Arctic ice sheets is the most critical change in the evolution of the modern natural environment. The foraminiferal stable isotopic data provide records for the important changes in the global climate and oceanic circulation. There are a number of data sets published in the literature on the Neogene stable isotope record for various purposes. However, most of these data cover relatively short age-intervals. Table 1 shows selected sites with a foraminiferal isotopic record longer than 10 Ma in the world oceans. None, except the present Site 1148, contains the whole Neogene (24—0 Ma) record, and the average time-resolution in most sites is relatively low. The oxygen isotopic curves of the Cenozoic presented by Savin et al.[2] and Miller et al.[1], actually, were compiled from a number of sites. In China, foraminoferal stable isotopic records have been mainly applied to the Quaternary[3—5].

Site 1148 is the deepest in the Leg 184, which penetrated 850 mcd and reached the early Oligocene sediment of 32 Ma. Foraminiferal stable isotopic analysis was made for a total of 1165 core samples taken from the sequence above 480 mcd. A continuous and high-resolution record is thus obtained for the whole Neogene. Compared with long records from other parts of the world oceans (table 1), the isotopic record of Site 1148 is likely to be the most complete and continuous one with higher average resolution than others, thereby providing excellent data for the study of Neogene isotope stratigraphy, paleoclimatology and paleoceanography.

Table 1 Selected sites with long Neogene records of oxygen stable isotope in the world oceans

Areas	Sites	Material	Age/Ma	Sample number	Time resolution/ka	References
W Pacific	1148	Benthic F	0—24	1163	21	this paper
	289	Benthic F	5—21	156	109	[6]
SW Pacific	588	Benthic F	4—24	293	68	[7]
	590	Benthic F	2—20	240	79	
E Pacific	575	Planktonic F	6—21	109	138	[8]
Indian Ocean	709	Benthic F	4—25	234	90	[9]
	216	Benth. + plankt. F	6—20	63	220	[10]
South Ocean	747	Benthic F	8—26	171	105	[11,12]
Atlantic	563	Benthic F	8—26	167	108	[11, 12]
	608	Benthic F	8—26	126	143	
	999	Bulk samples	10—26	120	133	[13]

1 Material and method

Benthic foraminifera were picked from 1165 core samples for oxygen and carbon stable isotope analysis. Of these 936 samples were collected from a continuous sequence covering the early Miocene to Quaternary (24—0 Ma) above 475 mcd at Hole 1148A that is located east of the Dongsha Islands, the northern South China Sea (18° 50.17.3′N, 116° 33.93′E, water depth 3308.7 m). There is a 2 Ma-hiatus (~26—24 Ma) found at 475 mcd at Hole 1148A, and below this is a Oligocene sequence in which all the calcareous microfossils were heavily mineralized[14]. Other 229 samples were taken from the late Pliocene to Quaternary section of Hole 1148B and the Quaternary section of neighboring Site 1147 (18° 50.11′N, 116° 33.28′E, water depth 3308.3 m). All the samples collected from Hole 1148B and Site 1147 were estimated in relation to Hole 1148A, based on a detailed correlation of magnetic susceptibility. The sampling intervals vary from 10 to 80 cm, depending upon the sedimentation rate. The time resolution of samples is 20.6 ka, on average, but varies with time spans, 12 ka between 0 and 6 Ma, 27 ka between 6 and 18 Ma, and 49 ka between 18 and 24 Ma. The time resolution is lowest between 18 and 20 Ma due to the strong dissolution of foraminifera.

