国家科学技术学术著作出版基金
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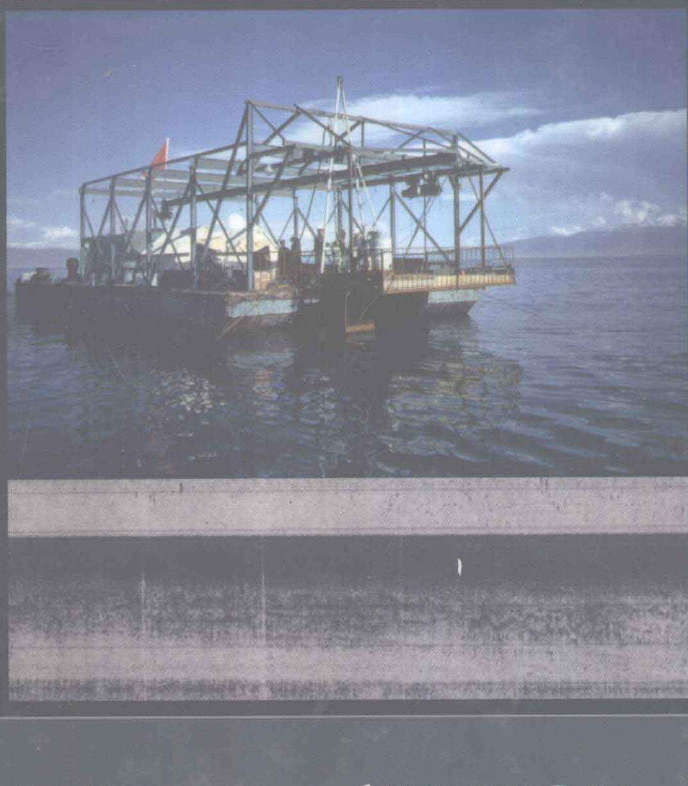
# LAKE QINGHAI

## Paleoenvironment and Paleoclimate

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SCIENCE PRESS
Beijing

Supported by the National Fund for Academic Publication
in Science and Technology

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Published by Science Press
http://www. sciencep. com
16 Donghuangchenggen North Street
Beijing 100717, P. R. China

Printed in Beijing, 2008

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ISBN 978-7-03-022909-0

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# 1 Introduction

The Qinghai-Tibet Plateau, the largest elevated landmass and larruping topographic feature on Earth's surface (Figure 1.1), today exerts an important control on the global atmospheric circulation, and in particular on the Asian monsoon circulation. Paleoenvironmental change on the plateau associated with variations in Asian monsoon strength over the past 60 ka can be observed from the study of sediment cores from modern lakes or other proxy records such as ice cores. High-resolution records from closed-basin lakes can be more interesting because lake-level fluctuations in such lakes respond sensitively to changes in the precipitation-evaporation balance in their catchments. These changes often relate to monsoon rainfall variations on regional scales. Climate proxy histories from the Qinghai-Tibet Plateau are indispensable for the global database used to test our understanding of the behavior of the climate system and as a guide to future conditions.

