Palaeogeography, Palaeoclimatology, Palaeoecology 483 (2017) 94–124

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

High-resolution palynological record of Holocene climatic and oceanographic changes in the northern South China Sea

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A R T I C L E I N F O

Article history:
Received 16 August 2016
Received in revised form 19 January 2017
Accepted 7 March 2017
Available online 9 March 2017

Keywords:
Asian monsoon
Holocene
Sea level change
Dinoflagellate cysts
Palynology
The South China Sea

A B S T R A C T

For the first time, palynological records of terrestrial palynomorphs and dinoflagellate cysts are investigated in a sediment core from the northern South China Sea (SCS) covering the last 12,500 years. Both terrestrial and marine palynomorph records show strong signals of the sea-level change during the studied interval. The highest herb pollen content was associated with extensive grasslands on the exposed shelf at the low sea-level stand during the Younger Dryas and early Holocene. The increase in fern spores and decrease in concentrations of dinoflagellate cysts and terrestrial palynomorphs was observed during the sea-level rise interval from 12,500 to ~6800 (or 6000) cal yr BP. Then, the sea level became stabilized and consistently low dinoflagellate cyst abundances and high abundances of fern spores were recorded.

A high abundance of *Impagidinium* in the period ~12,000–10,400 cal yr BP possibly resulted from increased input of western Philippine Sea waters into the SCS and the branching of the Kuroshio Current. A short-term decrease of *Impagidinium* at ~11,700–11,000 cal yr BP corresponding to the MWP-1B event might be associated with input of the East China Sea waters through the Taiwan Strait.

The relationship between the sedimentation rates and the concentrations of terrestrial palynomorphs indicates a water-dominant transport for pollen and spore dispersal prior to ~6300 cal yr BP, whereas wind transport became more prominent thereafter. The timing of this change corresponds to the highest sea-level stand at ~6800–6000 cal yr BP, when the present oceanographic setting was formed. The mid-Holocene Optimum can be seen by the highest abundance of subtropical-tropical broad-leaved arboreal pollen and by the highest abundances of *Dapsilidinium pastielsii*. Three strengthened winter monsoon intervals at ~5500 cal yr BP, 4000 cal yr BP, and 2500 cal yr BP are reflected by increases in *Pinus* pollen content after the present oceanographic condition formed.

1. Introduction

Studies of the South China Sea (SCS), located in the low-latitude Western Pacific Ocean and the East Monsoon climate region, play an important role in understanding climate change (e.g., Wang and Li, 2009). With well-preserved Holocene sedimentary strata and relatively high sedimentation rates, the northern SCS is considered one of the best areas for high-resolution paleoreconstructions of Holocene climatic and oceanographic changes. Significant efforts have been invested into reconstructions of the Holocene monsoon climate variability and hydrographic conditions, including the sea surface temperature (SST) and sea surface salinity (SSS), using a number of sediment cores from the northern SCS (e.g., Huang et al., 1997; Wang et al., 1999; Yu et al., 2005; He et al., 2008; Kong et al., 2014; Jiang et al., 2014; Dai and Weng, 2015). Most of these studies have shown similar general trends throughout the Holocene. However, the records of short-term monsoon climate or specific oceanographic events are not consistent or not always recorded by different proxies due to limited sampling resolution. These proxies include clay and grain-size records (Huang et al., 2011), alkenone-based SST (Huang et al., 1997; Pelejero et al., 1999; Wang et al., 1999), diatoms (Huang et al., 2009; Jiang et al., 2014), and pollen (Zhang and Long, 2008; Li et al., 2010; Dai and Weng, 2015).

