Vol. 44 No. 10 SCIENCE IN CHINA (Series D) October 2001

Transition of Quaternary glacial cyclicity in deep-sea records at Nansha, the South China Sea

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Received June 27, 2001

Abstract High-resolution oxygen isotope records over the last 2249 ka (MIS 1—86) have been obtained from cores of the upper section (105.08 m) at ODP Site 1143 (water depth of 2772 m) drilled in the Nansha area, southern South China Sea. The sampling resolution is at about 2 ka intervals, resulting in one of the best oxygen isotope records over the global ocean. The oxygen isotope curves, displaying details in the Pleistocene glacial cycles, have revealed a nearly 300 ka long stage of transition from a predominant 40 ka to 100 ka periodicity. Therefore, the "Mid-Pleistocene Revolution" should be considered as a process of transition rather than an abrupt change. Within the 100 ka glacial cycles, the changes in tropical sea surface water were found to lead those in high-latitude ice sheet. Our comparisons show that the ice sheet expansion and the glacial stage extension in the Northern Hemisphere with the 100 ka cycles must have been driven not by ice sheet itself, but by processes outside the high latitudes of the Northern Hemisphere.

Keywords: Quaternary, glacial cycles, Mid-Pleistocene Revolution, oxygen isotope stages, Nansha area.

The most outstanding contribution to paleoclimatology of the 20th century is the discovery of Milankovitch Cycles, ascribing the re-occurrence of Quaternary glaciations to periodic geometric changes of the Earth's orbit. And the most remarkable feature of the glacial periodicity is the shift from the predominately 40 ka oscillations in early Quaternary to the 100 ka cycles in late Quarternary. The feature was first found in deep-sea sediments[1] and then confirmed by its discovery in loess-paleosol sections[2]. However, changes in orbital eccentricity with a 100 ka periodicity can alter much too little the total amount of solar radiation received by the Earth's surface, and, hence, it remains an enigma why the 40 to 100 ka climatic transition occurred in the middle Pleistocene. This outstanding "100 ka problem" has long been puzzling the Earth science community[3].

Since the discovery of 40 and 100 ka periodicities before and after 0.9 Ma by deep-sea drilling at DSDP Site 502B in the Caribbean Sea about twenty years ago[4], much work has been published on the change in periodicity, and the debate around the problem is getting hotter with time[5,6] .Three major items have been disputed: (i) Was the shift from 40 to 100 ka climatic cyclicity a sudden change ("Mid-Pleistocene Revolution")[7] or a gradual process ("Mid-Pleistocene Transition")[8]? (ii) Did the shift arise from ice sheet dynamics when the ice volume in the Northern Hemisphere exceeded a certain threshold value[9], or was it a response of the global carbon cycle that generated changes in atmospheric CO_2 concentration[5]? (iii) Were the high[7, 10] or low latitudes[8] the root of the shift?

The main cause of all the debates lies in the insufficiency of data. High-quality age control, sufficient time resolution and adequate geographic coverage of stratigraphic sequences are needed to answer the questions. The high-quality sediment cores at Site 1143 taken from the Nansha area, southern South China Sea, during the ODP Leg 184 in 1999, and the resultant high-resolution oxygen isotope record of its Quaternary section have provided valuable data to address the above questions. This paper is a discussion on nature and origin of the shift in Quaternary climatic periodicity on the basis of the data from Site 1143.

