Palaeogeography, Palaeoclimatology, Palaeoecology 311 (2011) 256–267

Contents lists available at SciVerse ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

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

Bioturbational structures record environmental changes in the upwelling area off Vietnam (South China Sea) for the last 150,000 years

Andreas Wetzel [a,]*, Rik Tjallingii [b,c], Martin G. Wiesner [d]

[a] Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH-4056 Basel, Switzerland
[b] Institut für Geowissenschaften, Christian-Albrechts-Universität, Otto-Hahn-Platz 1, D-24118 Kiel, Germany
[c] NIOZ-Royal Netherlands Institute for Sea Research, Landsdiep 4, NL-1797 SZ Den Hoorn (Texel), The Netherlands
[d] Institut für Biogeochemie und Meereschemie, Universität Hamburg, Bundesstrasse 55, D-20146 Hamburg, Germany

ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form 29 August 2011
Accepted 6 September 2011
Available online 10 September 2011

Keywords:
Ichnofabric
Upwelling
Bioturbation
Oxygen minimum
South China Sea
Zoophycos

ABSTRACT

The sediments in the upwelling area off central Vietnam are totally bioturbated and display a low-diverse assemblage of bioturbational structures. During interglacial times (Marine Isotope Stage MIS 1, 5a, 5c, 5e), summer monsoon leads to pronounced upwelling and seasonally pulsed arrival of organic matter on the seafloor. These deposits are characterized by a 4-tier bioturbated zone with *Zoophycos*. *Zoophycos* producers used this seasonal food source and show a cache behavioral strategy. During glacial periods upwelling was weak and oxygenation of bottom water decreased as evidenced by bioturbational structures that show a decrease in size, penetration depth and diversity. Enlarged freshwater influx during glacial times fuelled primary production and led to estuarine circulation. The resultant oxygen minimum layer favored an increased deposition of organic matter that in turn affected sediment properties. During MIS 2 and 5b oxygenation was probably a little lower than today. During MIS 3 and 5d *Chondrites*-like burrows point to a stronger oxygen deficiency. During MIS 4 bottom water oxygenation was even lower and only biodeformational structures occur in soft sediment rich in benthic food. Based on these findings an ichnofabric model for food-rich, fairly soft deposits experiencing oxygen deficiency is suggested having biodeformational structures as low-oxygen end member.

1. Introduction

Biogenic sedimentary structures are autochthonous indicators of environmental conditions and are advantageous for paleoecological and sedimentological analyses. Trace fossils have been used for ecological studies for a long time (e.g., Abel, 1935; Ekdale et al., 1984; Pemberton et al., 2001). A biotope can be characterized often better by its bioturbation structures than by other paleontologic constituents, especially in the deep sea (e.g., Leszczyński, 1991; Wetzel, 1991; Wetzel and Uchman, 1998; Uchman and Wetzel, 2011). By studying modern analogs, the significance of marine trace fossils, ichnofabrics, and ichnofacies as ecologic proxies and environmental indicators can be improved.

The ecologic interpretation of trace-fossil communities (ichnocoenoses) is today mainly based on three concepts. *Ichnofacies* refers to recurrent trace-fossil associations that characterize the environmental setting in a general sense (Seilacher, 1967). *Index trace fossils* indicate a specific environmental situation, for instance, some types of *Chondrites* point to lowered oxygenation (e.g., Bromley and Ekdale, 1984). *Ichnofabrics* result from bioturbation at all scales and they include all aspects of the texture and internal structures of marine sediments (Bromley and Ekdale, 1986).

The various endobenthic organisms normally occupy different depth levels within the seafloor while sediment consistency, food availability, oxygenation and other factors change with depth in sediment; the subdivision of the available ecospace results in a tiering of the burrows (e.g., Wetzel, 1981, 1984, 1991, 2010; Ausich and Bottjer, 1982; Ekdale et al., 1984; Bromley, 1996). Crosscutting relationships provide information about tiered bioturbation or a succession of burrows in ichnofabrics.