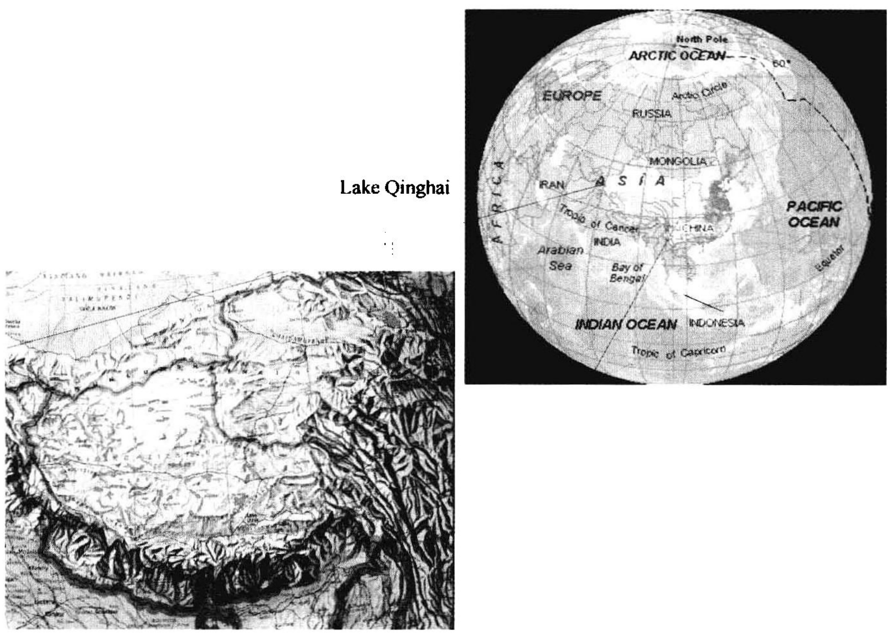


Figure 1.1 The Qinghai-Tibet Plateau, nearly $2\times10^6$ $km^2$ in size and an average altitude of over 4,000 m above sea level, exerts an important control on the most pronounced monsoon circulation of the globe, including the Indian and East Asian monsoon systems. Lake Qinghai lies on the northeast corner of the plateau. The Himalayas, the world's highest mountains, are the southern margin of the plateau.

Lake Qinghai (Qinghai Hu) lies in an intermountain basin at 36°55'N, 100°10'E near the northeast corner of the Qinghai-Tibet Plateau at an elevation of 3193.7 m a.s.l. (in 1985). It is a closed-basin lake with a catchment area of 29,660 $km^2$. In spite of a cold/semiarid climate, the large catchment provides an annual surface runoff of more than 1.6 $km^3$ along with an estimated 0.64 $km^3$ groundwater input per year, maintaining a perennial lake of 4,437 $km^2$ in size and a maximum water depth of 26.5 m (in 1985). It represents the largest water body now in the interior of China. Of the total annual catchment runoff today, about 1% is from meltwater of modern glaciers in the lake's upper catchment at altitudes above 4,800 m a.s.l. The annual precipitation today is about 380 mm, of which about 65% falls in summer from June to September. The lake today is at the outer margin of the Asian summer-monsoon influence (Figure 1.2). Past changes in the monsoon circulation undoubtedly influenced the precipitation-evaporation balance of the lake and its catchment, resulting in substantial changes in lake level and water chemistry. The reconstructed lake levels of Lake Qinghai and paleoenvironmental history may provide key-site information for the studies of the Asian monsoon evolution and the past global change. Aimed to achieve this goal, a field investigation including seismic profiling and piston coring of subbottom sediments was carried out in the

