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Temporal variations of the trace fossil *Zoophycos* in a 425 ka long sediment record from the South China Sea: implications for the ethology of the *Zoophycos* producer

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Abstract – A 425 ka long record from piston core GIK17925-3 taken in the northeastern South China Sea was used to study the environmental conditions controlling the distribution of the *Zoophycos* trace fossil. The 12 m long core offers a unique opportunity to study the response of the *Zoophycos*-producing animal to environmental variations over four glacial–interglacial cycles. The trace fossils show a strong glacial to interglacial variation in their abundance with a special preference for intervals with low sedimentation rates. Additional X-ray radiograph studies of piston cores from the Southeast Asian Marginal Seas show that the trace fossil *Zoophycos* is widespread in slope and deep-marine sediments, with the highest abundances encountered in low sedimentation rate settings. The preference of the *Zoophycos* producer for low sedimentation rates in a setting with strong seasonal fluctuations in food supply due to the shift between winter and summer monsoons, is interpreted to be the result of a cache-model behaviour, where food is collected during rich times and squirrelled away for poor times. Core GIK17925-3 also offers an opportunity to assess the impact of *Zoophycos* bioturbation on various palaeoenvironmental proxies. In this core, more than 30 % of the measured data points were more or less strongly affected by *Zoophycos* bioturbation. Together with the widespread occurrence this percentage indicates that *Zoophycos* may pose a serious threat to palaeoclimatic reconstructions in cores from low to moderate sedimentation rate sites.

Keywords: *Zoophycos*, South China Sea, Quaternary, ichnofossils, lebensspuren.

1. Introduction

Zoophycos belongs to a group of trace fossils encompassing a large number of mostly helically coiled spreiten structures (Häntzschel, 1975; Uchman, 1995; Chamberlain, 2000). The late Quaternary deep-sea *Zoophycos* typically consists of a helically coiled, continuous, lobate spreite surrounded by a marginal tube that is connected to the sediment surface through a vertical shaft (Fig. 1). Although the trace fossil is present in Cambrian to Quaternary strata, the producer of this enigmatic trace is still unknown and the behavioural explanations much debated (e.g. Alpert, 1977; Wetzel & Werner, 1981; Kotake, 1989; Bromley, 1991; Ekdale & Lewis, 1991; Fu & Werner, 1995; Locklair & Savrda, 1997; Gaillard, Hennebert & Olivero, 1999; Miller & D'Alberto, 2001; Löwemark & Schäfer, 2003; Olivero, 2003). *Zoophycos* from late Quaternary deep-sea sediments have been interpreted as the result of deposit feeding (Wetzel & Werner, 1981), gardening of micro-organisms (Fu & Werner, 1995) and caching of food-rich sediment for poorer times (Jumars *et al*. 1990; Bromley, 1991; Löwemark & Schäfer, 2003).

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The aims of this study are to examine the ecological and ethological implications from the geographic distribution of *Zoophycos* in the Southeast Asian Marginal Seas and from the stratigraphic distribution of *Zoophycos* in a core from the northeastern South China Sea. The 425 ka long record of core GIK17925-3 offers a unique opportunity to study the response of the *Zoophycos*-producing animal to environmental variations over the last four glacial–interglacial cycles. A second aim is to highlight the potential dangers of *Zoophycos* bioturbation to palaeoenvironmental reconstructions and age modelling in cores from the South China Sea and adjacent seas.

2. Material and methods

The 1215 cm long piston core GIK17925-3 (119°2.8′ E, 19°51.2′ N, 2980 m water depth) used in this study was taken from the northeastern South China Sea during the *SONNE 95* cruise in 1994 (Sarnthein *et al*. 1994). The core consists of hemipelagic muds and nannofossil oozes with some reworked ash layers.

Analyses of oxygen and carbon isotope values of the planktonic foraminifera *Globigerinoides ruber* (white variety) in the size fraction 315–400 μm (15–20 specimens) were made in 5 cm intervals with a Finnigan MAT-251 mass spectrometer at Kiel

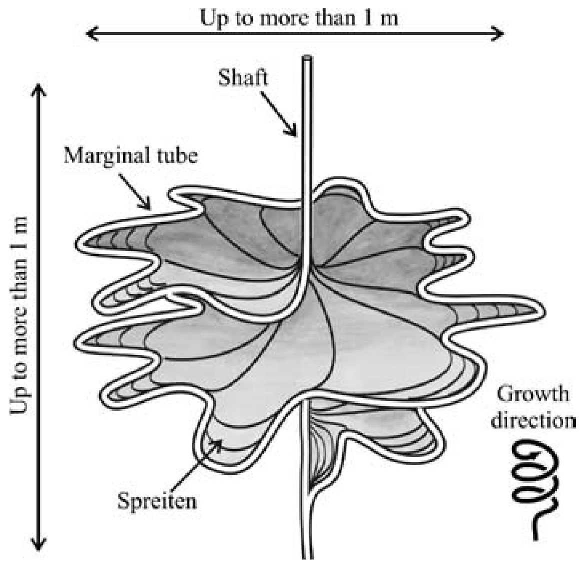

Figure 1. Conceptual model of the late Quaternary deep-sea *Zoophycos*, based on extensive studies of X-ray radiographs from Kiel Archives (Löwemark & Schäfer, 2003). The trace fossil consists of a continuous, upwards constructed, helically coiled spreite starting from a vertical tube. The trace fossil is surrounded by a marginal tube and an open vertical shaft connects it to the sediment surface.