The sediment samples were soaked in tap water for 1—2 days after drying at 60℃ in an oven, then washed through a 63μm-sieve and dried at 60℃. Foraminifera were picked from the coarser (>150 μm) fraction for stable isotope analysis. The well preserved specimens of benthic foraminifera (clean, intact, no signs of dissolution, and >0.30 mm) were chosen and washed with ethanol (>99.7%) in an ultrasonic bath in 40 kHz frequency for 3 times, with each time being 5 to 10 seconds. The washed specimens were dried at 60℃ in an oven for 5 h and then moved to the sample vial in a Finnigan automatic carbonate device (Kiel III) and reacted with ortho-phosphoric acid at 70℃ to generate CO_2 which was measured with a Finnigan MAT252 mass spectrometer at the Key Laboratory of Marine Geology of Ministry of Education, Tongji University, Shanghai. The results were regularly checked with the Chinese National Standard GBW04405 and international standard NBS19, and the standard deviation is 0.07% for $\delta^{18}O$ and 0.04% for $\delta^{13}C$ during year 2000. Conversion to the international Pee Dee Belemnite (PDB) scale was performed using NBS19 and NBS18 standards. Benthic foraminifera *Cibicidoides wuellerstorfi* were analyzed for most of samples from the Middle Miocene-Quaternary section and *C. kullenbergi* from the Early and Middle Miocene. In the case where *C.wuellerstorfi* or *C.kullenbergi* was absent in samples, *Cicibidoides* spp., *Oridorsalis* spp. and *Uvigerina* spp. were used as alternatives. The isotopic values of all the later species and genera have been transferred into *C. wuellerstorfi* equivalent values in accordance with the method proposed by Shackleton et al. (1995)[15].

2 Results

The major Miocene planktonic and nannofossil biostratigraphic and late Pliocene-Quaternary magnetostratigraphic events of Site 1148 are presented in fig. 1[14]. The age of each oxygen isotopic sample of benthic foraminifera was estimated through interpolation. Fig. 2 shows the age distribution of oxygen isotopic data at Site 1148 since 24 Ma.

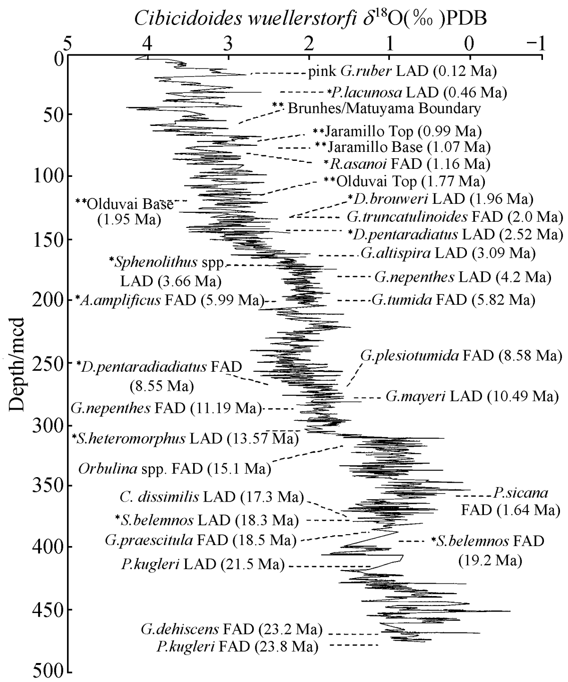

Fig. 1. Neogene oxygen isotope data of benthic foraminifers plotted against composite depth (mcd), major biostratigraphic events of planktonic foraminifera and nannofossil*, and paleomagnetic events** at Site 1148, northern South China Sea. Biostratigraphic and paleomagnetic data are based on Wang, Prell et al., 2000[14]. (Fourteen foraminiferal and nannofossil time levels (marked with asterisk) are applied for the age calculation of isotopic samples.

The general trend of oxygen isotopic variation of Site 1148, as expected, is similar to the previous Neogene records of benthic foraminifera, showing a step-like increase from the lightest value of –0.5‰ in the early Miocene to the heaviest value of 4.5‰ in the Quaternary. The total increase of 5.0‰ is a clear record of the global cooling and ice sheet expansion. A series of major $\delta^{18}O$ events has been recognized, including five $\delta^{18}O$ increase events for the intervals of 22.2—21.6 Ma, 14.5—13.6 Ma, 10.2—9.6 Ma, 7.2—6.2 Ma and 3.0—2.4 Ma, three $\delta^{18}O$ decrease events for the intervals of 23.8—22.2 Ma, 17.2—14.6 Ma and 7.8—7.2 Ma, and two $\delta^{18}O$ relatively stable stages in the intervals of 13.2—10.2 Ma and