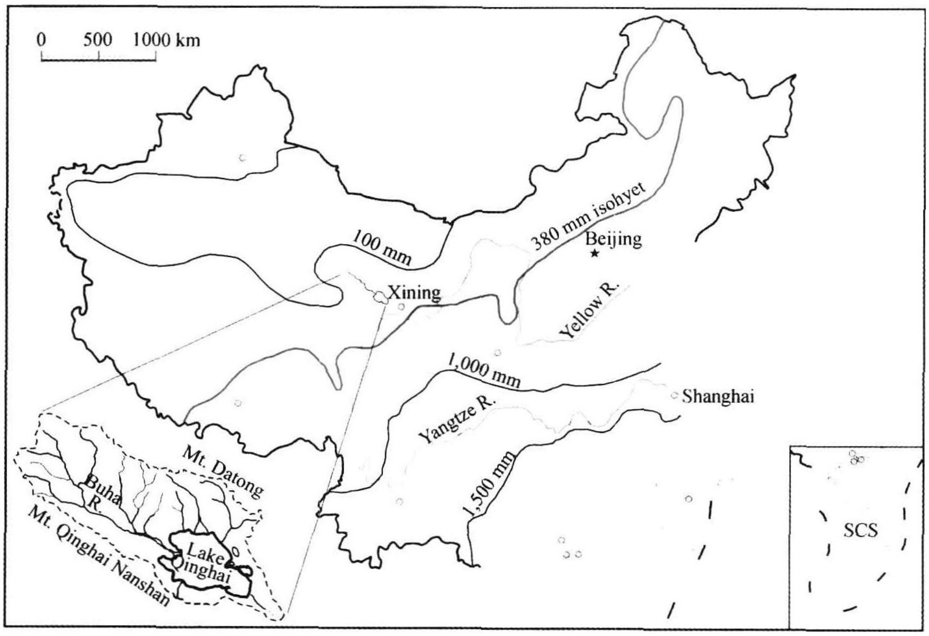


Figure 1.2 Precipitation gradient to the northwest, which decreases steadily from the southeast coast of China towards the drainage basin of Lake Qinghai, reflecting the pattern of the East Asian monsoon rainfall. Lake Qinghai is a hydrologically closed-basin lake, the lake-level of which responds sensitively to the changes of precipitation-evaporation balance.

summer of 1985 by a Sino-Swiss Expedition team. This cooperative study marked the beginning of the modern limnogeological study in China. Studies since then on paleoenvironment and paleoclimate of Lake Qinghai have been carried on increasingly by a number of research groups from both domestic and international institutions.

## 1.1 Aim and scope

This monograph reports the results obtained after 1991 from the investigation on two piston cores, Q14B and Q16C, and on the 26 m drill-core from Lake Qinghai with a multidisciplinary approach. It deals with several key paleoclimatic, paleo-limnological, and geochemical questions, such as:

1) What sediment evidence from Lake Qinghai can help to define the paleoen-vironmental and paleoclimatic conditions during the Marine Isotopic Stage 3 (MIS 3) and the Last Glacial Maximum (LGM) on the NE Qinghai-Tibet Plateau? Were the proxy records here coherent with the European records? Was the MIS 3 climate warmer and wetter than the Holocene on the plateau?

2) Is the pattern of climate change across the Lateglacial/Holocene transition, including the Younger Dryas, coherent with that recorded in the proxy records from the Greenland ice cores and northern Europe?

3) To what extent the Holocene lake-levels of Lake Qinghai can be quantitatively reconstructed based mainly on evidence from stratigraphic records? Does the reconstructed lake-level history reflect the Holocene pattern of the Asian monsoon changes in the region?

4) Is the mineralogical record useful for tracking changes in water chemistry and brine evolution of the closed-basin lake associated with the changes in effective moisture?

The monograph evaluates sediment records available by far from Lake Qinghai and other sites selected from the region with respect to the regional reconstruction of the paleoenvironmental and paleoclimate changes since the MIS 3. Studies related to the field investigations from the summer of 2005 (An *et al.*, 2006) are beyond the scope of this monograph.

## 1.2 Previous investigations

### 1.2.1 1961–1962 expeditions to Lake Qinghai

A major study of Lake Qinghai has been carried out in 1961–1962. A number of scientists from four institutes of the Chinese Academy of Sciences did a comprehensive field investigation on the lake, aiming at a systematic collection of geological, limnological, zoological and geochemical data. They attempted to study geological processes in the large closed-basin lake, including the deposition and preservation of organic matter and possible converting conditions towards petroleum source rock, and to provide an analogue for the study of sedimentary processes in ancient continental basins with respect to petroleum geology. During the field investigation, sediment cores retrieved from the modern lake bottom were limited to short cores of less than 1 m in length. Recovery of a continuous sediment record from the central basin of the lake was not the main focus of the 1961–1962 investigations. However, the published monograph (Lanzhou Institute of Geology, CAS, 1979) with substantial geological, limnological and zoological data provided a first comparative framework for our later studies from 1985.

