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Reconstructing sea surface temperature, sea surface salinity and partial pressure of carbon dioxide in atmosphere in the Okinawa Trough during the Holocene and their paleoclimatic implications

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Abstract The sediment core DGKS9603 collected from the Okinawa Trough was used as research target. By use of unsaturated index U_{37}^{k} of long-chain alkenone, $\delta^{13}C$ of POC and of planktonic foraminifera (*G. sacculifer*), the evolutions of sea surface temperature and partial pressure of carbon dioxide in the atmosphere during the Holocene were reconstructed in the Okinawa Trough. And in combination of $\delta^{18}O$ of planktonic foraminifera, the relative difference of sea surface salinity during the Holocene was also reconstructed. Consequently, three cooling events (E_1—E_3) were identified, each of which occurred at 1.7—1.6, 5.1—4.8 and 8.1—7.4 kaBP (cal), respectively. Of the three events, E_2 and E_3 are globally comparable, their occurrence mechanism would be that the main stream of the Kuroshio Current shifted eastward due to the enhanced circulation of the northeastern Pacific Ocean, which was driven in turn by amplified intensity of sunshine and subsequent enhancement of subtropical high pressure; E_1 corresponds to the Small Ice-Age Event occurring between 1550 and 1850AD in China. In the Okinawa Trough, E_1 might be also related to the eastward shift of main stream of the Kuroshio current driven by powerful Asia winter monsoon.

Keywords: Okinawa Trough, Holocene, cooling event, partial pressure of carbon dioxide in the atmosphere.

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The climatic change and its driving mechanism during the Holocene are the important comparable parameters for studying future pattern of climatic changes. Although many domestic and overseas scholars have paid much attention to the climatic change during the Holocene, almost their researches concentrated on the lake sediments and Antarctic ice core[1—6], paying little attention to marine sediments. The East China Sea, a typically open marginal sea, has played a particular role in the global climatic changes. The Kuroshio current, a boundary current of the northwestern Pacific Ocean, whose main stream is the strongest one in the process of heat exchange between atmosphere and ocean, has impacted directly on the climatic change of East Asia, even of the globe[7]. As to the climatic change, especially the abrupt change of climate during the Quaternary in the Okinawa Trough, domestic and overseas scholars have made detailed researches[7—10], but few researches were concerned about climatic changes during the Holocene [11]. In this paper, the sediment core DGKS9603 is used to reconstruct the evolution of sea surface temperature, sea surface salinity and partial pressure of carbon dioxide in the atmosphere during the Holocene in the Okinawa Trough using unsaturated index U_{37}^{k} of long-chain alkenone, $\delta^{18}O$ and $\delta^{13}C$ of planktoni foraminifera (*G. sacculifer*), and $\delta^{13}C$ of POC, so that the cooling events are identified and their relations to the Kuroshio current are discussed.

1 Analysis methods

Core DGKS9603 with a length of 5.85 m is located on the bottom of the middle Okinawa Trough (28°8.869′N, 127°16.238′E), where the water depth is about 1100 m. As for this core, pioneering studies were made in more detail on sedimentary characteristics, chronostratigraphy, sedimentation rate and paleoceanography. In this study, the upper part of the sediment core with a length of 57 cm (corresponding to 10.15 kaBP (cal) according to AMS^{14}C data) was subsampled at average intervals of 2.2 cm. The relative content of long-chain alkenone ($C_{37:2}$and $C_{37:3}$) for each sample was measured. The measuring procedures for this molecule were reported by Meng et al.[12]. On the previous basis, 17 samples were selected for the measurement of POC according to the change of sea surface temperature, the method for measuring the POC was reported by Cai et al.[13]. The data of $\delta^{18}O$ and $\delta^{13}C$ of planktonic foraminifera were quoted from two papers[9,12], respectively, and then the sea surface temperature (SST), the relative difference of sea surface salinity (ΔS) and the partial pressure of carbon dioxide in the atmosphere (P_{CO_2}) were calculated.

2 Results

(i) Reconstructing SST. On the basis of the measurement of long-chain alkenone$C_{37:2}$ and $C_{37:3}$, the unsaturated index U_{37}^{k} was calculated using the formula of Brassell[14]. Subsequently, SST was calculated using the formula $U_{37}^{k} = 0.031T + 0.092$[15]. The calculated results are shown in Fig. 1(a). It should be noted that the SST

