Climatic or tectonic control on organic matter deposition in the South China Sea? A lesson learned from a comprehensive Neogene palynological study of IODP Site U1433

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1. Introduction

In palynological analysis, all of the acid-insoluble organic matters, including palynomorphs (e.g., sporopollen (spores and pollen), freshwater algae, dinoflagellate cysts, fungal spores, and scolecodonts) and other organic particles (e.g., structured/amorphous organic matters, resins (ambers), wood debris, stomatal apparatus) collected from the rock or unconsolidated sediments comprise a palynofacies (Combaz, 1964). A variety of uses of these particles can be made depending on the specific aims of the researchers. The assemblages of different species in the overall palynomorph assemblage can be used to estimate/investigate the ages of the sediments (e.g., Macphail, 1997; Shu et al., 2008; Garzon et al., 2012; Akyuz et al., 2016; Miao et al., 2016a), reconstruct paleogeography, paleoecology and paleoclimate (e.g., Askin, 1989; Nichols, 1995; Jiang and Ding, 2008; Warny et al., 2009; Wu et al., 2011; Anderson et al., 2011; Miao et al., 2012), gather data on plant evolution (e.g., Walker, 1974; Nichols, 1995; Retallack, 1995; Miao et al., 2011; Griener and Warny, 2015) or be used as a proxy for paleoaltimeter (e.g., Axelrod, 1997; Miao et al., 2013a, 2016a; Sun et al., 2014). Quantitative data, such as percentages of different species, are widely used and occasionally include the number of morphologies (e.g., Jaramillo et al., 2006), the relative abundances, such as ratios of different ecological types (e.g., White et al., 1997; Warny et al., 2003), as well as the concentrations and fluxes (e.g., Luo and Sun, 2007; Miao et al., 2016b, 2017). Abundance, composition and preservation of the various components, together with the thermal alteration of the organic matters can be used to investigate depositional palaeoenvironments (e.g., Batten, 1982; Lorente, 1986; Batten and Lister, 1988; Tyson, 1984; Habib, 1979; Sweet and Cameron, 1991), petroleum or coal source potential (e.g., Batten, 1982; Ercegovac and Kosti, 2006), as well as biostratigraphic correlations on a regional, or local level (e.g., Surruck, 1996; Batten and Stead, 2005; Van der Zwan, 1991). In most of these palynological studies, the non-palynomorph component (mostly the structured/amorphous organic matters (SOM/AOM) or resins) is not discussed or vice versa, the paper focuses on non-palynomorphs but not on the palynomorphs. Very few studies have used...
quantitative methods on the entire palynofacies (e.g., Cirilli et al., 2009).

In this study, we identified and quantified for the first time eight different particle types in the palynological and structureless/amorphous class [sporopollen, algae (Concentricystes and Pediastrum), dinoflagellate, fungi, SOM/AOM, animal remains (scolecodonts), and stomatal apparatus]. Samples were collected from IODP Site 1433, a core of Neogene sediments from the South China Sea. The inferred relationships between the observed yield and paleoenvironmental changes, such as paleoclimate, tectonics of the basin, and evolution of continental drainage systems around/in the South China Sea are discussed.

2. Geological setting and materials

The South China Sea is one of the largest marginal basins in Southeast Asia. It receives most of its sediment from the modern Asian continent through a number of smaller and well-known larger river systems, including the Pearl, Red, and Mekong (Métivier and Gaudemer, 1999) (Fig. 1a). These sediments are deposited as a result of the various processes that reflect the competing influences of tectonics, chemical weathering, climatic and drainage basin evolution (Clift, 2006; Wei et al., 2006; Luo and Sun, 2007; Wan et al., 2012). They served as a robust proxy to investigate monsoon development. An intensification of summer monsoon would bring more precipitation, and therefore enhance the intensity of physical erosion as well as chemical alteration. However, building a climatic evolution within these specific areas is challenging as the record is complicated by factors such as provenance (Clift et al., 2008, 2014; Luo and Sun, 2007; Wan et al., 2007).