### 1.2.2 Sino-Swiss expedition in 1985

Remarkable progress in the reconstruction and understanding of the past global change was made between 1970 and 1985, but continuous proxy records from lakes in China with century to decadal scale were still too sparse to contribute significantly to the international study. The significance of Lake Qinghai for the study of Asian monsoon circulation has stimulated the formation of a Sino-Swiss joint project on the study of the paleoclimate and paleoenvironment of the high plateau lake, thanks also to China's opening-up policy. The major field investigation took place in the summer of 1985. Seismic profiles and piston cores were recovered from Lake Qinghai by the Sino-Swiss expedition team. The retrieved sediment cores were thereafter investigated and a series of scientific papers had been published before 1992 in English (Kelts *et al.*, 1989; Zhang *et al.*, 1989; Wang and Chen, 1990; Lister *et al.*, 1991) and in Chinese (Huang, 1988; Zhang *et al.*, 1989; Du *et al.*, 1989; Chen *et al.*, 1990; Kong *et al.*, 1990).

### 1.2.3 1987 drill-core project

After the initial expedition of 1985 with piston cores recovered from three subbasin centers, a new core with deeper penetration to recover the sediment sequence below the Q-reflector of seismic profiles was required in order to examine the basinal environmental conditions during the last Ice Age, and in particular to test the hypothesis of a unified ice cover on the NE Qinghai-Tibet Plateau (Kuhle, 1987). The fieldwork took place in the summer of 1987 and a drill core site was chosen at the middle of the eastern subbasin with a water depth of 23 m. A rotary drilling rig was assembled on a 90-ton barge, which was fixed by four anchors. The subbottom sediments down to 26 m were successfully cored by the drilling operation, although considerable difficulties were encountered with storms breaking the casing. The drill core named Q87 was the deepest core taken from the central areas of Lake Qinghai before the retrieval of cores in the summer of 2005 by the GLAD 800 coring system.

### 1.2.4 Post-1990 investigations

Since 1990, scientists from China and many other countries have conducted a number of field investigations for the study of paleoenvironment and paleoclimate of Lake Qinghai. In the summer of 1990, a fieldwork was carried out by a large group of scientists from several institutes of the Chinese Academy of Sciences. Data and results from the followed multidisciplinary studies on cores and samples collected from shores and the catchment of the lake were summarized in the monograph (Lanzhou Branch of Chinese Academy and Sciences, 1994). In addition, a number of projects were initiated for the studies of both long-term and short-term changes of the lake (e.g. Shen *et al.*, 2005a; Xu *et al.*, 2006). The most prominent field investigation, among all post-1990 fieldworks, was that done in 2005 and initiated by the Quaternary researchers of China and supported by the ICDP community. Cores were drilled with GLAD800 drilling rig and recovered from four offshore sites of the lake following the seismic investigations of three times on the lake (An *et al.*, 2006). The total length of all cores retrieved from the offshore sites reached 548 m. In addition, two deep cores, respectively drilled at the Erlangjian and Yilangjian sites on the northern shore of the lake, have been recovered, one of which drilled up to 1000 m below the land surface. Data and results from the ongoing laboratory investigations are expected to provide a long proxy record of the paleo-climate and paleoenvironment of Lake Qinghai with high-resolution for the study of the Asian monsoon changes.

## 1.3 Paleoclimate study of China: a brief review

### 1.3.1 East Asian monsoon—the modern climate system

A prominent feature of the East Asian monsoon today is the pronounced reversal of the climate system, exhibiting a distinct summer and winter component, that is, cold and dry in winter and hot and humid in summer. During the East Asian winter monsoon, strong northerly winds are prevailing and cover the entire region of the central and northern China and the South China Sea. This circulation pattern is controlled in general by a huge anticyclone over the Siberia-Mongolia. This is different from Indian monsoon in that the winter monsoon of India is not known to

