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Millennial-scale climate variability during the mid-Pleistocene transition period in the northern South China Sea

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ABSTRACT

Stable isotopes of foraminiferal multispecies (surface dwelling *Globigerinoides ruber*, thermocline dwelling *Pulleniatina obliquiloculata*, and benthic *Uvigerina peregrina*) and Mg/Ca ratios of *G. ruber* shells were analyzed with an average time resolution of ~370 yr for reconstructing the orbital- and millennial-scale changes in the East Asian monsoon and associated upper water structure during the mid-Pleistocene period of 800–1060 ka at ODP Site 1144 in the northern South China Sea (SCS). It has been found that generally the sea surface temperature (SST) were lower and the depth of thermocline (DOT) was deeper during glacial stages and vice versa during interglacial stages, indicating a strengthened winter monsoon and weakened summer monsoon during glacial stages. The sea surface salinity (SSS) was relatively lower during glacials, induced by the greatly reduced distance of this site to the shore during times of low sea level. Further, spectral analyses have revealed significant semi-precessional and/or precessional cycles in the planktic $\delta^{18}O$, SST and the proxies of SSS and DOT, showing the typical characteristics of tropical climate change. This means that during the mid-Pleistocene climate transition (MPT) period the East Asian monsoon evolution and associated changes of upper water column structure in the northern SCS were probably driven partly by tropical forcing, like in the southern SCS, and should not be related only to the high latitude ice sheet changes. Particularly, millennial-scale climate fluctuations (mainly ~1.4 kyr cycle) were found to exist throughout the glacial and interglacial stages during the MPT period in the northern SCS, but slightly different from the sawtooth-like D/O events recorded in late Quaternary Greenland ice cores. During the mid-Pleistocene terminations, the SST warming was synchronous with the northern ice sheet retreat, indicated by benthic $\delta^{18}O$, in the northern SCS, which is consistent to the previous findings in the late Quaternary SCS and apparently different from that in the western equatorial Pacific Ocean, providing new insights into the studies of East Asian monsoon evolution and rapid climate change.

1. Introduction

The mid-Pleistocene climate transition (MPT), in which the glacial periodicity shifts from the predominately ~40 kyr oscillations in early Pleistocene to the ~100 kyr cycles in late Pleistocene, was first found in deep-sea sediments (e.g., Shackleton and Opdyke, 1976; Prell, 1982) and later in loess-paleosol sections (Ding and Liu, 1989). Since then, much work has been published on the origin and structure of the MPT, and the debate around the problem remains vigorous in recent years (e.g., Berger et al., 1993a; Raymo, 1997; Mudelsee and Schulz, 1998; Shackleton, 2000; Raymo and Nisancioglu, 2003; Clark et al., 2006). However, changes in orbital eccentricity with a 100 kyr periodicity can change little amount of the total solar radiation received by the Earth's surface, and, hence, it is hard to explain why the 40 kyr to 100 kyr climatic transition occurred in the middle Pleistocene by the Milankovitch theory itself. The causes of the MPT were probably high latitude ice sheet dynamics when the ice volume in the Northern hemisphere exceeded a certain threshold value (Berger and Jansen, 1994), or global carbon cycle that generated changes in atmospheric CO_2 concentration (Shackleton, 2000; Hönisch et al., 2009; Koehler and Bintanja, 2009; Russon et al., 2011). In recent years, tropical forcing involving the global carbon reservoir (Wang et al., 2004) and sea surface temperature (SST) changes in the equatorial Pacific (e.g., Rutherford and D'Hondt, 2000; De Garidel-Thoron et al., 2005; Medina-Elizalde and Lea, 2005; Medina-Elizalde et al., 2008) were widely regarded as the trigger of the MPT. Rutherford and D'Hondt (2000) claimed that increased heat flow from the tropics to higher

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latitudes since 1.5 Ma strengthened the semi-precession cycle in the Northern Hemisphere, and triggered the transition from 40 kyr to sustained 100 kyr glacial cycles. SST changes in the western equatorial Pacific warm pool over the MPT period had been revealed to precede changes in global ice volume by ~3 kyr, implying atmospheric greenhouse forcing as the cause of the switch in climate periodicities at that time (Medina-Elizalde and Lea, 2005). Moreover, Clark et al. (2006) concluded that neither the mid-Pleistocene Revolution (MPR) at 900 ka nor the MPT in general was directly forced by orbital variations of insolation but rather by internal feedbacks of CO_2 and ice albedo as well as stronger silicate weathering during glacial lowstands. All these debates resulted from the insufficiency of data.

Since the Ocean Drilling Program (ODP) Leg 184 in 1999, the MPT has become a hot spot for paleoceanographic study in the South China Sea (SCS). It had been confirmed that the shift from 40 to 100 kyr climatic cyclicity was a nearly 300 ka long gradual process rather than an abrupt event ("Mid-Pleistocene Revolution") (Berger et al., 1993b), by high-resolution oxygen isotope records over the last 2 Ma at Site 1143 from the southern slope of the SCS (Wang et al., 2001). The MPT has been well documented in microfaunal (e.g., Foraminifera: Jian et al., 2000; Xu et al., 2005; Zheng et al., 2005; Nannofossil: Liu and Cheng, 2001; Diatom and radiolarian: Wang and Abelmann, 2002) and floral (Sun et al., 2003) as well as isotopic (e.g., Tian et al., 2002; Wang et al., 2004) climate proxies in the SCS. By summarizing these results, Li et al. (2008) provided a brief account on major paleoceanographic changes during the MPT period, and found rapid SST decrease at ~900 ka and substantially increased thermal gradient between the southern and northern SCS due to strengthened winter monsoon. However, previous studies on the MPT in the SCS could not be used to precisely explore the relationship between the high (ice volume) and low (e.g., tropical SST, East Asian monsoon) latitude processes because of their relatively low time resolution.