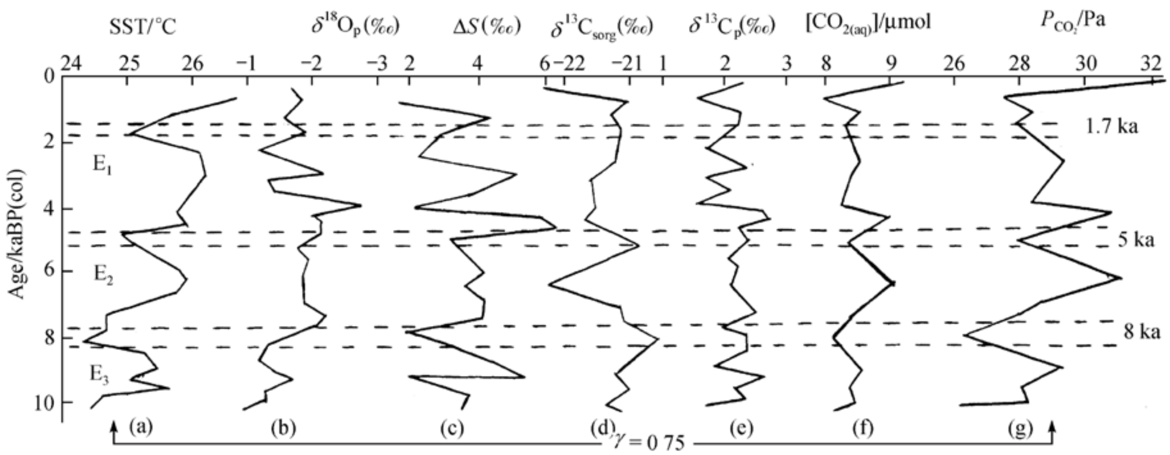

Fig. 1. The curves of SST, $\delta^{18}O_p$, $\delta^{13}C_p$, $\delta^{13}C_{sorg}$, $[CO_{2(aq)}]$, P_{CO_2} and ΔS in the sediment core DGKS9603. (a) SST; (b) $\delta^{18}O_p$; (c) ΔS; (d) $\delta^{13}C_{sorg}$; (e) $\delta^{13}C_p$; (f) $[CO_{2(aq)}]$; (g) P_{CO_2}.

derived from the U_{37}^{k} is lack of comparability with that derived from the transfer function of foraminifera in detail because the former is representative of annually averaged temperature, but its curve tends to be similar to that of $\delta^{18}O$ (Fig. 1(a), (b)).

(ii) Reconstructing ΔS. The variation of $\delta^{18}O$ of planktonic foraminifera is controlled by three factors: one is the change of $\delta^{18}O$ of global water due to increase/decrease of ice sheet ($\delta^{18}O_{WG}$); the second is the change of $\delta^{18}O$ of water due to the fluctuation of local SST; the last is the change of $\delta^{18}O$ of water related to the ΔS. Therefore, the difference of the measured $\delta^{18}O$ of planktonik foraminifera should be expressed as follows[16]:

$$\Delta\delta^{18}O_p = a + b\Delta T + c \cdot \Delta S, \quad (1)$$

where a is representative of the change of $\delta^{18}O$ of global sea water; b is representative of slope of the relationship between $\delta^{18}O$ of planktonic foraminifera and SST; ΔT is representative of the local change of SST; c is representative of the slope of the relationship between $\delta^{18}O$ of local sea water and salinity. For the Holocene, the change of $\delta^{18}O$ due to the global ice volume is reasonably negligible, consequently the formula (1) is rewritten as

$$\Delta\delta^{18}O_p = b \cdot \Delta T + c\Delta S. \quad (2)$$

It follows from formula (2) that

$$\Delta S = (\Delta\delta^{18}O_p - b\Delta T)/c. \quad (3)$$

It is shown from formula (3) that the key to derive ΔS is to determine coefficients b and c.

Coefficient b can be directly derived from the slope of regression line of relationship between $\delta^{18}O$ of planktonic foraminifera and SST(Fig. 2), so b = –0.19; the slope of the regression line of relationship between $\delta^{18}O$

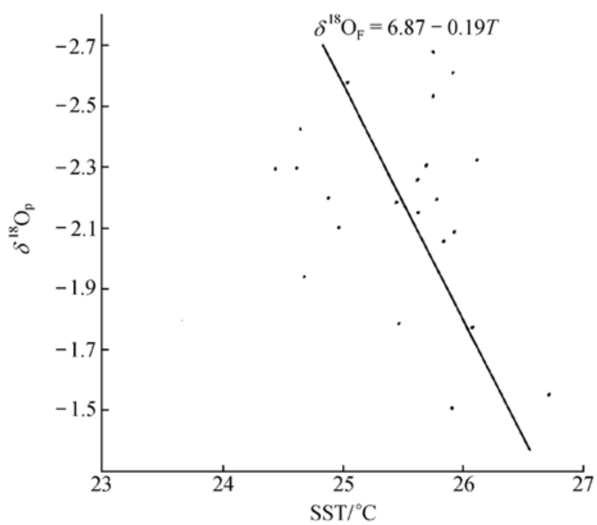

Fig. 2. $\delta^{18}O$ of planktonic foraminifera vs. SST.

and salinity of the western Pacific surface water is 0.19[18], so c = 0.19. ΔS is then obtained directly from the meas ured $\Delta\delta^{18}O$ of planktonic foraminifera. The calculated result is shown in Fig. 1(c).