Kong et al. (2014) reported results of paleoenvironmental reconstructions that underscore differences in regional and local dynamics. These authors found a difference in two SST records over the past 8.0 kyr that were reconstructed by using a long-chain alkenone unsaturation index from offshore of the Pearl River submarine delta and the continental margin in the northern SCS. Their study suggests that the SST change was not synchronous in the two locations; rather,

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http://dx.doi.org/10.1016/j.palaeo.2017.03.009
0031-0182/

the SST gradient was developing in the northern SCS (Kong et al., 2014). Even when different proxies were used on the same sediment core, higher-resolution events of paleo-monsoon climate record or paleoceanographic parameters were at variance. For example, different SSSs were reconstructed by diatom (Jiang et al., 2014) and by $\delta^{18}O$ of foraminifera (Wang et al., 1999) from core 17,940 from the north SCS.

For high resolution climatic and paleoocenographic reconstruction it is necessary to consider detailed factors impacting the records. On top of issues such as chronological resolution and different sensitivities of different proxies, biases induced by various laboratory techniques should not be ignored. For example, five weak Asian monsoon events reconstructed by Wang et al. (2005) are not corroborated by the results from Dykoski et al. (2005), although both studies used stalagmite $\delta^{18}O$ from Dongge Cave in mainland China.

In addition to the atmospheric temperature, precipitation, and river inputs, the currents from the western Pacific strongly influence the oceanographic conditions in the northern SCS, including the SST and SSS. Modern observations show that the open sea area of the northern SCS remains relatively warm year round because of the branch of the Kuroshio Current and the warm western Pacific waters from the Philippine Sea (Fig. 2) (Xue et al., 2004; Yuan et al., 2006). As a result, the signal of the summer Monsoon in the northern SCS is not as strong as on land. Thus, proxies that reflect both terrestrial and marine information are ideally suited for reconstructions of past climatic and oceanographic conditions of the northern SCS. Terrestrial palynomorphs (including pollen, spores, and some freshwater algae) and marine dinoflagellate cysts are reliable proxies. Moreover, technically, terrestrial palynomorphs and dinoflagellate cysts can be extracted using the same laboratory technique and identified under a microscope simultaneously, which will greatly reduce method-related biases.

Pollen and spores in marine sediments come from terrestrial vegetation, are transported by winds or water (including currents and rivers), and are deposited in the sea together with other sedimentary particles. Far from the sources, the pollen in the deep sea of the SCS were perhaps less influenced by river inputs and probably were deposited through wind activity. Therefore, pollen preserved in sediment cores are commonly used to reconstruct past vegetation and climate, especially during glacial-interglacial cycles when the surrounding vegetation underwent major changes (e.g., Sun and Li, 1999; Sun et al., 2003; Zhang et al., 2011; Dai et al., 2015). However, during the Holocene, vegetation surrounding the SCS did not change as much as the vegetation during glacial-interglacial cycles. Sun and Li (1999) suggested that the vegetation during the last 10 kyr was close to that of the present, based on the similarity between pollen assemblages during the Holocene and in the surface sediment from the northern SCS. Therefore, to infer climatic changes during the Holocene, a more detailed understanding of pollen transport and taphonomic conditions needs to be developed. For example, *Pinus* pollen, a most common genus in pollen assemblages from the region, is often interpreted as an indicator of cold climate because it is delivered primarily by winter monsoon to the SCS (e.g., Sun and Li, 1999), but in an open environment strongly influenced by water transport, an increase of *Pinus* pollen could be a signal of a strengthened hydrodynamic condition rather than a cooler climate (Heusser, 1988; Moss et al., 2005; Beaudouin et al., 2007). Thus, understanding the transport mechanism and taphonomy of *Pinus* pollen due to the sea-level rise is required to interpret environmental conditions.