High-resolution records of climate change have demonstrated that the sub-orbital (centennial- to millennial-scale) climate variability is a global phenomenon, which was not limited to the ice cores (e.g., Dansgaard et al., 1993; Grootes and Stuiver, 1997) and high latitudes of the North Atlantic (e.g., Heinrich, 1988; Bond and Lotti, 1995; Bond et al., 1997), but also extended to the tropical Pacific regions (e.g., De Garidel-Thoron et al., 2001; Stott et al., 2002; Yancheva et al., 2007), and monsoonal Asia (e.g., Sirocko et al., 1996; Schulz et al., 1998) including the SCS (e.g., Wang et al., 1999; Zhao et al., 2006). In the late Pleistocene, the sub-orbital climate changes occurred both in the Last Glacial stage and the Holocene (e.g., Bond et al., 1997; Wang et al., 1999, 2005a,b, 2008; Schulz and Paul, 2002), implying that there are important mechanisms other than the glacial/interglacial ice volume change (Raymo et al., 1998). Most researchers ascribed the sub-orbital climate changes to internal oscillations in thermohaline circulation and solar activity (e.g., Bond et al., 2001; Schulz and Paul, 2002; Wang et al., 2005a,b; Zhang et al., 2008). If the sub-orbital climate variability operates independently of the glacial/interglacial climate cycle, it should not be restricted to the late Quaternary. Raymo et al. (1998) found that the millennial-scale climate variability could be traced back to 1.2 Ma. They claimed that millennial-scale climate instability might be a pervasive and long-term characteristic of Earth's climate, rather than just a feature of the strong glacial/interglacial cycles of the past 800 ka. Afterwards, the millennial-scale climate variability was reported throughout the past 500 ka (McManus et al., 1999), during the MPT period in the North Atlantic (Weirauch et al., 2008), and even during the late Pliocene (McIntyre et al., 2001). These findings fundamentally changed the way Earth scientists thought about the operation of the Earth's climate system and the relative sensitivity of this system to rapid climatic shifts. Although the trigger of the rapid climate change is still unclear (Broecker, 2003), the debate around the problem has increased.

Because very high-resolution records are required for reconstructing the sub-orbital variations in monsoon climate, only fragmentary pieces of information from the middle Pleistocene history are available so far in the SCS. ODP Site 1144 in the northern SCS is distinguished by extremely high sedimentation rate over the last 1 Ma (e.g., Wang et al., 2000; Bühring et al., 2004). Its ultrahigh-resolution color reflectance (L*) data (4 cm interval; time resolution of ~10 yr), as a proxy of carbonate content in deep-sea sediments, demonstrate that the D/O-like millennial-scale climate fluctuations existed throughout the glacial and interglacial stages during the MPT period (Jian and Huang, 2003). This needs further evidence from high-resolution isotopic and other paleoceanographic proxy data. Here we present a high-resolution planktic and benthic foraminiferal $\delta^{18}O$ and Mg/Ca-derived SST records that capture the mid-Pleistocene period of 800–1060 ka at ODP Site 1144. The purpose is to investigate the changes in East Asian monsoon and associated upper water structure on both orbital- and millennial-scales, which will help us to understand the nature of rapid climate change and the mechanism of the MPT toward more extreme glacial maxima as well.

2. Materials and methods

The samples used in this study were collected from Site 1144 (20°03.18′N, 117°25.14′E, water depth 2037 m; ODP Leg 184; Fig. 1; Wang et al., 2000), which was taken from a sediment drift southeast of Dongsha Islands on the northern continental slope of the SCS. The hemipelagic sediment consists of gray–green clay with quartz and calcite silt, as well as nannofossil and foraminiferal ooze. No slumping structures or mass transport have been found in the sediment core. The sedimentation rate at this site reached 49 cm kyr^{-1} over the last 1.05 Ma (Wang et al., 2000), the highest rate in the SCS, offering an unprecedented opportunity to

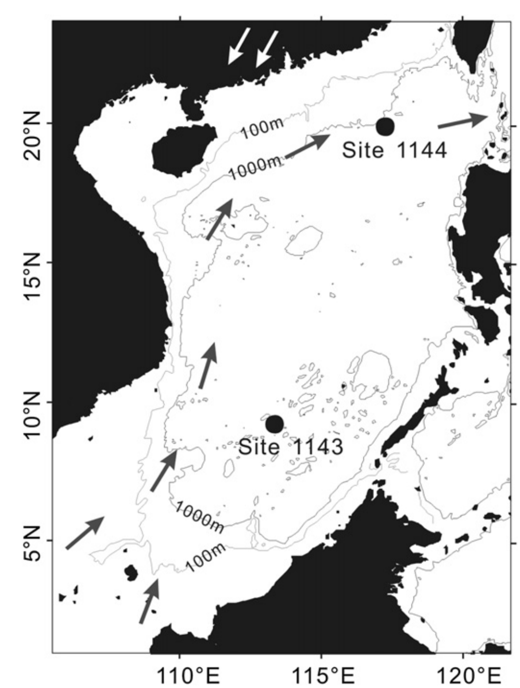

Fig. 1. Location of ODP Sites 1144 and 1143 in the South China Sea. Gray arrows show modern surface currents during summer; white arrows show winter monsoon.