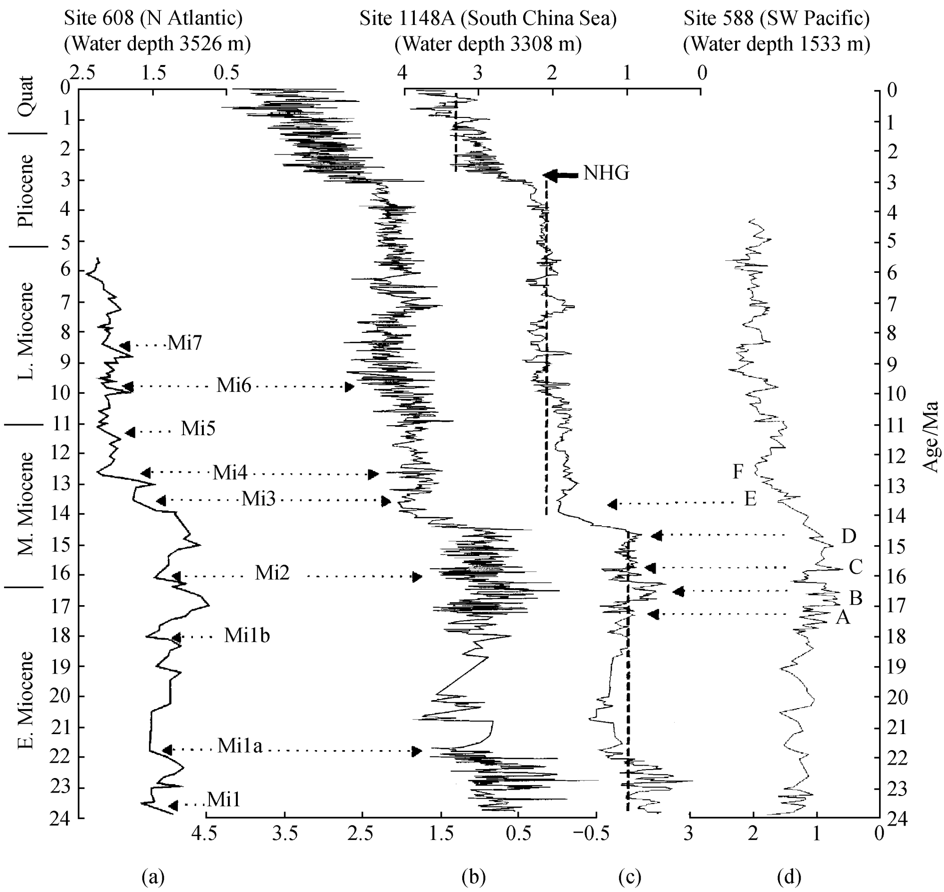

Fig. 2. Neogene oxygen isotopic stratigraphy of benthic foraminifera at Site 1148, northern South China Sea (b, c) and its comparison with Site 608 (North Atlantic)(a)[12] and 588 (Southwest Pacific)(d)[7,12,16]. Mi1-7 indicates Miocene δ^{18}O maximum events[12,16]; A—D indicate δ^{18}O minimum events, E and F indicate δ^{18}O maximum events[18,19]; NHG indicates North Hemispheric Glaciation; (c) the 5-point smoothing curve for Site 1148, and the vertical dotted lines indicate the average values for the three δ^{18}O terraces.

6.0—3.0 Ma, respectively.

3 Discussion

3.1 Neogene cooling events

The climate has profoundly changed from the warm "green-house world" to the cool "ice-house world" since the development of the large-scale ice sheet on the Antarctic in the early Oligocene. Since then a series of cooling events has taken place, culminating in the formation of the glacial-interglacial cycles in the Quaternary[2,11]. The five increase events of benthic foraminifera δ^{18}O found at Site 1148 clearly indicate the process of the global cooling since 24 Ma. An early Miocene increase in δ^{18}O between 22.2 and 21.6 Ma probably corresponded to the event Mi1a (22.4—21.8 Ma) designated by Miller et al. (1996)[16]. However, the increasing magnitude of $\delta^{18}O$ value at 1148 (1.5‰) is obviously higher than the previous records, probably due to the lighter $\delta^{18}O$ values in the earliest Miocene.