IODP Site U1433 is located in the southwestern part of the South China Sea basin. The cored section overlies an oceanic basaltic basement dated at ~17 Ma, with age control provided through a combination of biostratigraphic and magnetostratigraphic data (Li et al., 2015). The sediments overlying the basement are approximately 800 m thick. Lithologically, the bottom of the core is dominated by massive reddish and yellowish brown claystone and claystone with silt, with little coarser material present, although occasional thin silty turbidites occur, also do dark stains associated with bioturbation. The middle section primarily contains dark greenish gray clay and claystone with frequent medium to thick greenish gray nanofossil ooze and chalk interbeds. This part is divided into upper and lower subunits based on the occurrence of thick to very thick (> 1 m) greenish gray nanofossil chalk interbeds in lower subunits, compared to thinner beds in upper subunit. The upper portion of the core is composed of dark greenish gray clay with very thin interbeds of clayey silt (Li et al., 2015). The calibrated biohorizons and paleomagnetic data indicate an extremely low sedimentation rate (< 0.5 cm/ky) during the early to middle Miocene, when the basal reddish-brown clay was deposited. In the late Miocene to early Pleistocene, sedimentation rates varied between ~5–6 and ~9 cm/ky. The sedimentation rate during the Middle and Late Pleistocene increased sharply to around ~20 cm/ky (Li et al., 2015) (Fig. 1b).

Fig. 1. a. Bathymetric map of the South China Sea showing the location of IODP Site U1433 and b. Lithological column against age-depth model (after Li et al., 2015) and locations of samples (shown by blue arrows). FAD = first appearance datum, LAD = last appearance datum stratigraphic depths and ages. Topography is from the Shuttle Radar Topography Mission (SRTM) plotted by GeoMapApp. Major fluvial systems which deliver sediments into the South China Sea are also shown, together with the Molengraaff River of glacial age crossing the Sunda Shelf (Molengraaff and Weber, 1919). Green arrows show surface currents active during the modern summer monsoon. Isobaths are shown in 1000 m intervals. VCH = Vietnamese Central Highlands = (Li et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
3. Methods and results

3.1. Methods

One hundred and sixteen bulk sediment samples (Fig. 1b) were selected. Samples were chemically processed following a palynological technique summarized by Brown (2008). For each sample, the available amount (ranging from 2.4 to 27.3 g) of dried sediment was weighed. The sediment was spiked with a known quantity of Lycopodium spores to allow assessment of the absolute abundance and the flux of organic-walled microfossils to the sample. Acid-soluble minerals were digested in hydrochloric acid (HCL) and hydrofluoric acid (HF) to remove carbonates and silicates, respectively. The organic-walled particles were then concentrated by filtration through a 10-μm mesh sieve. In total, eight basic types were identified and tabulated: sporopollen, fresh water algae (Pediastrum and Concentricystes), dinoflagellate cysts, fungi, amorphous resin, SOM/AOM, stomatal apparatus, and scolecodonts.

Concentration was calculated using the equation of Benninghoff (1962):

\[ C = \frac{Pc \times Lc \times T}{(Le \times W)} \]

and flux: \( I = \frac{Pc \times Lt \times T \times R}{(Le \times W \times S)} \)

where \( C \) = concentration (number of particles per gram of dried sediment, grains/g), \( Pc \) = the number of each morphological particle counted, \( Lt \) = the number of Lycopodium spores per tablet, \( T \) = the total number of Lycopodium tablets added per sample, \( Le \) = the number of Lycopodium spores counted, \( W \) = the weight of dried sediment (with dried weight in grams); \( I \) = flux (given particles/cm²/ka), \( R \) = sedimentation rates (cm/ka); \( S \) = dry density of sample (g/cm³).