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be present to any significant extent (Lau and Li, 1984). Although the summer monsoon has complex space and time structure, it generally induces rain belts by drawn moist air from the southern oceans, which stretch northwards for many thousands of kilometers (Chang, 2004). The difference in heat capacity between land and oceans is a basic physical mechanism causing the prevailing southerly winds in summer months. The huge elevated landmass of the Qinghai-Tibet Plateau provides an important and direct influence of the thermal and dynamic forcing on the circulation of East Asia. Heat flux over the Plateau and latent heat release contribute to a strong tropospheric heat source, which maintains the large-scale Asian monsoon circulation (e.g. Flohn, 1968; Hahn and Manabe, 1975; Lau and Li, 1984).

The study of the East Asian monsoon is important because monsoon-related droughts and floods have enormous social and economic impacts on nearly one third of the world population. It also impacts on the global climate system including effects on the climate change (Chang, 2004). Some anomalies, such as those of sea surface temperature and snow cover over the Qinghai-Tibet Plateau, correlate well with the anomalies of the monsoon rainfall. More work has to be done for the improvement of long-range prediction of the monsoons.

### 1.3.2 East Asian paleomonsoon

The circulation pattern of the East Asian monsoon system in the past differed greatly from that of today when large-scale climate forcing and boundary conditions were enormously different from today. Factors affecting the circulation include changes in solar radiation induced by orbital changes, orographic change of the Qinghai-Tibet Plateau due to tectonic development, changes in glacial climate and cryospheric conditions, and internal feedbacks within the climate system. These factors act simultaneously and over different time scales to amplify or lessen the seasonal development of continental heating or cooling, land-sea pressure gradients, latent heat transport, and moisture convergence, all of which control the strength of the monsoon circulation. In the following sections, we review very briefly on the proxy records of the East Asian paleomonsoon evolution. The proxy record of stalagmite from caves in China is one of the important archives of paleomonsoon evolution with high resolution (e.g. Wang *et al.*, 2001; Yuan *et al.*, 2004), which will be discussed in Chapters 5 and 8.

#### *1.3.2.1 Loess records*

Uplift of the Qinghai-Tibet Plateau was considered to be the most prominent orographic impact on the initiation, intensification, and long-term ($10^6$ years) evolution of the Asian monsoon circulation (Ruddiman, 1997; An *et al.*, 2001). Model studies suggest that the plateau must be at least half its present elevation to induce a strong monsoon circulation (Prell and Kutzbach, 1992). High-resolution aeolian sequence preserved in the Loess Plateau of China reveal that the East Asian monsoon may have commenced at least 7.2 Ma ago and the pulsed uplift of the Qinghai-Tibet Plateau at about 3.4 and 7.2 Ma may have played an important role in inducing climate change (An *et al.*, 2001; An, 2004). The study of the aeolian deposits of Qin'an in the western Loess Plateau provided evidence indicating that large source areas of aeolian dust and energetic winter monsoon winds to transport the material must have existed in the interior of Asia by the early Miocene Epoch (Guo *et al.*, 2002), some 14 million years earlier than previously thought. The initial desertification in the Asian interior and changes in aridity and circulation thereafter in Asia are associated partially with the regional tectonic changes.