The middle Miocene $\delta^{18}O$ increase of benthic foraminifera reflected a major expansion of the Antarctic ice sheet and a severe cooling of bottom water[2,9,11—13,17—21]. As shown in fig. 2(a) for the $\delta^{18}O$ curve of the North Atlantic Site 608 and in fig. 2(d) for the Southwest Pacific Site 588, the typical middle Miocene $\delta^{18}O$ increase event was composed of two $\delta^{18}O$ maxima, i.e. Mi3 and Mi4 maxima of Miller et al. (1991)[11] or E and F maxima of Woodruff and Savin (1991)[18]. At Site 1148 the middle Miocene $\delta^{18}O$ increase occurred from 14.5 to 13.6 Ma with a 0.9‰ enrichment, which obviously coincides with event Mi3[11] or E[20]. No distinct Mi4 or F event was found at Site 1148.

Two $\delta^{18}O$ increase events occurred in the early (10.2—9.4 Ma) and latest late Miocene (7.2—6.2 Ma) respectively. The earlier event with an increase in $\delta^{18}O$ from 1.6 to 2.7‰ between 10.2 and 9.4 Ma is probably coincident with Mi6 maximum of Miller et al. (1991)[11], and has the heaviest $\delta^{18}O$ value known in the Miocene. Based on a detailed study of the Miocene benthic foraminifera at Site 289 on the Ontong-Java Plateau, West Pacific, Woodruff and Douglas (1981) documented that the $\delta^{18}O$ temperature was lowest at ca. 9 Ma which was accompanied by a marked faunal turnover and the formation of a deep-sea fauna similar to the present day[6]. At Site 1148 the $\delta^{18}O$ maximum value at ca. 9.4 Ma was 0.7‰ heavier than the Mi3 maximum at 13.6 Ma (fig. 2(b)), indicating that the bottom water temperature was 2.5℃ cooler than that in the middle Miocene $\delta^{18}O$ increase event. During the late Miocene interval of 7.2—6.2 Ma, the $\delta^{18}O$ values at Site 1148 increased from 1.5% to 2.6‰, and this event was probably related to the Messinian salinity crisis in the Mediterranean, resulting from the growth of the Antarctic ice sheet and global cooling[22,23].

A marked $\delta^{18}O$ increase from 1.7% to 3.6‰ occurred between 3.0 and 2.4 Ma at Site 1148. It is the highest increase (1.9‰) in the five $\delta^{18}O$ increase events. This $\delta^{18}O$ enrichment has been regarded as the global event indicating the formation of the North Hemisphere ice sheet and the onset of the Quaternary glacial-interglacial alternation of climate[15,24—28]. High-resolution $\delta^{18}O$ records of benthic foraminifera at Site 659 from the South Atlantic, off Northwest Africa, by Tiedmann et al. (1994) and Site 846 of the equatorial East Pacific by Shackleton et al. (1995) have revealed the detail of the formation process of the northern hemisphere ice sheet during the interval from 3.15 to 2.5 Ma[15,27]. The $\delta^{18}O$ increase event at Site 1148 is similar to that at South Atlantic Site 659 in terms of the total increment, the increase in glacial stages and the amplitude of oscillation, but obviously higher than the equatorial East Pacific Site 846 and other Pacific Sites such as Sites 590 of the Southwest Pacific[25], 586 of the Ontong Java Plateau[26] and 849 of the equatorial East Pacific[28]. The reason for these differences is unclear.