Table 1. Age points used to establish the age model for core GIK17925-3

Depth (cm)	Age point	Age cal. (ka)
60	Younger Dryas, top	11.6‡
105	AMS	13.9
125	AMS	14.5
130	2.2	18.0*
255	3.3	55.5*
270	4.2	65.0 ?*
285	5.1	79.5*
315	5.31	96.3*
340	5.33	103.5*
390	5.51 top	116†
440	5.51 base	126†
455	5.53	132†
500	6.2	136†
550	6.44	157‡
560–620	6.5	163–174‡
660	6.6 base	184‡
670	7.1 top	193‡
710	7.3	215.5‡
770	7.5	240.5‡
800	8.02	247.5‡
830	8.24	260.5‡
850	8.4	267.5‡
900	8.5	287.5‡
930	8.6	294‡
960	9.1	313‡
1040	9.3 base	330‡
1095	11.1	368‡
1190	11.3	418‡
1210	12.2	426‡

Isotope event ages derived from * Martinson *et al.* (1987), † Shackleton *et al.* (2003), and ‡ Buehring, Sarnthein & Erlenkeuser (2004). AMS – accelerator mass spectrometry.

University, Germany. Three AMS ^{14}C datings on mixed foraminifer samples were performed at the Institute of Geological and Nuclear Sciences, New Zealand. The system error for modern samples is estimated to 0.6 %. This leads to an age uncertainty (σ) of 140 to 330 years for the samples measured (Table 1).

Sand content, total organic carbon content (TOC) and carbonate content were determined in 10 cm intervals. For the analysis of calcium carbonate ($CaCO_3$) and total organic carbon (TOC) concentrations, dried bulk sediment was first ground to powder, and then two weighed samples (∼0.1 g) were measured using a LECO CS-244 carbon/sulphur analyser at the Sun Yat-Sen University, Kaohsiung, Taiwan. One of the two weighed samples was directly measured for total carbon (TC) content of the sediment. The procedure involves heating the sample at 850 °C and measuring the combustion products by infrared energy detector. The other sample was digested with 2.4 N HCl to remove carbonates. The carbonate-free residue was washed thoroughly with deionized distilled water and dried, and then the residual carbon was measured. This value represents the TOC content of the sediment. The difference between the two carbon measurements (TC and TOC) gives the total inorganic carbon (TIC) content. $CaCO_3$ concentration is calculated by wt %$CaCO_3$ = wt %TIC/12 × 100, assuming all of the inorganic carbon was present as calcite or aragonite.

The X-ray radiographs for this study were produced at the Institute of Geosciences, Kiel, using the method described by Bouma (1964) and Werner (1967). Plastic boxes 25 × 10 × 1 cm were pushed into the sediment, cut out with a nylon string and placed in vacuum-sealed plastic pouches. The sediment slabs were placed directly on the X-ray film bags and exposed to 35 kV for 10 to 15 minutes. Using the X-ray radiographs, all sedimentological and geochemical data points were checked for the presence of *Zoophycos* spreiten. All data points where *Zoophycos* was observed, no matter how small or how marginal the contamination might have been, were referred to as *Zoophycos*-affected and were plotted as grey diamonds in the depth-plots to allow an assessment of the influence of *Zoophycos* on the measured values.

Additionally, radiographs from five cores from the South China Sea, five cores from the Sulu Sea and one core from the Celebes Sea were included in the study to assess the abundance of *Zoophycos* in deep-sea sediments from the Southeast Asian Marginal Seas. In core MD012388 from the Celebes Sea, radiographs were only available from limited sections directly surrounding tephra layers (Löwemark *et al*. 2004).

3. Oceanographic and environmental background

The surface circulation in the South China Sea is controlled by the East Asian monsoon system with a northeast monsoon driving a cyclonic gyre over the whole basin during winter and the southwest monsoon driving an anticyclonic gyre, primarily in the southern part of the basin, during summer (Wyrtki, 1961; Liang, Jan & Tang, 2000). This alternation between summer and winter monsoon results in a strong seasonality of the primary productivity and the organic material reaching the sea floor (Nair *et al*. 1989; Shaw *et al*. 1996; Liu *et al*. 2002). In the northern South China Sea, the redox boundary in the sediment is typically situated at 10–20 cm depth, although in areas with locally enhanced productivity it lies directly below the sediment surface (Sarnthein *et al*. 1994).