3.2. Results

The diversity of palynomorphs and organic particles tabulated for this study is quite complex (Fig. 2). In order to provide an overview of each category, a series of microphotographs of all key morphological types discussed are presented (Figs. 3, 5, 8, 10, 12, 14, 16, 18) before each type’s concentrations and fluxes (Figs. 4, 6, 7, 9, 11, 13, 15, 17, 19, 20).

In total, > 120 morphological types of plant pollen and spores (sporopollen) were found (Fig. 3). Their concentration increased gradually from ~2 grains/g to over 10,000 grains/g, except for higher values during the period between 13 and 11 Ma; the lowest recovery was surprisingly during the Middle Miocene Climatic Optimum (MMCO, 18–15 Ma). Besides these times, the most outstanding change was at ~8 Ma, where a sharp increase from ~200 to 5000 grains/g is observed. We will refer to this sudden increase as the ~8 Ma event. Flux followed a roughly similar trend with relatively fewer fluctuations, except for the obvious change at ~8 Ma (Fig. 4). Regarding the fresh water algal Concentricystes, it is found in only two samples prior to 8 Ma and becomes steadily more abundant in samples of 8 Ma and younger (Figs. 5, 6). The other major component of the fresh water algal group is Pediastrum, slight differences can be identified in this genus (Fig. 5). They are absent from the assemblage before ~8 Ma and present is consistently high abundance after ~8 Ma (Fig. 7). Dinoflagellate cysts are common with rich types found only after 14 Ma (Fig. 8). Their concentrations vary throughout the interval studied, but become more stable after ~8 Ma. The flux clearly shows more steady higher values after the ~8 Ma event (Fig. 9). Fungi are very abundant and diverse; > 30 morphologic types were found and grouped into three basic assemblages according to the cells numbers: single celled, double celled and multicellular (Fig. 10) (Miao et al., 2017). The fungal concentrations and flux trends also show more steady high values after the ~8 Ma event (Fig. 11). The SOM/AOM are very common in most samples (Fig. 12), the concentrations are at their lowest during MMCO and higher at ~13 Ma; the ~8 Ma event is obvious, again marked by a change from high fluctuations to more steady values. The flux distribution follows a similar pattern but with a generally increasing trend (Fig. 13). Patterns of distribution of resins (Fig. 14) were similar to those of the SOM/AOM (Fig. 15). The stomatal apparatus were rare in most samples, the morphologies are easy to identify because the obvious stomatal pore, guard cell, the subsidiary and epidermal cell (Fig. 16); both concentration and flux were low during MMCO and increased afterwards, the changes at ~8 are obvious (Fig. 17). Scolecodonts, the portion of a jaw of a polychaete annelid (a common type of fossil-producing segmented worm useful in invertebrate paleontology) (Fig. 18), is only found here in 6 samples before 8 Ma. The patterns of concentration and flux were a little different from those of any other particles although the changes at ~8 Ma are evident (Fig. 19).

In summary, the sporopollen, fungi, dinoflagellate cysts, SOM/AOM and resins generally showed consistent patterns throughout the whole core: specifically, both concentrations and fluxes were at their lowest during MMCO, after which the concentrations showed relatively complicated trends but the fluxes all generally increased and become quite steady after 8 Ma. Meanwhile, records of stomatal apparatus, Concentricystes, Pediastrum and scolecodonts are relatively low and discontinuous, mostly close to zero during MMCO but they too show a more steady distribution after ~8 Ma.