3.2 Neogene warming events

Against the general background of $\delta^{18}O$ stepwise increase, there are three $\delta^{18}O$ decrease events occurring at 23.8—22.2 Ma, 17.2—14.6 Ma and 7.8—7.2 Ma, respectively. In the interval from 23.8 to 22.2 Ma, the $\delta^{18}O$ values vary between –0.5‰ and 1.3‰, and these include the lightest value in the Neogene at Site 1148. The values of the minimum and maximum peaks are 0.4‰ and 0.3‰ lighter than those during the late Early Miocene "Climate Optimum". However, most previous work shows that the $\delta^{18}O$ values in the early period of the early Miocene are 0.2‰—0.5‰ heavier than those in the late period of the early Miocene[7,9,11,12,21,22]. Diagenesis is known to cause the depletion of foraminifer $\delta^{18}O$[13]. At Site 1148, the sediments of 23.8—22.2 Ma are buried below 430 mcd. Although no definite recrystallization was observed under the microscope examination for benthic foraminifer tests, some fine calcite crystals were found adhered on the inner surface of some foraminifer tests. It will require further work to check if these crystal grains are the cause of the observed depletion in $\delta^{18}O$.

In the $\delta^{18}O$ decrease event between 17.2 and 14.6 Ma, most of the minima are lighter than 0.8‰. The lightest values (~0‰) occurred at 16.4 and 16.2 Ma respectively, being 1.6‰ lighter than the value at the beginning of the event (17.2 Ma). Another three $\delta^{18}O$ minima occurred at 17.2, 15.8 and 14.5 Ma, respectively. Based on oxygen isotopic data from 9 sites of the global oceans, Woodruff and Savin (1991) designated A, B, C and D minima for the $\delta^{18}O$ decrease event in the interval from 17 to 14 Ma[18]. According to Flower and Kennett (1995), these 4 minima occurred at 17.25, 16.30, 15.70 and 14.57 Ma, respectively[20]. At Site 1148, the 4 minima occurred at 17.2, 16.4, 15.8 and 14.5 Ma, which may be correlated with A, B, C and D minima of Flower and Kennett (1995) individually. These $\delta^{18}O$ minima indicate the warm stages between 17 and 14 Ma[8] or " the middle Neogene climatic optimum"[29], "the middle Miocene warmth"[30], "the Miocene climatic optimum"[19,22] and "the Miocene Climatic Optimum 1"[31]. The $\delta^{18}O$ data of Site 1148 have, therefore, confirmed the global Miocene warmth and show the relatively higher-temperature bottom water during the period. However, during this warming event there were two $\delta^{18}O$ maxima occurring at 17.2—16.8 and 16.2—15.8 Ma respectively, of which the latter probably coincided with the early Miocene Mi2 event of Miller et al. (1991)[11].

The $\delta^{18}O$ decrease in the interval from 7.5 to 6.7 Ma is less distinct as compared with other decrease events, showing a depletion of about 0.4‰. A similar event has been reported rarely elsewhere and is probably correlated to the $\delta^{18}O$ decrease at Site 588 of the Southwest Pacific during the "Climatic Optimum 3" between 7.6 and 6.6 Ma[31].

3.3 Neogene stable stages

As shown in fig. 2(c), the $\delta^{18}O$ curve of Site 1148 clearly distinguishes three terraces at 23.8—14.5, 13.6—3.0 and 2.4—0 Ma and two slopes at 14.5—13.6 and 3.0—2.4 Ma. The $\delta^{18}O$

values of the three terraces average 0.968‰, 2.045‰ and 3.237‰, respectively. Taking 0.26‰ of $\delta^{18}O$ as 1℃ of temperature change[32], the $\delta^{18}O$ differences between the three terraces indicate that the average temperature of the bottom water was 4.1℃ lower in the interval of 13.6—3.0 Ma and 4.6℃ lower again in the interval of 2.4—0 Ma. Both the earlier and later terraces are characterized by high-amplitude fluctuations. However, the amplitudes of $\delta^{18}O$ variations are markedly lower in the middle terrace. In the time intervals of 13.6—10.2 Ma and 6.0—3.0 Ma, the $\delta^{18}O$ is most stable and the amplitude of fluctuation is generally less than 0.5‰. Similar phenomena have been found at Site 586 of the Ontong Java Plateau, Southwest Pacific[26], Site 849 of equatorial East Pacific[33] and Site 659 of North Atlantic[27]. Flower and Kennett (1994) have attributed higher $\delta^{18}O$ variations to the instability of the East Antarctic ice sheet in the early and early middle Miocene, whereas the lower variation in $\delta^{18}O$ after the major $\delta^{18}O$ increase from 14.5 to 14.1 Ma indicated a more stable East Antarctic ice sheet[19]. The stability in $\delta^{18}O$ in the two intervals of 13.6—10.2 and 6.0—3.0 Ma may reflect a constant temperature and salinity of the bottom water in the South China Sea.