The deep South China Sea is an appropriate area to study organism–sediment interactions because the environmental factors and their variation are well known; in particular, bathyal sediments provide a long-term continuous record of environmental changes at a reasonable resolution in time (e.g., Sarnthein and Wang, 1999; Clemens et al., 2003). However, only a few studies address aspects of bioturbation in the deep South China Sea (Wetzel, 2002, 2008, 2009; Löwemark et al., 2004a, 2006). The latter author focused on the long-term record of the trace fossil *Zoophycos*, the former analyzed the modern situation after deposition of the 1991 Mount Pinatubo ash layer (Wiesner et al., 2004). However, a study addressing general aspects of a long-term bioturbational record is missing.

* Corresponding author.
E-mail address: Andreas.Wetzel@unibas.ch (A. Wetzel).

0031-0182/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2011.09.003

In the semi-enclosed marginal basin of the South China Sea the change of the environmental conditions from glacial to interglacial times offers the chance to study the response of the burrowing organisms: Do the ichnofabrics differ from bathyal sediments not affected by upwelling? How do the ichnofabrics off Vietnam compare with those found in other upwelling areas, for instance, off NW Africa? How do the ichnofabrics record the effects of a pronounced oxygen minimum during glacial times when enhanced freshwater influx led to estuarine conditions? Is the *Zoophycos* producer a good indicator for seasonal organic matter deposition in slowly accumulating settings as in the northern South China Sea, where it is only present in glacial deposits characterized by a strongly seasonal, upwelling-related deposition of organic matter (Löwemark et al., 2006)?

2. Regional setting

The South China Sea is a western marginal sea of the Pacific Ocean, surrounded by the Southeast Asian mainland in the north and west and the islands of Borneo, Palawan, Luzon and Taiwan to the south and the east (Fig. 1). The South China Sea has large shelf regions, such as the Sunda Shelf and the Gulf of Tonkin, and deep basins as between the Philippines and Vietnam.

The most prominent connection between the South China Sea and the Pacific Ocean is the Bashi Channel, between Taiwan and Luzon (Philippines), which has a sill depth of ~2600 m (Fig. 1). Oxygenated bottom waters (ca. 2 ml O_2/l; Wyrtki, 1961) are introduced into the South China Sea via that connection (Chao et al., 1996). Modern deep-water circulation in the South China Sea is characterized by rapid renewal and a short residence time of only 40–120 years resulting in oxygenated bottom waters (Broecker et al., 1986; Gong et al., 1992).

The entire region of the South China Sea is under the influence of the monsoon system, and in the absence of major oceanic inflow, the currents follow the main wind direction and undergo a seasonal reversal (e.g., Tomczak and Godfrey, 1994; Liu et al., 2002). During summer, northeasterly directed winds affected by a coast-parallel mountain range in Vietnam result in a wind jet at ~10°N. This leads to pronounced coastal upwelling and a clockwise surface current pattern (Xie et al., 2003). During November–March the northwest monsoon reverses the direction of flow establishing a counterclockwise surface current pattern and upwelling takes place off the northwest Luzon coast and off the northern Sunda Shelf (Liu et al., 2002). During the high season of the monsoons, particle flux to the seafloor increases by a factor of 3–4 whereby ~70% of the total annual organic matter flux is exported to the deep sea (Wiesner et al., 1996). El Niño events, however, suppress upwelling and intense wind mixing and lead to a significant reduction of particle flux. Today the carbonate compensation depth (CCD) is located in ~3500 m water depth (e.g., Wang et al., 1995); however, it has dropped to >4000 m water depth during glacial times (e.g., Thunell et al., 1992).