4. Discussion

4.1. Provenance

Sediments deposited in the marine environment include organic matters of a variety of origins. Individual analyses can provide details that elucidate the type of environment that existed during deposition. For instance, SOM/AOM are positively correlated with distance from shore (Thomas et al., 2015) and their relative flux can guide sequence stratigraphic studies. Sporopollen are widely accepted as a product of terrestrial plants with the exception of rare marine plants (Liao and Sun, 2007), Pediastrum and Concentricystes are mainly derived from terrestrial fresh water realms (Dorning and Harding, 1998), such as lakes and rivers. Dinoflagellate cysts are mainly marine phytoplankton although some forms also indicate freshwater environments. Fungi are regarded as the most widespread living eukaryotic organisms, occurring on most environments (e.g., Cantrell et al., 2011); however the majority of the fungal assemblage recovered from this study is of terrestrial origin (Miao et al., 2017). The resins, stomatal apparatus and scolecodont are complicated, and can all be produced from both terrestrial and oceanic plants and/or animals. Therefore, the varying amounts of these particles reflect broad environmental conditions over a large spatial scale from land to offshore.

4.2. Driving forces

It is quite noteworthy that a change of all eight types of palynomorphs appeared at the same time interval, ca. 8 Ma. In order to discuss the driving forces for the trends and changes, we combined all morphologies together to show the changes in total organic particles (Fig. 20a, b), the ratios of sporopollen and dinoflagellate to total organic particles (Fig. 20c, d) and compared them to total organic carbon content and sedimentary rates (Li et al., 2015) (Fig. 20e, f), respectively. The first two graphs (Fig. 20a, b) show broadly increasing trends showing some anti-correlation against the global δ13C record (Zachos et al., 2008) (Fig. 20g), i.e., which overall increase gradually as climate is cooling; and some weak correlation with the global δ18O record (Zachos et al., 2008) (Fig. 20h).

4.2.1. Paradoxical paleoclimate explanation

Comparison between trends in the total concentration of organic matters, flux rate and global δ18O are often widely used to propose that the changes in total organic matter abundance through time are mainly driven by paleoclimate changes, such as changes in temperature and moisture. Modern observations show that aboveground biomass across the tundra biome in the Northern Hemisphere high latitudes
Fig. 2. Representative palynofacies showing different morphologies of sporopollen and non-pollen grains and added Lycopodium clavatum from the IODP U1433 core (A: algae (dinoflagellate cysts); C: microcharcoal (not discussed in this study); F: fungi; L: Lycopodium clavatum; SOM/AOM: structured/amorphous organic matters; SP: sporopollen; R: resin; SA: stomatal apparatus).

Fig. 3. Light microscope photographs of selected morphologies of sporopollen. a: Polypodiaceae; b: Lycopodiaceae; c: Podocarpus, Podocarpaceae; d: Iridaceae?; e: Palmae; f: Casuarinaceae; g: Alnus, Betulaceae; h: Sonneratia, Sonneratiaceae (Lythraceae); i: Quercus, Fagaceae; j: Melastomataceae; k: Nyssa, Nyssaceae; l: Sapindaceae; m: Ilex, Aquifoliaceae.
significantly increased as mean annual temperature increases (MAT) (Wang et al., 2016), which means that, theoretically, biomass production increases as the climate becomes warmer. If such observations can be used as references for the general relationships between the temperature and biomass, we can infer that the highest temperature period of the late Cenozoic was the MMCO (Flower and Kennett, 1994) (Fig. 20g); and the sea-surface temperature in the tropics was ~4 °C to 6 °C higher during the MMCO and then subsequently decreased continuously (Zhang et al., 2014; Herbert et al., 2016). The sporopollen assemblage in Inner Asia indicated a dense forest with a rather humid climate during the MMCO (Miao et al., 2012, 2013b), with a large number of warm- and wet-adapted mammals, such as Platybelodon, Pliopithecus, Anchitherium, Chalicotherium, Kubanochoerus and Palaeotragus appearing (Deng, 2016). These observations support an East Asian summer monsoon (precipitation) intensification along with a warmer Asia (Miao et al., 2016c). So, the biomass should have reached a maximum during the MMCO and then decreased afterwards, similarly to the content of total organic carbon collected from the same core (Li et al., 2015) (Fig. 20e); however, all the organic particles follow very different patterns to those that are traditionally observed in response to climate variation, and all were at their lowest during the MMCO and seem to increase since 8 Ma. Consequently, the trends in concentrations and fluxes seen in this study are likely not driven by climate (at least temperature) but by other forcing mechanisms, especially around 8 Ma. Precipitation should obviously be considered as the region is strongly affected by monsoonal circulation. The geochemical and mineralogical records from the South China Sea have been interpreted to show that the East Asian summer monsoon has intensified since 8 Ma (Liu et al., 2017). The sporopollen results from ODP Site 1143 would be consistent with greater moisture and, potentially, with enhanced monsoonal
activity since ~8 Ma (Luo and Sun, 2007). However, the age of the inception of monsoonal conditions is debated. For instance, chemical weathering constraints and erosion records from the South China Sea favor the onset of strengthening as early as the Early Miocene (at ~23 Ma) with a decrease in strength after 8 Ma (Clift et al., 2008; Clift et al., 2014; Wan et al., 2007). Steinke et al. (2010) even suggested that an abrupt weakening in the EASM around 7.5 Ma was most likely the driving force for decreasing aridity in East and South Asia at 8–6 Ma, leading to widespread ecosystem changes in that region. Overall, the monsoon evolution at ~8 Ma remains unclear, and should not be considered as the main driving force behind changes at ~8 Ma in the South China Sea.
Fig. 10. Light microscope photographs of selected morphology of fungi (Miao et al., 2017). a: Exesisporites; b: Biporisporites; c: Alternia; d: Meliola; e: Diporisporites; f: Spegazzinia type; g: Striadiporites; h: Tetraploa aristata; i: unknown type.