Modern deep-water circulation in the South China Sea is characterized by a rapid renewal resulting in a short residence time of only 40–120 years and well-oxygenated bottom waters (Broecker *et al*. 1986, 1988; Gong *et al*. 1992). The estuarine style processes controlling glacial deep-water circulation in the South China Sea appear to have been similar to the present. Based on benthic $\delta^{13}C$ signals it has been suggested that the lowered sea level during glacial times, together with fresh-water input from the SE Asian mainland, could have led to stagnating deep-water circulation and oxygen depletion in the bottom waters, especially in the southwestern part of the South China Sea, far away from the only remaining opening to the open ocean (Wang *et al*. 1999). However, from the comparison of $\delta^{18}O$ of benthic foraminifers at ODP Hole 806B 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 carbon isotopes from the same cores display large similarities in the temporal variation (Lin, 2003), questioning the hypothesis of extreme oxygen minima during glacial periods proposed by Wang *et al*. (1999).

In any case, in the northeastern part of the South China Sea bottom water conditions were probably more influenced by variations in the strength of the inflowing Lower Pacific Intermediate Water. Hiatuses observed in the nearby ODP Hole 1144 imply that the inflow reached an extreme maximum during glacial terminations and early interglacial intervals while it was far more sluggish during glacial times (Buehring, Sarnthein & Erlenkeuser, 2004). Glauconite layers in core GIK17925-3 partly match these erosional events although at least two glauconite layers are observed in glacial intervals as well, suggesting that deep-water circulation might have been vigorous even under glacial sea-level low-stand conditions.

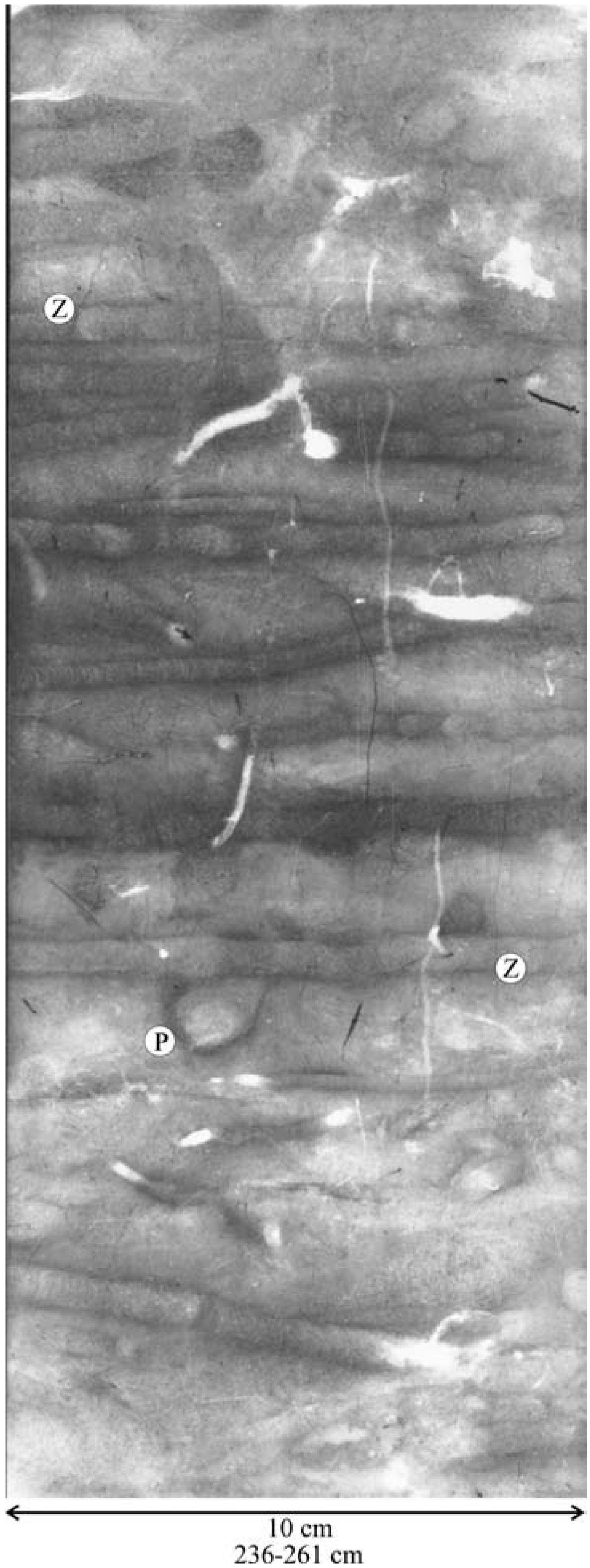

Figure 2. X-ray radiograph showing *Zoophycos*-rich interval in core GIK17925-3. Z – examples of *Zoophycos* spreiten; P – *Planolites*-like burrow.