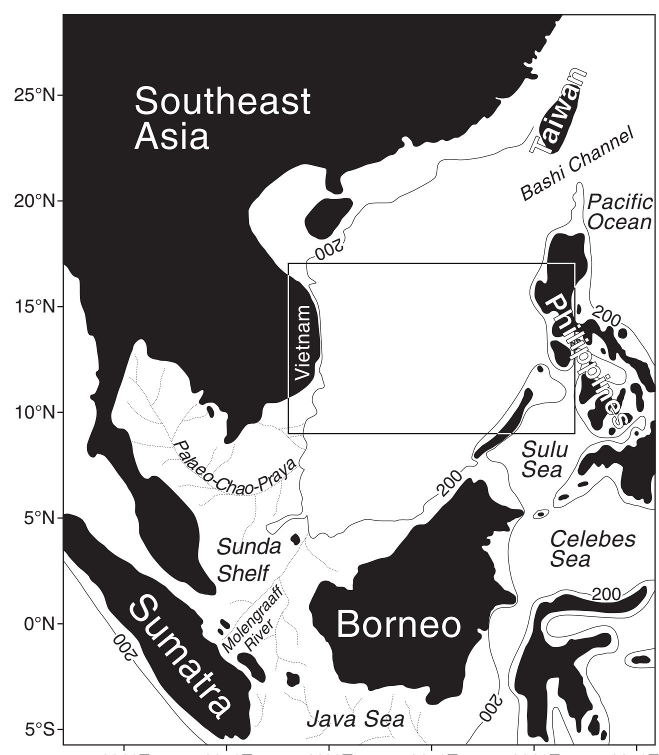

Fig. 1. Location of the study area. Inset represents area shown in Fig. 2.

In the South China Sea there is a strong shift in monsoon regime between glacial and interglacial conditions. Glacial periods are characterized by strong winter monsoon and weak summer monsoon, during the interglacials the situation is reversed (e.g., Wang et al., 1999; Jian et al., 2001; Liu et al., 2007). During the Holocene short periods of strengthened winter monsoon occurred at ~6, ~2.7 and ~0.2 ka and two short periods of intensified summer monsoon at ~7.5 and ~3.4 ka (Li et al., 2010). On orbital timescales, the strength of the summer monsoon exhibits a linear response to summer insolation (e.g., Liu et al., 2007; Griffiths et al., 2009).

During glacial times strengthening of the winter monsoon intensified upwelling and inflow of nutrient-rich waters into the northern South China Sea that in turn enhanced primary production seasonally (Wang et al., 1999). Weakened summer monsoon, however, resulted in reduced precipitation in subtropical China and to low upwelling intensity off central Vietnam. Fluvial discharge from Mekong and rivers draining the emerged Sunda Shelf increased significantly and an estuarine circulation was established (Wang et al., 1999). The supposed estuarine circulation in turn led to a pronounced O_2-minimum layer that developed especially in the southern part of the South China Sea during glacial periods (Wang et al., 1999; Löwemark et al., 2009). However, from the comparison of $\delta^{18}O$ data of benthic foraminifera at ODP Hole 806 B on the Ontong–Java Plateau with four cores from the northern South China Sea, Lin (2003) concluded that the Lower Pacific Intermediate Water continued to contribute to the South China Sea deep water during glacial periods. Stable isotopes from the same cores display large similarities in the temporal variation (Lin, 2003), questioning the hypothesis of extreme oxygen minimum during glacial periods (Löwemark et al., 2006).

3. Material and methods

Cores were collected during cruise 187 of the German research vessel *Sonne* in 2006 to the South China Sea (Wiesner et al., 2006). The present study is based on 7 cores, comprising one long 12-cm diameter gravity core and 6 short, 50×50 cm^2 box cores (Fig. 2; Table 1). Station 187-61 was found to be representative for all these cores and hence, only this site is discussed in detail. Additional information was provided by already published core data (Fig. 2; Table 1) and a core from the northern South China Sea studied in detail with respect to the trace fossil *Zoophycos* (Löwemark et al., 2006; Table 1).

Descriptions of all cores are based on onboard visual observations, digital camera images, and radiographs. For the X-ray radiography, about 1 cm thick sediment slabs were taken onboard from the spilt core surface directly after opening and sealed to prevent desiccation (Werner, 1967). The slabs were irradiated at the Academic Center of Radiology of Kiel (Germany) using a Swissray ddR Multi System operated at 40 kV and 100 mAs and automatically controlled radiation time. For a three-dimensional (3-D) analysis of the sedimentary structures, serial sections in vertical and horizontal directions were prepared.