During the Quaternary Period, the windblown loess deposit developed extensively in northern China, forming a large Loess Plateau with an area of about 640,000 $km^2$ and an average thickness of ~150 m (Liu, 1985). The formation of the loess deposits in the past 2.5 Ma represents an intensified drier and windier climate if compared with the late Miocene and Pliocene climate, largely in accordance with the Quaternary glaciation of the Northern Hemisphere (Shackleton *et al.*, 1984; Liu *et al.*, 1985; Kukla and An, 1989). Changes in Siberia High, which were associated with continental ice-sheets and sea-ice cover, may have played an important role in controlling the winter monsoon intensity (Ding *et al.*, 1992). A number of loess-paleosol sections were intensely investigated particularly in the past two decades as it has been recognized as one of the important and continuous terrestrial proxy records for the study of the past global changes. Chronology of the Quaternary loess deposits is mainly based on paleomagnetic stratigraphy (Heller and Liu, 1982; Liu *et al.*, 1988; Kukla and An, 1989; Stevens *et al.*, 2007). Magnetic susceptibility and grain-size profiles of loess-paleosol sequences from the Loess Plateau were used as the main proxy records for the reconstruction of the East Asian monsoon fluctuations in the past 2.5 Ma. In general, paleosol layers, particularly those of well-developed paleosol layers, show higher values in magnetic susceptibility and lower percentage in coarser particle fraction than in loess layers. They are formed during warm and wet period, representing events of strengthened summer monsoon. Loess layers involve higher fraction of fine sand and have lower values of magnetic susceptibility. The $>63\mu m$ particle content in a loess-paleosol sequence is employed as a proxy indicating wet-dry variations of paleoclimate or as a dust-storm indicator when a high content occurs. Quartz particle size was also considered to be an ideal index because the quartz particles resist pedogenic alteration (An and Porter, 1997).

This index was used for tracing winter monsoon conditions at the Loess Plateau and six events relating to strengthened winter monsoon between 110 and 70 ka correlate well with those cold events (C19–C24) identified by the *Neogloloquadrina pachyderma* (s.) records from North Atlantic during the last interglacial period (McManus *et al.*, 1994; An, 2000). The quartz particle-size data from the Luochuan loess section show good correlation with the *N. pachyderma* (s.) record of the past 80 ka (Bond *et al.*, 1993), suggesting that the Heinrich Events may have had fingerprints in the Chinese loess (Porter and An, 1995).

The characteristics of the East-Asian winter monsoon variability in terms of the Milankovitch periodicities of climate change over the past 2.5 Ma were examined by the study of the Baoji loess-paleosol section based on grain-size data (Ding *et al.*, 1994) and a comparison of the proxy-record with a DSDP (Site 607, N. Atlantic) $\delta^{18}O$ record (Liu *et al.*, 1999). The results indicate that an abrupt transition of winter monsoon variability from various periodicities to dominant 41-ka cycles occurred at 1.7–1.6 Ma as one of the two major shifts in climate modes. Another major shift at 0.8–0.5 Ma is characterized by a relatively gradual transition from constant 41-ka cycles to predominant 100-ka climatic oscillations. This 0.8–0.5 Ma shift matches that registered in deep-sea $\delta^{18}O$ records, whereas the 1.7–1.6 Ma shift is absent in global ice volume changes. However, the strong 41-cycles shown in the Baoji loess record are episodically missing in the proxy records of Luochuan and Xifeng loess-paleosol sections in the central Loess Plateau, which is attributed to the relatively low time-resolution of the paleosol units or the unstable depositional process of the dust (Lu *et al.*, 2004). Rather, the longer cycles of approximately 400 ka and 100 ka relating to eccentricity frequencies of the solar irradiance are well recorded. In addition, other non-orbital cycles of 66-, 56-, 33- and 27-ka show quite strong intensity in the loess record, which has been attributed to unstable dust deposition processes and pedogenic processes in the paleosol units.

#### *1.3.2.2 Marine records*

Oceanic conditions of the Western Pacific, which is one active component of the climate system, impact on the East Asian monsoon circulation at present, as well as in the past. The Western Pacific Warm Pool (WPWP), the largest expanse of warm water today with average annual temperature exceeding 28℃, provides strong latent heat export. Thus it plays a leading role in driving atmospheric circulation (Webster, 1994; Gagan *et al.*, 2004). It is also the major source of atmospheric moisture. According to Dodson *et al.* (2004), the switch on and off of this moisture source through sea-level variation would have both regional and global implications, for example, in controlling the vigor of ENSO. Cyclones originating in tropical and subtropical regions in the south may affect the climate of southern China and adjacent islands from spring to autumn, while in summer they may extend as far north as the southern coasts of Japan and Korea, bringing intense storms. The January and July monsoon circulation is illustrated by the seasonal reversal of wind patterns and an enormous change from winter to summer precipitation pattern (refer to Figure 1 in Clemens *et al.*, 2003). It may also be illustrated by the marked difference of average temperature patterns between January and July for both hemispheres in the PEP II region (see Figure 2 in Dodson *et al.*, 2004).