1 Material and methods

ODP Site 1143 is located at 9° 21.72′N, 113° 17.11′E, at a water depth of 2772 m. Three holes were drilled at the site, with a coring depth of 510 mcd1), revealing a history over the past 12 Ma. The uppermost 100 m consist mostly of greenish gray clayey sediments rich in calcareous nannofossils and foraminifers[11] . The present study covers the upper section of 105.08 m sampled mostly at 10 cm intervals, equivalent to a time resolution of about 2 ka. The samples were oven-dried and sieve-washed, and foraminifer tests were picked from the coarse fraction residues >0.154 mm for isotope analyses. For all the samples, benthic foraminifers *Cibicidoides wuellerstorfi* (0.3—0.9 mm in diameter, 2—8 specimens) or *Uvigerina* spp. (0.4—0.9 mm in length, 3—6 specimens), and planktonic foraminifers *Globigerinoides ruber* (0.30—0.36 mm in diameter, 10—15 specimens) were analyzed, except a few ones from which no sufficient foraminiferal tests could be picked due to low fossil abundance and poor preservation. A total of 898 samples of benthic and 1015 samples of planktonic foraminifers were analyzed for oxygen and carbon isotopes in the Laboratory of Marine Geology, Tongji University, using the technique described elsewhere[12]. Because of the oxygen isotope difference between infaunal and epifaunal species of benthic foraminifers, a constant 6.4‰ was subtracted from each δ^{18}O value of *Uvigerina* to be comparable with values from *Cibicidoides wuellerstorfi*. Fig. 1 shows the oxygen isotope curves of benthic and planktonic foraminifers from ODP Site 1143.

2 Stratigraphy

The Brunhes/Matuyama porality reversal at Site 1143 was identified at ~ 42.5 m, and a large amount of mictotektites was observed at 42.81 m, assigning an age of 0.78 Ma[13]. Biostratigraphically, the last occurrence (LO) of pink-*G. ruber* (0.12 Ma) at 8.07 m, the first occurrence (FO) of the same form (0.40 Ma) at 25.03 Ma, the LO of nannofossil *Emiliania lacunosa* (0.46 Ma) at 27.27 m, the LO of benthic foraminifer *Stilostomella* (0.75 Ma) at 48.74 m, the LO of nannofossil *Calcidiscus macintyrei* (1.59 Ma) at 83.40 m, the LO of planktonic foraminifer *Globigerinoides fistulosa* (1.77 Ma) at 83.40 m, and the FO of *Globorotalia truncatulinoides* (2.0 Ma) at 96.09 m[11,14], all have provided age control of the section.

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1) mcd, meter of composition depth, simplified as “m” in the following text.

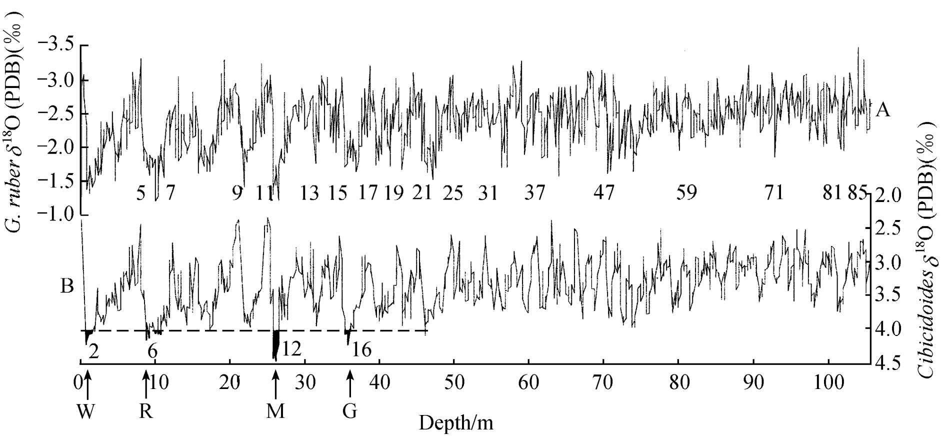

Fig. 1. Oxygen isotope curves of the upper section ODP Site 1143. A, Planktonic foraminifer *Globigerinoides ruber*; B, Benthic foraminifer *Cibicidoides wuellerstorfi*. Figures denote Marine Isotope Stages (MIS). Notice the heaviest values of benthic oxygen isotopes at MIS 2,6,12,and 16 (dash line shows $\delta^{18}O$ = 4‰), recorded as glaciations in the Alps: W, Würm; R, Riss; M, Mindel; G, Günz.