3.4 Neogene oxygen isotope stratigraphic correlation

In the last decade oxygen isotopic records of benthic foraminifera have been extensively applied to stratigraphic correlation upon the base of the biostratigraphic and magnetostratigraphic frameworks. Based on the isotopic and carbonate data of DSDP Leg 85, the central equatorial Pacific, Vincent and Killingley (1988) recognized 8 time levels for the early and middle Miocene[8]. Miller et al. (1991), Wright and Miller (1992) and Miller et al. (1996) identified 10 Miocene increase events in benthic foraminiferal $\delta^{18}O$[11,12,15]. In terms of benthic foraminiferal isotopic data of 10 global sites Woodruff and Savin (1991) designated 6 $\delta^{18}O$ and 7 $\delta^{13}C$ events for the Miocene stratigraphy[18]. These million year scale isotopic events have been applied to the deep-sea stratigraphy[13,19,20,22,23,31], although there are still problems in their age determination and hence correlation between different sites. The magnetostratigraphy of Site 1148 remains to be established, but we believe that the $\delta^{18}O$ increases at intervals of 22.2—21.6, 16.2—15.8, 14.5—13.6 and 10.2—9.4 Ma are correlated with the $\delta^{18}O$ events Mi1a, Mi2, Mi3 and Mi6 of Miller et al. (1991,1996), and the $\delta^{18}O$ maximum at 13.6 Ma with the E event of Flower and Kennett (1995). The $\delta^{18}O$ decreases at 17.2, 16.4, 15.8 and 14.5 Ma at Site 1148 then correspond to events A, B, C and D of Flower and Kennett (1995). However, as noted by Miller et al. (1991)[11,12], more $\delta^{18}O$ events should be found in the Miocene as higher-resolution records became available. For example, based on higher-resolution foraminiferal $\delta^{18}O$ records, the middle Miocene event E has been split into three increases (E1, E2 and E3) by Flower and Kennett (1994)[19]. As the average time resolution in the present study has come up to a level of 27 to 49 ka in the section before 6 Ma at Site 1148, more $\delta^{18}O$ events on the 100 ka scale have been found. However, the ages of these events need to be carefully calibrated within the biostratigraphic and magnetostratigraphic framework in the further.

4 Conclusions

The step-like increase curve of benthic foraminiferal $\delta^{18}O$ of Site 1148 since 24 Ma exhibits a trend of gradually cooling of climate in the South China Sea, which fits well with other global data sets. Five increases, three decreases and two stable stages in $\delta^{18}O$ have been identified. Among these $\delta^{18}O$ events, the decrease at 17.2—14.5 Ma, and increases at 14.5—13.6 and 3.0—2.4 Ma are the most pronounced and cosmopolitan, reflecting the Miocene climatic optimum, major expansion of the Antarctic ice sheet and formation of the North Hemisphere ice sheet, respectively. The heaviest values in $\delta^{18}O$ at 10.2—9.4 Ma indicated the coldest bottom water in the Miocene. The lighter and high-amplitude fluctuation in $\delta^{18}O$ at 24.0—14.0 Ma reflected the instability of the Antarctic ice sheet and the warmer bottom water in the early Miocene. The intervals of 12.6—10.6 and 6.0—3.2 Ma are marked by the lowest-amplitude fluctuation in $\delta^{18}O$, representing the most stable temperature and salinity in the bottom water of the South China Sea.

