BIOGENIC REWORKING OF TEPHRA LAYERS IN THE SOUTH CHINA SEA (CORE MD972142) AND THE CELEBES SEA (CORE MD012388)

Ludvig Löwemark[1*], Chung-Hua Chen[1], Chih-An Huh[1], Teh-Quei Lee[1], Yuen-Ping Ku[1], Kuo-Yen Wei[2], Chih-Wei Chen[2], Tzu-Chien Chiu[2], Min-Te Chen[3]

[1]*Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 115, Taiwan R.O.C.*

[2]*Department of Geosciences, National Taiwan University, Taiwan R.O.C.*

[3]*Institute of Applied Geophysics, National Taiwan Ocean University, Taiwan R.O.C.*

**Corresponding author: ludvig@earth.sinica.edu.tw*

ABSTRACT

Bioturbation in oxic deep-sea settings is mostly considered, if considered at all, to consist of a 2-10 centimeters thick homogenized layer. The mixing of the sediment in this layer results in a smearing of any environmental signals analyzed. A number of mathematical approaches have therefore been proposed to estimate the extent of this smearing and smoothing and to deconvolute the records back into the original signal. However, in most cases the mixing of the sediment is a heterogeneous process consisting of several palimpsest steps of bioturbation. In this study, using X-ray radiographs of two cores from the South China Sea and the Celebes Sea, we show that discrete traces such as *Scolicia*, *Thalassinoides*, and *Zoophycos* account for a significant part of the redistribution of the material in tephra layers. Particles may be transported vertically over tens of cm and concentrated into discrete aggregations. The composition of the traces preserved also can be used to estimate the intensity and potential hazard of deep-reaching bioturbation. Deep-reaching burrows constitute a serious threat to high-resolution stratigraphy. It is therefore recommended that X-ray radiographs should routinely be made before sub-sampling the cores for paleoceanographical and paleoclimatological studies, especially before AMS-^{14}C dating.

Keywords: bioturbation, tephra, high-resolution stratigraphy, mixed layer, tiering, trace fossils, *Thalassinoides*, *Scolicia*, *Zoophycos*.

Introduction

From an ichnological perspective, traces left in the sediment and preserved as trace fossils represent a recording of animal behavior. Because the behavior of benthic animals is controlled by substrate consistency and composition as well as a number of environmental factors, trace fossils can be used for paleoenvironmental reconstructions (e.g., Ekdale et al., 1984; Savrda and Bottjer, 1989; Tyszka, 1994). In paleoceanographical and paleoclimatological studies, however, bioturbation is a nuisance, causing a smearing of the sedimentary record resulting in a smoothing of the proxy records used to reconstruct past environmental changes (e.g., Berger and Heath, 1968; Schiffelbein, 1984; Bard, 2001). Considerable attention has consequently been devoted to the mathematical modeling and deconvolution of the signal distortion caused by bioturbation (e.g., Berger et al., 1977; Mat isoff, 1982; Trauth, 1998), and several studies have examined the vertical redistribution of distinct tracers such as radioactive isotopes (Carpenter et al., 1982; DeMaster and Cochran, 1982; Thomson et al., 2000), tephra

Lynch, 1983), microtectites (Glass, 1969), and natural and artificial chemical substances (Mahaut and Graf, 1987; Conte et al., 1994; Wheatcroft et al., 1994). Mathematical models of the redistribution of tracers and the effect of bioturbation on environmental proxy records have a common shortcoming; they assume that the mixing is homogeneous with no significant sediment transport taking place through single, distinct, deep-reaching burrows (e.g., Anderson, 2001; Bard, 2001). Most models assume that the mixing takes place through homogeneous mixing in the mixed layer, possibly with a gradually decreasing intensity through the transition layer, and that below this homogeneously mixed zone the sediment is preserved in the historical layer (Ruddiman and Glover, 1972; Matisoff, 1982; Anderson, 2001). Little attention, however, has been given to the fact that bioturbation commonly is a very heterogeneous process actually consisting of several palimpsest steps of mixing and vertical sediment transport. The resulting bioturbation left in the stratigraphic record is in fact the deepest reaching traces with the highest preservation potential, the last burrowers (Bromley, 1996). These burrows often are of a more persistent type with open shafts connecting to the surface allowing the passive or active introduction of surface material deep into the sediment. Thus, even if the original mixed layer was perfectly homogenized, the end-result may be a mixture of several generations of distinct single burrows piping material up and down from different levels. This vertical piping of material within the sediment can result in local inhomogenities causing grave paleoenvironmental misinterpretations if sampled for analysis. The risk of inadvertently sampling specimens vertically displaced by heterogeneous