The oxygen isotope curve of benthic foraminifers is the basis of precise correlation of deep-sea deposits. The curves of Site 1143 correlate very well with the SPACMAP curve[15] and those from various oceans, providing a detailed chrono-stratigraphic framework for the site. Fig. 2 shows the benthic foraminiferal $\delta^{18}O$ correlates with that from ODP Site 677, eastern Pacific Ocean (1° 12′N, 83° 44′W, w.d. 3461m)[16]. As seen from fig.2, the upper section of 105 m at ODP Site 1143 covers Marine Isotope Stages (MIS) 1—86, corresponding to the last 2.249 Ma according to the time scale by Shackleton et al.[19].

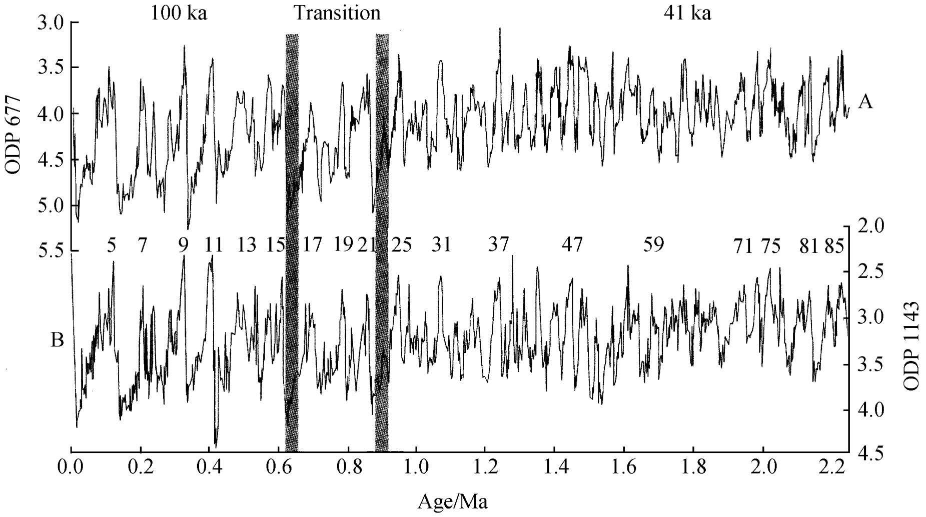

Fig. 2. Correlation of benthic-foraminiferal oxygen-isotopic curves between ODP Site 1143, South China Sea, and ODP Site 677, Eastern Pacific[16], showing the common features and correspondency. Figures denote MIS. Notice the early part of the sequence predominated by 40 ka cycles, and late part by 100 ka cycles, and the transitional nature of the middle part.

The Quaternary oxygen isotope curve of Site 1143 has the highest time resolution among the existing long sequences over two million years. There are not many long sequences of high-resolution isotope record from the deep-sea drill sites, and those with a time range over 2 Ma from various oceans are listed in table 1. Only the record from ODP Site 677, East Pacific, is comparable with our Site 1143, both having a time resolution of about 2.2 ka. The high-resolution isotope records have enabled us to explore the shift of glacial cyclicity in detail.

Table 1 High-resolution long sequences of oxygen isotope record in the global ocean

Ocean	ODP Site	Resolution	Time length	References
East Pacific	677	2.3 ka	2.6	Shackleton et al., 1990 [19]
	1143 (plankton)	2.2 ka	2.25	This paper
	1143 (benthic)	2.5 ka	2.25	This paper
West Pacific	806	4.0 ka	2.20	Berger et al.,1993[7]
Indian	758	6.4 ka	2.50	Farrell & Janecek,1991[20]
Atlantic	607	3.4 ka	2.98	Ruddiman et al.,1989[21]

3 “Revolution” or “transition”

In the early 1980s, the deep-sea drilling discovered a major shift in glacial cyclicity around 0.9 Ma, with an increase of amplitude and a decrease of frequency in climatic oscillations at the turn from MIS 23 to MIS 22[4]. Ten years later, a much better continuous sediment sequence was recovered by the ocean drilling on the Ontong Java Plateau, Western Pacific, and the term “Mid-Pleistocene Revolution” was given to this shift[7].