Marine records of dinoflagellate cysts, which are directly associated with upper water masses, can also contribute to the reconstructions of past oceanographic and climatic conditions. Dinoflagellates are one of the major groups of modern marine plankton. Almost half of all dinoflagellate species are heterotrophic, whereas the other half are phototrophic; the latter are commonly referred as autotrophic (Dale, 2009). During their life cycle, many dinoflagellates produce resting cysts that are resistant to physical, chemical, and biological degradation because of organic walls (e.g., Dale, 1996). Distributions of modern dinoflagellate cysts in marine environments are controlled by sea-surface temperature (SST), salinity (SSS), primary productivity, sea-ice cover, and other oceanographic conditions (e.g., Dale, 1996; Rochon et al., 1999; de Vernal et al., 2001, 2005; Marret and Zonneveld, 2003; Pospelova et al., 2005, 2008; Zonneveld et al., 2013). Therefore, being preserved in sediments, organic-walled dinoflagellate cysts are commonly used as indicators of past environmental conditions (e.g., Dale, 1996; de Vernal et al., 2001, 2005; Mudie et al., 2002; Zonneveld et al., 2008; Bringué et al., 2014; Pospelova et al., 2015). The ratio between cysts produced by heterotrophic and autotrophic taxa is commonly considered an indicator of coastal proximity or primary productivity (e.g., Harland, 1983; Dale, 1996; Mudie and Rochon, 2001; Pospelova et al., 2008). Dinoflagellate cyst analysis has been carried out in the SCS by Zhao and Morzadec-Kerfourn (1992a, 1992b), Mao and Hariand (1993), Wu and Sun (2000), Kawamura (2004), Mao et al. (2007), and Wang et al. (2004, 2011). Wu and Sun (2000) investigated the distribution of the dinoflagellate cysts from the surface sediments in the SCS and reported spatial distributions of *Spiniferites* spp. as well as other common cyst taxa such as *Impagidinium*, *Operculodinium centrocarpum* sensu Wall and Dale 1966, *Polysphaeridium zoharyi*, *Lingulodinium machaerophorum* and cysts of *Protoperidinium*. Thus far, most of the work on dinoflagellate cysts in the SCS has focused on changes in dinoflagellate cyst assemblages for the purposes of stratigraphy or ecological preference of individual taxa. No work has been performed on well-dated Holocene sediment cores to reconstruct past climatic or oceanographic conditions in the SCS based on dinoflagellate cysts.

In addition, most research cores used for Holocene research, except those from the Dongsha section of the SCS, have sedimentation rates too low to resolve centennial-scale paleoenvironmental events. Comparatively, the Zhujiang (Pearl River) section of the northern slope of the SCS has high sedimentation rates, with some sedimentary materials contributed by the Pearl River and by rivers in Southwest Taiwan. This section is only mildly influenced by turbidity currents as reflected by geochemical (Huang et al., 2016) and carbonate (Li et al., 2008a) records. Thus, the Zhujiang section of the northern SCS provides an ideal location for high-resolution sedimentary studies of the Holocene climate and oceanographic conditions. Reconstructions of climatic and oceanographic conditions in this section have not been carried out until now.

In this study, we use a sediment core from the Zhujiang Section of the northern SCS to conduct a high-resolution study of terrestrial palynomorphs with dinoflagellate cyst records over the past 12.5 kyr. Our objectives are: (1) to determine whether terrestrial (pollen and spores) and marine (dinoflagellate cysts) palynological assemblages record regional sea-level changes and the relevant hydrographic conditions in the SCS (e.g., the open of the Taiwan Strait); (2) to interpret the signals of monsoon climate changes using pollen and dinoflagellate cysts after taking into account the potential impact of pollen and spore dispersal from sea-level variations; and (3) to determine short-term regional events by comparing our findings with reconstructions based on other paleo-proxies of climatic and oceanographic conditions.

2. Regional settings

2.1. Physiography

The South China Sea (SCS) is a marginal sea of the western Pacific. It is surrounded by the South China mainland, the Indochina Peninsula, and a chain of islands spanning from Luzon to Borneo (Fig. 1). The SCS has a narrow shelf in the east, and the shelf widens to the west. On the northern shelf, submarine deltas were developed off the Pearl River, the Red River (Song Hong), and other small rivers. The northern continental slope is between the shelf-break zone and the deep basin, with a water depth of ~300–3700 m. It is divided into the following five sections, based on directional, geomorphological, and topographic characteristics: the Yingqong section, the Shenhu section, Zhujiang (Pearl River) section, the Dongsha section, and the Taiwan Shoal section