Fig. 11. Diagrams showing concentration and flux of total fungi recovered at Site U1433 after Miao et al. (2017) (colors represent logarithmic values; grays represent linear values); the yellow rectangle represents the MMCO and the blue line the 8 Ma mark. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Light microscope photographs of selected morphology of SOM/AOM. a, d, e, h, i: structured organic matters; b, c, f, g: amorphous organic matters.
4.2.2. Tectonic basin evolution and drainage changes

Besides paleoclimate, tectonically-driven basin evolution and drainage changes (river system or sea current) are also considered as co-existing factors which could be reflected in the deposition at IODP Site U1433.

Within the South China Sea, studies have suggested that seafloor spreading ended at 20.5 Ma (Barckhausen et al., 2014), or that there was a cessation at ~17 to 15 Ma according to earlier estimates based on IODP drilling (Briais et al., 1993; Li et al., 2015; Li et al., 2014). After the Middle Miocene, tectonic activity in the basin became relatively weaker until the uplift of the Vietnamese Central Highlands and the extrusion of a thick basaltic sequence, mostly after ~8 Ma (Carter et al., 2000; Cung et al., 1998). Such weakening in tectonic activity is reflected by the decreasing volumes of lava emplacement (Hoang and Flower, 1998; Wang et al., 2001). A paleogeographic map of the South China Sea at 17 Ma and 8 Ma shows that Luzon and the Philippine arc have been moving from the Pacific towards the South China Sea progressively over this interval, noting the emergence of Borneo prior to

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Fig. 13. Diagrams showing concentration and flux of SOM/AOM at Site U1433 (colors represent logarithmic values; grays represent linear values); the yellow rectangle represents the MMCO while the blue marks the 8 Ma time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 14. Light microscope photographs of selected resin morphologies. a: nearly rectangular resin; b–d, h: amorphous resins; e–g: suborbicular resins.