4. Results

4.a. Oxygen isotope stratigraphy and age model for GIK17925-3

The downward transport of surface material by the *Zoophycos*-producing animal poses a serious problem for high-resolution stratigraphy in late Quaternary piston cores (Wetzel, 1981; Löwemark & Werner, 2001; Leuschner *et al*. 2002). However, recognition of the *Zoophycos* spreiten in radiographs allows an identification of potentially contaminated data points (Fig. 2). The stable oxygen record clearly shows marine

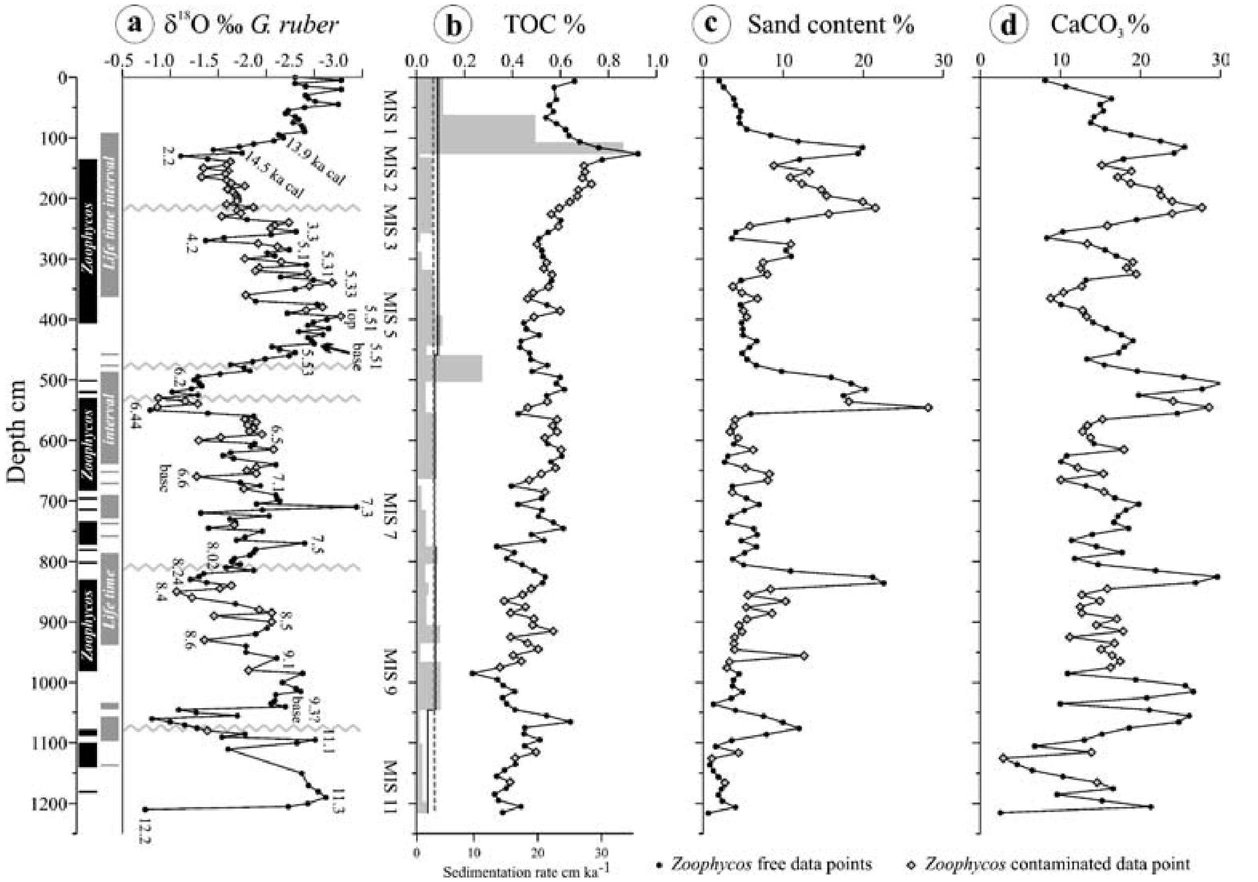

Figure 3. Stable oxygen isotope stratigraphy and sediment parameters measured in core GIK17925-3. Black circles represent data points unaffected by *Zoophycos* bioturbation, grey diamonds represent *Zoophycos*-contaminated data points. (a) Occurrence of *Zoophycos* spreiten (black bars) and tentative life-time intervals (grey bars) of the producer. Stable oxygen isotope record of *Globigerinoides ruber* and age points used for the age model. Vertical waved lines indicate unconformities, possibly major stratigraphic gaps. MIS – Marine Isotope Stage. (b) Linear sedimentation rates and total organic carbon (TOC) plotted versus depth. Gray filled area represents linear sedimentation rates between age points used for the age model, solid black line represents linear sedimentation rates for the respective glacial–interglacial cycles, and dotted grey line shows average linear sedimentation rate for the entire core. (c) Sand content plotted versus depth. (d) Carbonate content plotted versus depth.