(iii) Reconstructing P_{CO_2}. Popp et al.[19] have established the relationship between carbon isotopic effect ε_p occurring in the photosynthetic carbon-fixing process and CO_2 concentration of sea surface water, that is,

$$\varepsilon_p = a\log[CO_{2(aq)}] + b, \quad (4)$$

where a and b are constants, equal to –32.9 and 14.3, respectively[20]. It is obvious that if the ε_p is known the concentration of CO_2 dissolved in sea water can be easily determined. Hayes put forward the relationship of ε_p to carbon isotopic composition of primary producer (δ_p) and carbon isotopic composition of dissolved CO_2 (δ_d):

$$\varepsilon_p = 1000[(1000 + \delta_p)/(1000 + \delta_d) - 1]. \quad (5)$$

However, for marine sediments, both δ_p and δ_d cannot be measured directly, and can only be replaced by some kinds of indexes. Fairbanks determined the relationship between δ_d and $\delta^{13}C$ of planktonic foraminifera ($\delta^{13}C_p$) by experimental methods[23] as follows:

$$\delta_d (‰) = \delta^{13}C_p - 8.3. \quad (6)$$

It was reported by Ran et al.[24] that the relationship between carbon isotopic composition of organic carbon in plankton ($\delta^{13}C_{org}$) and δ_p is

$$\delta_p = \delta^{13}C_{org} - 1. \quad (7)$$

Now let's consider if the carbon isotopic composition of POC in sediments ($\delta^{13}C_{sorg}$) can be used to replace $\delta^{13}C_{org}$. In sediments, two factors affect $\delta^{13}C_{sorg}$, one is the early diagenism, the other is the relative proportion of organic carbon of plankton to that of terrigenous material. With regard to the Holocene, the effect of diagenism on $\delta^{13}C_{sorg}$ can be reasonably negligible. Besides, it is shown from the measured results that the range of $\delta^{13}C_{sorg}$ in sediments of Core DGKS9603 is –22.38‰—–20.68‰, comparable to that of $\delta^{13}C$ of marine organism (–21.6‰—–20‰)[13] but far from that of $\delta^{13}C$ of POC from the Yangtze River (–25.4‰—–24.2‰)[25], which indicates that it is reasonable to calculate δ_p in formula (7) by using $\delta^{13}C_{sorg}$ istead of $\delta^{13}C_{org}$.

Based on the above analysis, the concentration of dissolved CO_2 in sea surface water is calculated by using formulae (4)—(7) and the data of $\delta^{13}C_p$ and $\delta^{13}C_{sorg}$. The calculated results are shown in Fig. 1(f).

Suppose CO_2 is in the state of equilibrium between dissolution and release within the atmosphere-sea interface, Henny law can be used as follows[24]:

$$P_{CO_2} = \frac{1}{a}[CO_{2(aq)}], \quad (8)$$

where a is a constant related to water temperature and salinity. Ran et al. gave the functional curves of a vs. sea water temperature with the salinity in the range 34‰—36‰, from which constant a can be directly read out at a special temperature point. Conveniently, 26 values of temperature during the Holocene reconstructed from Core DGKS9603 are incorporated into 4 temperature values, i.e. $T_1 = 27$, $T_2 = 26$, $T_3 = 25$ and $T_4 = 24$℃, the a values for the 4 temperatures are $a_1 = 2.83\times10^{-2}$, $a_2 = 2.91\times10^{-2}$, $a_3 = 3.0\times10^{-2}$ and $a_4 = 3.1\times10^{-2}$, respectively. The calculated P_{CO_2} results are shown in Fig. 1(g).

3 Discussion

(i) Change of SST and identification of cooling events in the Okinawa Trough during the Holocene. One effect of climatic change is the fluctuation of SST. Therefore, SST was used to check climatic change during the Holocene in the Okinawa Trough.