Sea surface temperature (SST) reconstructions from foraminiferal Mg/Ca, alkenone, and revised coral Sr/Ca palaeothermometry agree that SSTs in the Indo-Pacific Warm Pool (IPWP) during the LGM were ~3℃ cooler than at present (Gagen *et al.*, 2004). This reconstructed temperature supports the inference that tropical sea-surface temperatures (SSTs) were lower than the previous estimates (CLIMAP members, 1981; Thunell *et al.*, 1994), implying a weaker hydrological cycle and enhanced aridity on continents during glacial periods. Marginal seas along Asian continent on the Western Pacific had prominent climatic and environmental impact on the region during the late Quaternary glacial cycles because large eustatic sea-level fluctuations resulted in major landward and seaward migrations of the coastline, as well as the closure or opening of the marginal seas via strait gateways to the ocean, which had significant impact on the paleoceanographic circulation (Wang, 1999). The South China Sea (SCS), a marginal sea intensely studied recently, turned to be semi-closed due to an about 100-m (or more) decrease in sea level during the LGM; winter temperature was 6–10℃ colder with a seasonality much stronger than it is today (Wang and Sun, 1994). As such, much information on the history and variability of the Asian paleomonsoon associated with Quaternary glacial-interglacial cycles can be deciphered from the marine proxy records of the Western Pacific. A number of proxy records obtained by multiple approaches of isotopes, micropaleontology, sedimentology and geochemistry have been applied to investigate some major unknowns of monsoonal paleoclimate at SCS, which include continental aridity and moisture, wind strength, temperature, salinity, and productivity near the sea surface (Wang *et al.*, 1999). Briefly, the oxygen isotopic approach was applied to study SST, sea surface salinity (SSS), upwelling, monsoon wind intensity, and the implied global ice volume. The stable carbon isotopic records were used to indicate changes in surface water nutrient level, wind intensity and upwelling. The combined records of silt modal grain-size are useful for tracing fluvial input relating to summer monsoon precipitation and aeolian dust associated with winter monsoon wind. The alkenon biomarker $U^{k}_{37}$ index and planktonic foraminiferal (PF) census data were used to estimate SST and SSS. In the most recent review, Wang *et al.* (2005) has evaluated marine proxies, pointing out that some of them were well studied such as census counts of the planktonic foraminifera *Globigerina bulloides*, whereas there were also potential deficiencies in the interpretation of individual proxies. In the significantly weaker upwelling regions of the South and East China Seas, *G. bulloides* is however not as dominant as *N. dutertrei*, and therefore the later was applied as an upwelling indicator (Jian *et al.*, 2001). Table 1 in the review paper provided a summary with more information regarding the proxy data and related publications for paleomonsoon reconstructions.