The shift in climate cyclicity is displayed even more clearly at Site 1143. The amplitude of δ^{18}O fluctuations in glacial/interglacial cycles increased from less than 1‰ in the early part of the sequence to nearly 2‰ in the later part, and the periodicity also rose from 40 ka to 100 ka. (fig.2). However, the two changes did not occur together, and the benthic δ^{18}O value in MIS 22 in the time of “Mid-Pleistocene Revolution” became as heavy as 4‰, surpassing that of any preceding glacial stage, whereas the 100 ka cycle was set up only in MIS 16, or nearly 0.3 Ma later after the “Mid-Pleistocene Revolution”. The glacial cycle from MIS 23 to 22 lasted only 60 ka, and a transition period was required until the 100 ka cycle appeared (fig.2). Thus, the climate transition in the middle Pleistocene was a long process of changes rather than an abrupt event.

In essence, the transition to 100 ka cycles is associated with the growth of larger ice sheet which does not melt as dictated by the 40 ka obliquity cycle but continues to grow. Accordingly, the amplitude of sea-level fluctuations in glacial cycle also increased by 33 m[4]. On the other hand, the glacial cycles in practical records are not confined to 40 ka or 100 ka in duration (fig.2). Around 1.15 Ma ago, for example, there was a long cycle far exceeding 40 ka, which may be considered as an unsuccessful attempt at cyclicity shift[17]; and the time span of the cycles within the late Pleistocene varies from 84 ka to 116 ka, with the 100 ka cycles to be “quantum” in the sense that they are 4 or 5 precessional cycles long[8]. Therefore, only the 100 ka cycles appeared with the “Mid-Pleistocene Revolution” at MIS 23—22 about 0.9 Ma, whereas the stable 100 ka cyclicity with a typical saw-tooth like δ^{18}O curve was set up 0.2—0.3 ma later at MIS 16 (fig.3). The recent study on a high-resolution magnetic susceptibility time series based on a number of deep-sea sites of the South Atlantic has discriminated a “Mid-Pleistocene Transition interim state” lasting from 0.92 to 0.64 Ma, with initiation and terminal events before and after it (I and II in upper panel of fig.3)[17] .