isotope stages (MIS) 1 through 11, with a lowermost heavy point presumably corresponding to the end of glacial stage 12 (Fig. 3a). The values range between slightly more than -1.0 ‰ during glacial stages MIS 6, 10 and 12, and almost -3.0 ‰ during interglacial stages MIS 1, 5 and 11. These interglacial–glacial fluctuations with an amplitude of slightly less than 2 ‰ agree well with interglacial–glacial variations observed in many nearby cores, such as MD972142 from the southeastern South China Sea (Chen *et al*. 2003; Wei, Chiu & Chen, 2003). Of special interest are the relatively light isotope values formed by *Zoophycos*-bioturbation-affected points during MIS 2. In other cores from the South China Sea, MIS 2 normally displays heavy isotope values as cold or colder than stages 6, 10 and 12 (e.g. Wang *et al*. 1999; Wei, Chiu & Chen, 2003; Buehring, Sarnthein & Erlenkeuser, 2004). In contrast, the heaviest point in stage 2 is considerably lighter than in other cold stages.

The age model for the $\delta^{18}O$ record of core GIK17925-3 was based on peak-by-peak correlation with isotope curves from other well-dated cores (Martinson *et al*. 1987; Shackleton *et al*. 2003; Buehring, Sarnthein & Erlenkeuser, 2004) and two AMS ^{14}C-dates (Table 1). A third AMS ^{14}C date (20.28 ka, NZA 6488) at 205 cm was obtained directly from a *Zoophycos* spreite.

The average linear sedimentation rate is about 2.8 cm ka^{-1}, but there are significant variations with maxima over 30 cm ka^{-1} and minima just below 1 cm ka^{-1}. Average linear sedimentation rates for individual glacial–interglacial cycles reveal a gradual down-core decrease in linear sedimentation rates due to compaction (Fig. 3b).

On short time scales, there seems to be a rather clear relationship between sedimentation rates and glacial–interglacial cycles. Low overall sedimentation rates dominate most interglacial and glacial stages, whereas peak sedimentation rates match glacial terminations, especially in the upper half of the core. In the lower half a similar tendency was observed, although it is less obvious due to the compaction in the lower part of the core and to difficulties in properly assigning the isotope events disturbed by several hiatuses and the large number of *Zoophycos*-contaminated data points in some critical intervals.

4.b. Total organic carbon (TOC), sand and carbonate content in core GIK17925-3 and the effect of *Zoophycos* bioturbation

Total organic carbon shows a gradual increase from around 0.4 % in the lowermost part to about 0.6 % near the core top. A similar rise was also observed in a 500 ka long record from core MD972142 from the southeastern South China Sea (Chen *et al.* 2003). Superimposed on this long-term diagenetic trend are fluctuations of 0.2 to 0.4 %, with higher values corresponding to glacial intervals and glacial termination I and lower values to interglacial conditions (Fig. 3b). This glacial carbon enrichment is a feature observed in many other cores from the South China Sea (e.g. Thunell *et al*. 1992; Kienast *et al*. 2001; Chen *et al*. 2003). Because the fluctuations in TOC content are relatively small, data points affected by *Zoophycos* bioturbation show little difference to unaffected points.

Sand and carbonate content both display a pronounced glacial–interglacial cyclicity with strong peaks usually corresponding to late glacial and termination intervals (Fig. 3c, d). Generally, the carbonate content follows the sand content, indicating that the sand primarily consists of foraminiferal tests. Some sand-enriched layers, however, contain numerous glauconite grains and other strange particles and thus may record extended phases of zero deposition and/or erosion (waved lines in Fig. 3a). Yet, the carbonate also displays several peaks that seem unrelated to sand content and climatic shifts. There are also a few curious data points suggesting some influence on the records by *Zoophycos* production. In MIS 2 there is a second peak that consists entirely of potentially contaminated data points. It is therefore not clear whether this second peak represents a true increase in sand and carbonate in the early part of stage 2, or is the result of downcore transport of coarse material from the upper peak. Another strange sand maximum occurs at the end of stage 9 where a single point is strongly enriched in sand, suggesting that it may consist of sand brought down by the *Zoophycos* producer from the peak in sand content one metre above. However, as for TOC, sand and carbonate content of the spreiten material may to a large extent be controlled by the selective behaviour of the producing animal rather than by the conditions at the palaeo-sediment surface.

4.c. Geographic distribution of *Zoophycos* in Southeast Asian Marginal Seas

The X-ray radiographs of the studied cores from slope to deep-marine settings in the Southeast Asian Marginal Seas reveal that *Zoophycos* spreiten are present in 11 out of 12 cores. Only one core from the Sulu Sea is completely lacking *Zoophycos* spreiten (Fig. 4).

Figure 4. Bathymetric chart showing core locations studied in the South China Sea, Sulu Sea and Celebes Sea. Open large circles – cores containing *Zoophycos*. Filled grey circles – cores without *Zoophycos*. Small black diamonds show positions of other cores discussed in the text and in Table 2. Depth contours in metres.