Orbital-scale variability of summer and winter monsoon intensities was examined based on marine proxy records from the SCS. The pollen data of a core at the ODP Site 1144 provided a paleomonsoon proxy-record for the past 1 Ma, using tree-pollen influx to indicate winter-monsoon strength and fern spore proportions to reflect summer-monsoon strength. The spectrum analyses of the pollen percentages of pine and herbs show the presence of 100-, 41- and 21-ka Milankovitch cyclicities and the tropical-specific 10-ka semi-precession cycles (Sun *et al.*, 2003). The relative intensity of summer and winter monsoons over the past 2 Ma was also assessed by the proxy record of clay mineral assemblage from a core at the ODP Site 1146 (Liu *et al.*, 2003). In general, strengthened summer-monsoon winds during interglacial periods were represented by higher smectites/(illite+chlorite) ratios, and conversely, the lower ratios indicate strongly intensified winter monsoon during glacial periods. Seasonality may have been enhanced between 1.2 and 0.4 Ma, as suggested by the higher mean values of the ratios. Orbital-scale cyclicity can be observed by means of spectral analysis of the ratio data, and the 41-ka cycles are particularly prominent between 2 and 1.2 Ma. Wehausen and Brumsack (2002) employed K/Si ratios from the high-precision element records of Pliocene core intervals from the ODP Site 1145 as a proxy of reconstructing the history of chemical weathering associated with summer monsoon precipitation. The high correlation of the K/Si record with the Northern Hemisphere summer insolation reflects the astronomical forcing (precession of equinoxes) of summer monsoon at 3.2–2.5 Ma.

The high-resolution proxy records from the SCS deep-sea cores provided important contribution to the understanding of climate change since the marine isotopic stage 3 (MIS 3) in association with the East Asian monsoon evolution. Based on the study of 10 sediment cores and 40 core-top samples from the SCS, the following conclusions were drawn in regard to the paleoclimate of the last 40 ka (Wang *et al.*, 1999). Heinrich Event 4 probably corresponded to an arid and cool phase in South China. Major events of freshwater flooding associated with summer monsoon rain occurred also in the late Stage 3, as evidenced by short lasting SSS minima in the southern and western SCS. The summer monsoon-driven fluvial runoff and sediment supply intensified right after the LGM insolation minimum, parallel to the early start of Antarctic ice melt and about 3,500 years prior to the $\delta^{18}$O signal of post-glacial sea-level rise. The Younger Dryas did not induce a cooling but an arid episode. Cold spells occurred roughly every 3,000 years during the Holocene.

The SST of the LGM, as generally agreed by all interpretations from various proxy records, indicates a colder climate with winter monsoon much intensified in the northern SCS than it is today (Wang and Wang, 1990; Wang *et al.*, 1995; Huang *et al.*, 1997; Chen *et al.*, 1999). This is accordant with geological evidence from various environmental archives at nearly all reported sites from different regions over the Northern Hemisphere. It is not surprising to have such a good accordance primarily because the cause of the LGM cold episode is the insolation minimum at that time. While the cause of the Younger Dryas, the well-established phenomenon of northern Europe, is debated since at least 20 years ago, a positive excursion of foraminiferal $\delta^{18}$O from Sulu Sea record was interpreted as a YD equivalent (Linsley and Thunell, 1990; Kudrass *et al.*, 1991). However, considerable debate exists on whether the heavier $\delta^{18}$O values during this time interval are indeed a reflection of decreased SSTs or of other environmental processes (Steinke *et al.*, 2001). The authors thus measured other proxy records for the SST reconstruction, with a particular attempt of detecting a possible YD climate setback in the tropical SCS. The reconstructed SSTs estimated from three different foraminiferal transfer functions did not indicate any consistent cooling. The $U^{k'}_{37}$ SST estimates however show a cooling of ca. 0.2–0.6 ℃ compared to the Bølling-Allerød period. Apparently, more efforts are still needed in order to provide a confirmation of the YD impact on this region (Maloney, 1996).

As clearly stated and recommended by Wang *et al.* (2005), in order to improve our understanding of the monsoon variability on decadal to millennial time scales from marine records, we first need to improve our knowledge of monsoon proxies by means of a systematic collection of long-term series of sediment trap data along with numbers of carefully calibrated core-top data sets, as well as the satellite data of coeval meteorological observations. This approach and outcomes will surely help to evaluate a dozen proxies reported and to determine how much of their variability is uniquely associated with monsoon dynamics (Clemens *et al.*, 2003). It is equally important to have a substantial improvement on dating of marine sediment archives in terms of methodology and accuracy. For a better understanding of monsoon variability on the sub-orbital time scales, continuous, undisturbed cores in large

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