Fig. 15. Diagrams showing concentration and flux of total resins at Site U1433 (colors represent logarithmic values; grays represent linear values); the yellow rectangle represents the MMCO. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
8 Ma and the emplacement of the Central Highlands lavas at 8 Ma (Hall, 2002). All these evidence suggest that the Mekong Basin and surrounding lands, driven by tectonics during the last 17 Ma, were moving towards a location which promoted the accumulation of all organic particles. Furthermore, tectonics was also driving long-term uplift and widening of the Tibetan Plateau, where the headwaters of the Mekong River lie. Accelerated clastic sedimentary rates from about < 0.5 cm/k.y. to ~20 cm/k.y. can be observed after 8 Ma (Li et al., 2015) (Fig. 20f). This indicate that Site U1433 start receiving increasing volumes of terrestrial sedimentary materials after that time, which is a trend opposite to that seen in the Pearl and Red River systems (Clift, 2006). Prior to 8 Ma, the possible sources are complex according to the geochemical and mineralogical provenance (Liu et al., 2017), probably representing a mix from Indochina, the Dangerous Grounds, and Palawan, but it seems clear that the Mekong Basin became the main contributor of sediment after 8 Ma (Liu et al., 2017), explaining the synchronous signal seen in all organic matter types at 8 Ma, and the somewhat more stable signal seen in sediments younger than 8 Ma, while the multiple sources prior to 8 Ma would explain the disparity and complexity of the signals. The drainage system changes associated with the tectonically-driven basin evolution best explain the ~8 Ma event. Indeed, based on the clastic sedimentation as well as geochemical and mineralogical provenance proxies, Liu et al. (2017) argued that most of the sediments deposited at Site U1433 since 8 Ma have been derived from the Mekong River, with lesser inputs from other small rivers draining coastal Vietnam, including the Central Highlands. Regional sediment budgets for this area (Clift, 2006; Ding et al., 2016) show a sharp increase in sedimentation rates at around this time, consistent with the Mekong either initiating or moving its mouth to the present location. Luo and Sun (2007) also ascribed this event to tectonic
Fig. 19. Diagrams showing concentration and flux of scolecodonts at Site U1433 (colors represent logarithmic values; grays represent linear values); the yellow rectangle represents the MMCO. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 20. Diagrams showing (a) total concentrations and (b) total fluxes of all types, ratios of (c) sporopollen and (d) dinoflagellate cysts to total organic particles, (e) organic carbon (wt%) and (f) linear sedimentation rate in the IODP Site U1433 (Li et al., 2015), (g) global ice volume/temperature and (h) carbon isotope records (Zachos et al., 2008) (shallow blue strip and yellow rectangle represent the change at ~8 Ma and MMCO (Middle Miocene Climatic Optimum)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
deformation occurring around the southern South China Sea. They imply that tectonic activity onshore resulted in the rapid uplift of surrounding islands, most significantly Borneo, as well as the Central Highlands of Vietnam, which would explain the higher fluxes in sporopollen data collected from ODP 1143 (for location, see Fig. 1). Certainly, uplift of the Central Highlands would also have resulted in intensified fluvial run-off and a possible increase in all particles.

5. Conclusion

The study presents the evolution of eight types of palynological and structureless particles deposited during 17 Ma in the South China Sea and sampled at IODP Site U1433. The increasing trends in concentration and flux of organic matters are likely to reflect tectonic activity rather than palaeoclimatic changes such as the Asian summer monsoon. The distribution of organic matters of various source (terrestrial, marine and multiple-origin particles) all evidenced a major shift at 8 Ma. This 8 Ma event likely reflects the onset of the sediment influx form the Mekong River as a result of drainage system evolution.

Acknowledgments

This research used samples and/or data provided by the International Ocean Discovery Program (IODP). Funding for this research was provided by the U.S. Science Support Program to Louisiana State University as well as by the NSFC Grants (41290252, 41772181). The research was carried out at the Center for Excellence in Palynology (CENEX) in Baton Rouge, Louisiana. The visiting scholar fellowship to Yunfa Miao is funded by the Chinese Academy of Sciences through a partnership with CENEX. PC thanks the Charles T. McCord Jr. Chair in Petroleum Geology and USSAC for support during this study.

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