This clearly illustrates the widespread distribution of this trace fossil in deep-sea sediments of the Southeast Asian Marginal Seas. However, as displayed in Table 2, the abundance of *Zoophycos* strongly varies in the cores. Whereas most cores only contain a limited number of spreiten, core GIK17925-3 from the northern South China Sea contains over 300 spreiten. In core MD012388 from the northern Celebes Sea only 13 spreiten were counted; however, considering that this number is based on only 315 cm out of a total core length of 3402 cm, it is reasonable to assume that the actual spreiten number for the entire core will be considerably larger. From the geographic distribution of *Zoophycos*, no correlation between bathymetry and *Zoophycos* abundance can be established; rather, the abundance of *Zoophycos* seems to be determined by the sedimentation rate. Unfortunately, age models only exist for GIK17950-2 (Lin *et al*. 1999), MD012388 (Löwemark *et al*. 2004) and GIK17925-3 (this study). The sedimentation rate at the other locations can only be crudely estimated through correlation with nearby cores (Table 2). Although factors affecting the number of *Zoophycos* spreiten in the cores, such as core length and age interval of the cores, could not be determined for most of the cores, a fairly clear preference for low

Table 2. Abundance of *Zoophycos* spreiten in the cores from Southeast Asian Marginal Seas

Core	Latitude	Longitude	Water depth (m)	Sedimentation rate (cm ka^{-1})	Number of *Zoophycos* spreiten
GIK14210-5	9.9°N	119.8°E	1212	5–20[a]	5
GIK14218-2	9.2°N	120.3°E	1937	5–20[a]	2
GIK14224-1	7.5°N	121.5°E	4976	100–200[a]	4
GIK14233-4	8.8°N	121.8°E	4934	100–200[a]	0
GIK14233-5	8.8°N	121.8°E	4934	100–200[a]	2
GIK16520	18.4°N	116.0°E	3766	7[b]	10
GIK16527	18.9°N	115.8°E	2695	20–40[c]	8
GIK17925-3	19.9°N	119.0°E	2980	3	322
GIK17950-2	16.1°N	112.9°E	1865	1–14[d]	5
GIK17958-1	11.6°N	115.1°E	2580	10[e]	1
GIK17960-1	10.1°N	115.6°E	1711	10[e]	1
MD012388	6.7°N	122.9°E	3302	15[f]	13*

[a](Wetzel, 1983).
[b]Sedimentation rate estimated from nearby core SO50-31KL (Chen & Huang, 1998).
[c]Sedimentation rate estimated from nearby cores 17937-2, 17938-2 and 17939-2 (Wang *et al.* 1999).
[d](Lin *et al.* 1999).
[e]Sedimentation rate estimated from core 17957-2 (Shyu *et al.* 2001) located between cores 17958-1 and 17960-1 SW of the Spratly Islands.
[f](Löwemark *et al.* 2004).
* In core MD012388, X-ray radiographs were only available from limited intervals in connection with tephra layers; only 315 cm of a total core length of 3402 cm were analysed (Löwemark *et al.* 2004).

sedimentation rates is evident. The three cores showing extremely high sedimentation rates also display a very low abundance of *Zoophycos*. In contrast, in core GIK17925-3 where sedimentation rates are particularly low, *Zoophycos* spreiten occur in profusion. Cores with moderate sedimentation rates of 5 to 40 cm ka^{-1} display a moderate abundance of *Zoophycos*. Thus, it seems the *Zoophycos* producer is favoured by slow sediment input.

4.d. Stratigraphic distribution and abundance of *Zoophycos* spreiten

The down-core distribution of *Zoophycos* in GIK17925-3 exhibits a conspicuous division into *Zoophycos*-rich and *Zoophycos*-barren intervals. *Zoophycos*-rich intervals roughly correspond to intervals starting directly after interglacial maxima and ending with the termination of the following glacial interval (Fig. 3a). This distribution also corresponds to the variations in linear sedimentation rate. In the upper half of the core, high sedimentation rates correspond to *Zoophycos*-barren intervals, whereas low sedimentation rate intervals are characterized by high abundances of *Zoophycos*. In the lower part of the core a similar trend is observed, although compaction, less good age control, and hiatuses make the relation to sedimentation rates less obvious. Nevertheless, increases in sedimentation rate are observed at terminations III, IV and V. In contrast, no unambiguous relation between *Zoophycos* abundance and sediment parameters can be established; *Zoophycos* shows no preference to particular TOC content, neither to TOC-rich nor to TOC-poor intervals. As for sand and carbonate content, *Zoophycos* is generally absent in the sand- and carbonate-rich intervals of glacial terminations, but is common in other sand- and carbonate-rich intervals such as MIS 2 and 3. *Zoophycos* spreiten thus occur during carbonate maxima as well as minima. The fact that one of the sand peaks in MIS 2 entirely consists of *Zoophycos*-affected points also suggests that neither sand nor carbonate content is controlling *Zoophycos* abundance.