It is shown from Fig. 1(a) that the climate has changed strongly during the Holocene in the Okinawa Trough, and the range of SST is 24.5—26.7℃. In the period of 10—0 kaBP (cal), SST has experienced three cycles with their respective unequal occurrence frequencies. Each of cycles shows an obvious cooling episode or event (E_1, E_2 and E_3), Which occurred in 1.7—1.6, 5.1—4.8, 8.1—7.4 kaBP (cal) and lasted 0.1, 0.3, 0.7 ka, respectively. Compared with the current averaged temperature (26.7℃) of surface sea water, the temperatures of sea water during 3 events dropped by 1.7, 1.8, and 2.2℃, respectively, but the drops in temperature were lower than that during the last glacial maximum (2.4℃)[12]. With regard to the occurrence time of cooling event, E_2 and E_3 are consistent with the previously reported cooling events, that is, they all occurred in 5 and 8.2 kaBP, respectively, which indicates that cooling events E_1 and E_2 occurred globally, and E1 corresponds to Small Ice-Age Event occurring in 1550—1850 AD. However, the three cooling events were not shown obviously on the $\delta^{18}O$ curve of planktonic foraminifera, just because the $\delta^{18}O$ curve was affected not only by SST, but also by salinity.

(ii) Relationships between cooling events and evolution of Kuroshio Current. Kuroshio Current, a boundary current with high temperature and high salinity, is an important factor in the subtropical circulation system of the northwestern Pacific Ocean. The evolution of Kuroshio Current has directly influenced the climatic change of East Asia, even of the globe[7] and in turn was not only controlled by the strength of subtropical high pressure of the northwestern Pacific Ocean in the geological epoch[27], but also affected by East Asian monsoon. When Kuroshio Current passes by some area, it must leave high-temperature and high-salinity records in the sediments there, and *vice versa*. When E1 and E2 recorded in sediments of the core DGKS9603 occurred, both SST and ΔS dropped obviously (Fig. 1(a),(c)), demonstrating that the occurring of E_1 and E_2 was closely related to the swing of the Kuroshio main stream. Sawada et al. reported that 8—7 and 5 ka ago, the intensity of the northwestern Pacific circulation was increased to result in the increase in the Kuroshio Current speed and the northward shift of its south branch[27]. In combination with the fact that the sea level of Chinese marginal sea fell at the time of 8 and 5 kaBP, it is deduced that the low-temperature and low-salinity records in Core DGKS9603 may be made by the eastward shift of the Kuroshio main stream. Shieh et al. have confirmed the eastward shift of the Kuroshio Current occurring about 8 ka ago. Because the subtropical high pressure over the northwestern Pacific Ocean is closely related to the heat equilibrium of North America continent, the cooling events (E_2 and E_3) occurring in the Okinawa Trough are then linked closely with the globally climatic system. About eight and five thousands years ago when drought occurred globally, E_2 and E_3 occurred at the same time. E_1 occurring 1.7—1.6 kaBP (cal) ago would be also related to the eastward shift of the Kuroshio main stream, which was driven by the strengthened East Asian winter monsoon during the Small Ice Age.

(iii) Response of P_{CO_2} to global climate change. It is shown from Fig.1(g) that the variation of P_{CO_2} is rather drastic in a range of 261—327 Pa. The present P_{CO_2} value is the greatest (327 Pa) and close to the measured one (340 Pa); the minimum P_{CO_2} occurred about 8 kaBP (cal) ago. The variation pattern of P_{CO_2} is similar to that of SST, showing strongly positive correlation ($r = 0.75$). It is noticeable that the three cooling events correspond to three decreases in P_{CO_2}, and the drop ranges are 48, 49 and 66 Pa. Of three cooling events, more drop in SST, more decrease in P_{CO_2}, which indicates that there must be a constraint-response relationship between SST and P_{CO_2}. As discussed above, the drop in SST is closely related to the eastward shift of the Kuroshio main stream due to the increase in its speed, which must have induced the development of upwelling to bring a large amount of nutrient to the surface seawater, subsequently the decarbonation caused by the photosynthesis was intensified to reduce the concentration of dissolved CO_2 in sea water [$CO_{2(aq)}$], so the P_{CO_2} in atmosphere was also reduced. In addition, the P_{CO_2} does not respond to climatic change passively, but rather plays a driving role in the climatic change. Therefore, the positive correlation between P_{CO_2} and SST also indicates that the global climate must tend to warm up with increasing CO_2 concentration in the air.

4 Conclusions

During the Holocene, three cooling events (E_1—E_3) occurred in the Okinawa Trough. Of the three events, E_2 and E_3 coincide with global cooling events which occurred in 5 and 8.2 kaBP (cal), respectively. The occurrence of the two events was related to the eastward shifts of the Kuroshio main stream driven by subtropical high pressure over the northwestern Pacific Ocean. E_1 corresponded to the Small Ice Age occurring in 1550—1850 AD, its occurrence was also related to the eastward shift of the Kuroshio Current driven by the East Asian winter monsoon. Three cooling events induced the decrease in P_{CO_2} for three times.

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