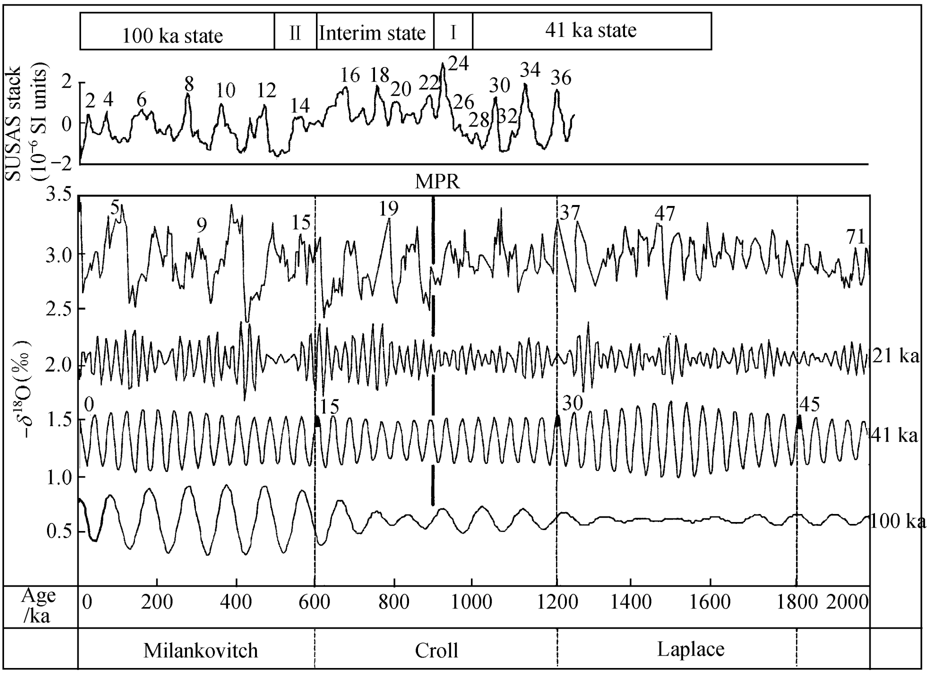

Fig. 3. The 40 to 100 ka transition in glacial cyclicity from the early to late Quaternary. Upper panel shows the transition recorded by SUSAS (subtropical South Atlantic magnetic susceptibility)[17]; I, Initiation, II, Termination. Middle panel shows the benthic-foraminiferal oxygen-isotope curve of Site 1143, Nansha; MPR, Mid-Pleistocene Revolution. Lower panel shows cycles extracted from $\delta^{18}O$ curve of ODP Site 806, Western Pacific centered at three components of orbital cycles, 21 ka of precession, 41 ka of obliquity, and 100 ka of eccentricity. Milankovitch, Croll and Laplace are three subdivisions of the Quaternary corresponding to obliquity cycles (1—15, 16—30, 31—45)[18].

The transitional nature of the middle Pleistocene climate shift is manifested not only before the 0.9 Ma “Revolution”, but also afterwards. It is interesting to note that together with the “Mid-Pleistocene Revolution”, Wolfgang Berger proposed also a threefold division of the Pleistocene at the same time[7]. According to the differences in orbital periodicity, the 1.8 Ma with 45 obliquity cycles were divided into three parts labeled by the names of scientists-contributors to the recognition of orbital cycles, the youngest 0.6 Ma showing strong 100 ka cycles as Milankovitch chron, the oldest 0.6 Ma characterized by 40 ka cycles as Laplace chron, and the interval from 0.6 to 1.2 Ma with transitional features as Croll chron. Thus, the “Mid-Pleistocene Revolution” was no more than a turn inside the transitional stage, while the 100 ka periodicity started to strengthen as early as 1.2 Ma ago (fig.3). A recent inspection of filtered record of $\delta^{18}O$ curve from ODP Site 659 (18° N, 21° W) , tropical Atlantic, shows that the cyclicity of the frequency band of 90—130 ka began to expand since 1.5 Ma, implying that the shift to the 100 ka cycle was triggered in the early Pleistocene[6].

4 High or low latitudes origin

It was realized twenty years ago that the eccentricity as insolation forcing is much too weak to explain the 100 ka glacial cycle, and the role of the 100 ka cycle is to modulate the effect of 20 ka precession cycles[22]. However, what is the mechanism controlling the glacial cyclicity? and why are the glacial cycles different in length?

The numerous answers to the questions can be split into two groups ascribing the cyclicity changes either to the ice sheet dynamics in the Northern Hemisphere, or to carbon dioxide in the atmosphere. The former group can be exemplified by Berger who believes in abrupt change at the Mid-Pleistocene Revolution and argues that long-term topographic changes by ice erosion of repeated glaciations and deepening of the shelves in the region of the Arctic allow the ice sheet in the Northern Hemisphere to grow in size[9]. Recent modeling shows that progressive removal of the sediment layer by glacial erosion results in exposure of crystalline hard bedrock which allows Laurentide ice sheet thickness to increase[10]. The changes in ice-sheet dynamic conditions enable the ice sheet in the Northern Hemisphere to grow beyond the 40 ka obliquity cycle. Raymo is the representative of the opinion that changes of CO_2 concentration in atmosphere are responsible for the shift to the 100 ka cycle. She believes that the late Cenozoic uplift of plateaux intensified the rock erosion which consumed CO_2 in atmosphere, and when the CO_2 concentration dropped below a threshold “greenhouse level”, the ice sheet became easy to grow and shifted into the 100 ka cycle[8]; and an increase in global aridity associated with a decrease in North Atlantic Deep Water strength directly triggered the cyclicity shift[3]. Shackleton compared the $\delta^{18}O$ record in deep-sea sediments with that in atmospheric oxygen trapped in Antarctic ice and found that at the 10 ka period, ice volume change lags behind atmospheric CO_2 and water temperature, hence the 100 ka cycle should not be caused by ice sheet dynamics, but probably by CO_2[5]. In sum, all proponents for ice sheet dynamics ascribe the origin of the 100 ka cycle to high latitudes; but proponents for CO_2 forcing are diverse. The changes in atmospheric CO_2 may be caused by variations in North Atlantic Deep Water production[3] for the high latitudes origin, or by fluctuations in heat transport from the low to high latitudes for the low latitudes origin[6]. Thus, it is a crucial question in Quaternary climatology, i.e. where is the origin of the 100 ka cycle, the low or high latitudes?