5. Discussion

5.a. *Zoophycos* ethology

The stratigraphic distribution of spreiten within core GIK17925-3 and the overall distribution of *Zoophycos* in the Southeast Asian Marginal Seas suggest a clear preference for sedimentation rates below 5–10 cm ka^{-1}. Note that some fossil *Zoophycos* also match periods of low sedimentation or firmgrounds representing omission surfaces (e.g. Ekdale & Lewis, 1991; Olivero, 1996; Olivero & Gaillard, 1996; Gaillard, Hennebert & Olivero, 1999; MacEachern & Burton, 2000). Probably it is not the low sedimentation rate *per se* that is preferred by the *Zoophycos*-producing animal. Even at 'high' sedimentation rates the organism should not have any problem keeping its head over the sediment input. Rather, the food flux at low sedimentation rates in deep-marine settings is not sufficient to sustain a vigorous benthic infauna that would constantly destroy the upper parts of the *Zoophycos* system. Low sedimentation rates thus appear to be a prerequisite for massive *Zoophycos* colonization. This view is corroborated by detailed observations from the continental slopes off West Africa (Wetzel & Werner, 1981) and Portugal (Löwemark & Schäfer, 2003), where *Zoophycos* was found absent from rapidly deposited, and nutrient-rich sediments, but was abundant in slowly deposited sediments with moderate TOC content.

Any interpretation of the distribution of *Zoophycos* needs to consider the stratigraphic offset between the core depth of the spreiten, and the stratigraphic position of the actual sediment surface at the time of spreiten construction, as suggested by Wetzel & Werner (1981). The often deep penetration of the *Zoophycos* producer implies that the spreiten are preserved at levels down to one metre below the palaeo-sediment surface. Taking this great burrowing depth of *Zoophycos* into account, the *Zoophycos* colonization of site 17925-3 started well after optimal interglacial conditions had ended and stopped with the onset of the terminations. However, neither the actual position of the spreiten nor the colonization periods, derived from assumed burrowing depths of 50–100 cm, correspond to any physical or chemical sedimentary parameters. Nevertheless, the division into *Zoophycos*-rich and barren intervals corresponding to certain climatic stages clearly points toward particular preferences of the trace maker. If *Zoophycos* represented a deposit feeding behaviour, then a strong preference for TOC-rich intervals would be expected. Alternatively, a preference for high-accumulation intervals would be expected; the higher the burial rate of organic carbon, the more nutritious the organic matter in the sediment will be. The lack of any direct relations between sediment parameters and *Zoophycos* suggests that the answer must be sought in hydrological variations not directly reflected in the sediment parameters measured.

As discussed above (Section 3), deep-water circulation in the South China Sea likely operated in similar ways during glacial and interglacial periods. For that reason, it is not likely that climatically induced changes in bottom water circulation are responsible for the fluctuations in *Zoophycos* abundance. In contrast, variations in the surface circulation may have had a crucial influence on the benthic fauna.

Most of the produced organic material is remineralized in the surface waters; only approximately 10–20 % of the primary production in the photic zone leaves the surface waters. Because 70–90 % of the sinking material is remineralized within the first 900 m (Suess, 1980), and because of the marine-snow effect (Honjo, 1982), the effect of high-productivity events ('benthic snow storms') is of great importance to the benthic fauna at depths below 1000 m. In the South China Sea there is a strong shift in monsoon regime between glacial and interglacial conditions, glacial intervals being characterized by strong winter monsoon and weak summer monsoon, and the interglacials characterized by a strong summer and weak winter monsoon (Wang *et al*. 1999; Jian *et al*. 2001), leading to distinctly different primary productivity regimes during glacial and interglacial conditions. Today, locally enhanced productivity in the generally oligotrophic northern South China Sea results in local shifts of the redox boundary from 10–20 cm up to the sediment surface, indicating the importance of shifts in the production regime to the benthic fauna. The *Zoophycos* then would be a response to conditions where food collected during rich times needs to be squirrelled away for poorer times, as suggested in earlier studies (Jumars *et al*. 1990; Bromley, 1991). This is probably why high abundances of *Zoophycos* often characterize areas marked by strong seasonality in primary productivity, such as the West African margin (Wetzel & Werner, 1981) and the Arabian Sea (Leuschner *et al*. 2002). In contrast, *Zoophycos* is almost completely absent from low sedimentation rate sites in the warm and oligotrophic eastern Mediterranean Sea, where weak seasonality prevails and food flux is extremely low due to well-oxygenated deep waters and high temperatures (Löwemark & Werner, 2001).

The introduction of organic-rich surface material into pelleted lamellae in the spreiten by the late Quaternary *Zoophycos* (Chamberlain, 1975; Ekdale, 1977; Wetzel & Werner, 1981; Fu & Werner, 1994, 1995; Leuschner *et al*. 2002; Löwemark & Schäfer, 2003), together with the distribution of *Zoophycos* in the Southeast Asian Marginal Seas, suggest that the occurrence of *Zoophycos* is a response to ephemeral pulsed input of food in deep-sea settings where quiet, calm conditions and low sedimentation rates prevail.