Among the $\delta^{18}O$ increase and decrease events at Site 1148, the increases occurring at 22.2—21.6, 16.2—15.9,14.5—13.6 and 10.2—9.4 Ma correspond to events Mila, Mi2, Mi3 and Mi6 of Miller et al. (1991), and the decreases at 17.2, 16.4, 15.8 and 14.5 Ma correspond to events A, B, C and D of Woodruff and Savin (1991).

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References

1. Miller, K. G., Fairbank, R. G., Mountain, G. S., Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion, Paleoceanogr., 1987, 2(1): 1—19.
2. Savin, S. M., Keller, G., Douglas, R. G. et al., Miocene benthic foraminiferal isotopic records: A synthesis, Mar. Micropaleont., 1981, 6: 423—450.
3. Jian Zhimin, Chen Minben, Lin Huiling et al., Stepwise paleoceanographic changes during the last deglaciation in the southern South China Sea: the records of isotopes and microfossils, Science in China, Ser. D, 1998, 41(2): 187—124.
4. Jian Zhimin, Stable isotopic evidences of the glacial deep water properties in the South China Sea, Science in China, Ser. D, 1998, 41(4): 337—344.
5. Zhao Quanhong, Wang Pinxian, Progress in Quaternary paleoceanography of the South China Sea: A review, Quaternary Sciences (in Chinese with English abstract), 1999, 6: 481—501.
6. Woodruff, F., Douglas, R. G., Response of deep-sea benthic Foraminifera to Miocene paleoclimatic events, DSDP Site 289, Mar. Micropaleont., 1981, 6: 617—632.
7. Kennett, J. P., Miocene to early Pliocene oxygen and carbon isotope stratigraphy of the Southwest Pacific, DSDP Leg 90, in Init. Rep. DSDP (eds. Kennett, J. P., von der Borch, C. C.), 1986, 90(pt.2):1383—1411.
8. Vincent, E., Killingley, J. S., Oxygen and carbon isotope record for the Early and Middle Miocene in the central equatorial Pacific (Leg 85) and paleoceanographic implications, in Init. Rep. DSDP (eds. Mayer, L., Theyer, F., Barron, A. J. et al.), 1985, 85: 749—769.
9. Woodruff, F., Savin, S. M., Abel, L., Miocene benthic foraminifer oxygen and carbon isotopes, Site 709, Indian Ocean, in Proc. ODP Sci. Res. (eds. Duncan, R. A., Backman, J., Peterson, L. C. et al.), 1990, 115: 519—528.
10. Vincent, E., Berger, W. H., Carbon dioxide and polar cooling in the Miocene: The Monterey hypothesis, AGU, Washing-

ton, D.C., Geophys. Monogr., 1985, 32: 455—468.