The Nansha sea area where ODP Site 1143 was drilled is located within the Western Pacific Warm Pool, a typical low latitudes region. A comparison between its benthic $\delta^{18}O$ record (representing deep water originating from higher latitudes) and planktonic one (representing local area, i.e. low latitudes) may throw some light on the above discussion. In the 100 ka cycle dominating late Quaternary, four glaciations, namely MIS 2,6,12,16, are best developed with benthic $\delta^{18}O$ values exceeding 4‰ (fig.1), and this is a global feature seen also in other oceans (e.g., ODP Site 677, fig. 2). These four glaciations are well documented as large-scale glacial advances in mountains and sea regressions in shelves, corresponding to Würm (MIS 2) , Riss (MIS 6), Mindel (MIS

12) and Günz (MIS 16) glaciations in the Alps[8] (fig. 1). Therefore, only the larger amplitude glaciations are recorded in mountains and shelves, and it is unrealistic to expect to find all glatiations in coastal plains. A close-up examination of the benthic and planktonic δ^{18}O curves of Site 1143 shows that the heaviest δ^{18}O value in the four glaciations appeared in plankton first, followed by the benthon. In other words, the glacial “troughs” in the plankton oxygen isotope curve are more “obtuse”, as compared to the sharp trough in the benthic curve, and the occurrences of maximal glacial values in the surface water lead those in the deep water. Therefore, the strong phases in 100 ka cycles are characterized by an early response in low-latitude tropical surface water, with the high-latitude ice sheet signals lagging behind, clearly supporting the significant role of low latitude ocean in the 100 ka cycle.

A similar order was observed in the response to the “Mid-Pleistocene Revolution” by foraminiferal faunas in Core SO 17957 (10° 53.9′N, 115° 18.3′E, w.d. 2195 m). The plankton fauna has recorded immediate changes in water temperature and thermocline depth at 0.9 Ma, whereas the benthic fauna changed its assemblage only at the Brunhes/Matuyama reversal, i.e. more than a hundred ka later together with alteration of the deep water masses[23]. This is one more evidence for the low-latitude origin of the Mid-Pleistocene transition. Even more convincing proof comes from the carbon isotope records. The δ^{13}C curves from Site 1143 and other cores clearly show the role of carbon cycle in the glacial periodicity, which will be discussed elsewhere.

5 Conclusions

One hundred meter cores in the upper section of deposits recovered from ODP Site 1143 were analyzed for oxygen isotope, yielding for the first time a high-resolution deep-sea record of the Quaternary climatic changes in the China seas and the Western Pacific. In result, the process of the 40 to 100 ka transition in glacial cyclicity from the early to late Pleistocene has been displayed in detail, and this has provided further evidence to show that the “Mid-Pleistocene Transition” was not an abrupt event caused by ice-sheet dynamic changes in high latitudes, but a long process associated with carbon cycle and atmospheric CO_2. The low-latitude changes have been found to lead those in the high latitudes, implying the crucial role of the low-latitude ocean in long-term changes of the global climatic cycles.

Although the time scale discussed here is far beyond human life, the understanding of the cause and mechanism of the glacial cycles exerts a direct impact on the environment prediction of the human society in the future, as the Earth climate system results from integration and coupling of processes with various time scales. An example is the on-going debate about the glacial cycle in the future. As different answers to whether the current interglacial is an extra-long one, and the warm climate will last for long time[24]; or the current interglacial is closing to its end, and we are facing a new severe glaciation[8] will influence our evaluation of the impact of the “greenhouse effect” on the human society, the above discussion is by no means a superfluous concern.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 49999560) and NKBRSF Project (Grant No. 2000078500).

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