5.b. Impact on high-resolution stratigraphy

Marginal basins are particularly suited recorders of palaeoenvironmental changes because they often amplify climatic changes and better preserve proxy records due to higher sedimentation rates and shallower water depths (e.g. Clift *et al*. 2003; Giosan & Flood, 2004). Therefore, the almost ubiquitous presence of *Zoophycos* in slope and deep-marine settings in the Southeast Asian Marginal Seas may pose a serious threat to palaeoenvironmental reconstructions aiming at the response and influence of the palaeomonsoon and the Western Pacific Warm Pool to the global climate system at centennial to millennial timescales. The detrimental effect of *Zoophycos* bioturbation on high-resolution records has recently been exposed by radiocarbon studies comparing the age of *Zoophycos* spreiten material with directly surrounding host sediment. In cores from the Iberian margin, age differences of up to more than 3000 years were observed (Löwemark & Werner, 2001), and in the Arabian Sea, where sedimentation rates are considerably lower, age errors of up to 10 000 years were measured (Leuschner *et al*. 2002).

Whereas last-glacial-maximum-to-present records usually are taken at sites with sedimentation rates as high as possible (> 10 cm ka^{-1}) to obtain the best possible resolution of the studied interval, several marine records covering longer parts of the Pleistocene may rely on lower sedimentation rate sites (< 5 cm ka^{-1}) to increase the stratigraphic span of the records. High abundance of *Zoophycos* at low-sedimentation settings puts such records in danger of being seriously affected by *Zoophycos* bioturbation. The relatively small number of spreiten observed per core in moderate

(5–10 cm ka^{-1}) and high sedimentation rate (> 10 cm ka^{-1}) settings should not lead to ignoring the potential bias caused by *Zoophycos* in these cores. The cores from the Southeast Asian Marginal Seas as well as studies from the West African margin (Wetzel & Werner, 1981), the Arabian Sea (Leuschner *et al*. 2002) and the Portuguese margin (Löwemark & Schäfer, 2003) show that the trace fossil is often concentrated in certain stratigraphic intervals, possibly in phases of lower sedimentation rates. Because of the frequent, large and rapid shifts between different climatic regimes, the downward transport of palaeo-surface sediment may lead to serious misinterpretations and age errors, especially when different proxies or proxies from different species are compared (Löwemark & Grootes, 2004).

In core GIK17925-3, the effect of *Zoophycos* bioturbation is best demonstrated by the AMS ^{14}C-date at 205 cm, which was taken directly from a *Zoophycos* spreite. This age does not agree with the age estimate derived from stable isotope stratigraphy, suggesting that the measured age reflects a mixed age of down-mixed younger foraminifers and tests from the ambient sediment layer. Another example of potentially biased data points is found during MIS 2, where the isotope values show significantly lighter δ^{18}O values than would be expected from comparison with earlier glacial intervals from the same core. With most of stage 2 actually consisting of *Zoophycos*-affected points, it is legitimate to suspect that these data points might in fact reflect a mixture of glacial foraminifers and later admixed isotopically lighter foraminifers. A downward transport of foraminiferal tests from the early part of Termination I into the spreiten could explain the lighter than expected isotope values of the *Zoophycos*-contaminated data points. Neighbouring δ^{18}O records of ODP core 1144 (Buehring, Sarnthein & Erlenkeuser, 2004) and piston core GIK17924 (M. Sarnthein, unpub. data) reveal short term variations of up to more than 0.5 ‰ that can be correlated with climatic fluctuations recorded in the Greenland ice cores. Thus, the incomplete and low resolution record of GIK17925-3 itself does not lead to a quantification of the absolute deviations introduced by *Zoophycos* bioturbation.

6. Conclusions

Studies of X-ray radiographs from the South China Sea, the Sulu Sea and the Celebes Sea revealed that the trace fossil *Zoophycos* is widespread in slope and deep-sea sediments of the Southeast Asian Marginal Seas. Highest abundances of spreiten were observed in low sedimentation rate settings. In the 425 ka long record from piston core GIK17925-3 in the northeastern South China Sea, the abundance of spreiten showed a strong interglacial–glacial cyclicity with *Zoophycos* conspicuously missing during the termination intervals, characterized by strong increases in linear sedimentation rates. The preference for low sedimentation rate settings in an area characterized by a strong seasonality in food supply (caused by the shifting monsoon directions during summer and winter) suggests that the late Quaternary *Zoophycos* represents a cache behaviour where food is collected on the sediment surface during pulses of high food flux, such as monsoon related upwelling events. The food is then squirrelled away for poorer times deep in the sediment, out of reach to other benthic organisms.

The high abundance of spreiten observed in low sedimentation rate records (< 5 cm ka^{-1}) clearly points out the dangers to stratigraphic records obtained from low sedimentation rate settings. Although the absolute number of *Zoophycos* spreiten in moderate to high sedimentation rate settings may be rather low, the *Zoophycos* spreiten are often concentrated in certain (low-sedimentation rate) stratigraphic intervals, increasing their potential to seriously bias climate reconstructions. To avoid this bias, radiographs may be helpful to direct proper sampling.

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