11. Miller, K. G., Wright, J. D., Fairbanks, R. G., Unlocking the ice house: Oligocene-Miocene isotope, eustasy, and margin erosion, J. Geophys. Res., 1991, 96(B4): 6829—6848.
12. Wright, J. D., Miller, N. G., Miocene stable isotope stratigraphy, Site 747, Kerguelen Plateau, in Proc. ODP, Sci. Res. (eds. Wise, S. W., Jr Schlich, R., Palmer, A. A. et al.), 1992, 120: 855—866.
13. Mutti, M., Bulk $\delta^{18}O$ and $\delta^{13}C$ records from Site 999, Colombian Basin, and Site 1000, Nicaraguan Rise (latest Oligocene to middle Miocene): Diagenesis, link to sediment parameters, and paleoceanography, in Proc. ODP Sci. Res. (eds. Leckie, R. M., Sigurdsson, H., Acton, G. D. et al.), 2000, 165: 275—283.
14. Wang, P., Prell, W. L., Blum, P. et al., Proceedings of the Ocean Drilling Program, Initial Reports Volume 184 (CD-ROM), Nat. Sci. Found. & Joint Oceanogr. Inst., Inc., 2000.
15. Shackleton, N. J., Hall, M. A., Pate, D., Pliocene stable isotope stratigraphy of ODP Site 846, in Proc. ODP Sci. Res. (eds. Pisias, N. G., May, L.A., Jeneck, T. R. et al.), 1995, 138: 337—355.
16. Miller, N. G., Mountain, G. S. et al., Drilling and dating New Jersey Oligocene-Miocene sequence: Ice volume, global sea level, and Exxon records, Science, 1996, 271: 1092—1095.
17. Shackleton, N. J., Kennett, J. P., Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analyses in DSDP Sites 277, 279, and 281, in Init. Rep. DSDP. (eds. Kennett, J. P., Houtz, R. E., Andrews, P. B. et al.), 1975, 29: 743—755.
18. Woodruff, F., Savin, S. M., Mid-Miocene isotope stratigraphy in the deep sea: High-resolution correlations, paleoclimatic cycles, and sediment preservation, Paleoceanography, 1991, 6(6): 755—806.
19. Flower, B. P., Kennett, J. P., The middle Miocene climatic transition: East Antarctic ice sheet development, deep ocean circulation and global carbon cycling, Palaeo. Palaeo. Palaeo., 1994, 108: 537—555.
20. Flower, B. P., Kennett, J. P., Middle Miocene deepwater paleoceanography in the southwest Pacific: Relating with East Antarctic ice sheet development, Paleaceanogr., 1995, 10(6): 1095—1112.
21. Pagani, M., Arthus, M. A., Freeman, K. H., Miocene evolution of atmospheric carbon dioxide, Paleoceanogr., 1999, 14(3): 273—292.
22. Hodell, D. A., Woodruff, F., Variations in the strontium isotopic ratio of seawater during the Miocene: Stratigraphic and geochemical implications, Paleoceanogr., 1994, 9(3): 405—426.
23. Kennett, J. P., Marine Geology, Englewood: Prentice-Hall, Inc., 1982, 813.
24. Shackleton, N. J., Opdyke, N. D., Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^6 year scale, Quat. Res., 1973, 3: 39—55.
25. Elmstrom, K. M., Kennett, P., Late Neogene paleoceanographic evolution of Site 590: Southwest Pacific, in Init Rep. DSDP (eds. Kennett, J. P., von der Borch, C. C., Baker, P. A. et al.), 1983, 90(Part 2): 1361—1381.
26. Whitman, J. M., Berger, W. H., Pliocene-Pleistocene carbon isotope record, Site 586, Ontong Java Plateau, in Proc. ODP Sci. Res.(eds. Berger, W. H., Kroenke, L. W., Janecek, T. R. et al.), 1993, 130: 333—348.
27. Tiedemann, R., Sarnthein, M., Shackleton, N. J., Astronomic timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of Ocean Drilling Program site 659, Paleoceanogr., 1994, 9(4): 619—638.
28. Mix, A. C., Pisias, N. G., Rugh, W. et al., Benthic Foraminifera stable isotope record from Site 849 (0—5 Ma): Local and global climate changes, in Proc. ODP Sci. Res. (eds. Pisias, N. G., Mayer, L. A., Jenecek, T. R. et al.), 1995, 138: 371—412.
29. Tsuchi, R., Neogene events in Japan and the Pacific, in Pacific Neogene Event Studies (ed. Tsuchi, R.), Shizuoka: Kurofune Printing Co. Ltd., 1987, 102—104.
30. Tsuchi, R., Neogene Events in Japan and Southeast Asia, in Annual Technical Meeting 1989 and IGCP-246, Proceedings, Thailand: Chiang Mai Univ., 1991, 169—177.
31. Barron, J. A., Baldauf, J. G., Development of siliceous sedimentation in the north Pacific during the Miocene and Early Pliocene, in Pacific Neogene Events (ed. Tsuchi, R.), Tokyo: Univ. Tokyo Press, 1990, 43—63.
32. Moore, T. C. Jr., Pisias, N. G., Keigwin, L. D., Cenozoic variability of oxygen isotopes in benthic foraminifera, in Climatic in Earth History, National Academy Press, 1982, 172—182.
33. Cannariato, K. G., Ravelo, A. C., Pliocene-Pleistocene evolution of eastern tropical Pacific surface water circulation and thermocline depth, Paleoceanogr., 1997, 12(6): 805—820.