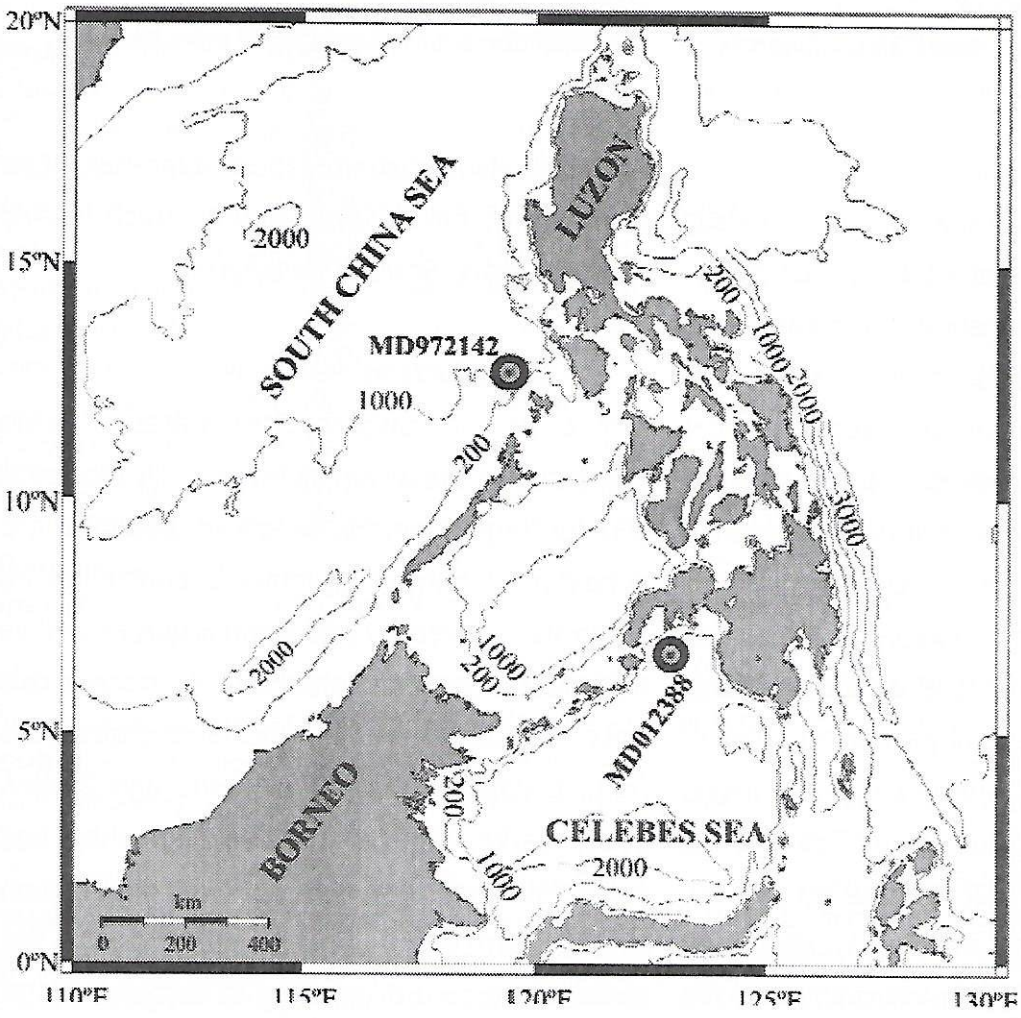


Fig. 1

Bathymetric chart showing the core locations of MD972142 in the South China Sea and MD012388 in the Celebes Sea. Depth contours in meters.

layers (Ruddiman and Glover, 1972; Officer and bioturbation in combination with the increasingly smaller sample volumes needed for modern analytical techniques pose a serious problem to high-resolution paleoclimatological studies.

The aim of this study is to examine the spatial distribution of biogenically reworked tephra in order to better understand the potential errors that may be caused by bioturbation in high-resolution stratigraphy and also to study how the composition of the traces preserved can be used to estimate the intensity of hazardous deep-reaching bioturbation.

Materials and methods

This study was performed on tephra layers from cores MD972142 from the southeastern South China Sea (12°41.133'N, 119°27.90'E, 1,557 m water depth) and MD012388 from the northeastern Celebes Sea (6°43.52'N, 122°55.91'E, 3,302 m water depth) (Fig. 1). Due to the severe flooding of the basement at the Institute of Earth Sciences, Academia Sinica, following the 2001 typhoon Nari (Sui et al., 2002), large parts of the core material from core MD972142 were lost, only those core sections sampled for tephra analyses could be recovered. Out of the more than 18 tehpra layers observed in the core (Wei et al., 1998), only 6 were considered for this study. The tephra layers were labeled 42a through 42f from top to bottom (Fig. 2). The age model for MD972142 is based on correlation of stable oxygen isotopes, AMS-^{14}C dating, last appearance date of *Globigerinoides ruber* (pink), the Brunhes/Matuyama boundary and the Australasian microtektite peak (Chen et al., 2003; Wei et al., 2003).

In core MD012388 at least 30 cm long sections around the tephra layers were sampled for X-ray radiographs. In all, 11 ash layers labeled 88a through 88k were sampled (Fig. 3). The stable isotope record used for the chronological framework only covers the upper 20 m; in the lower part an approximate age model was adapted based on the average sedimentation rate in the upper part of the core. This means that the lowermost ash layers are situated in MIS 7, ca. 205 ka BP.

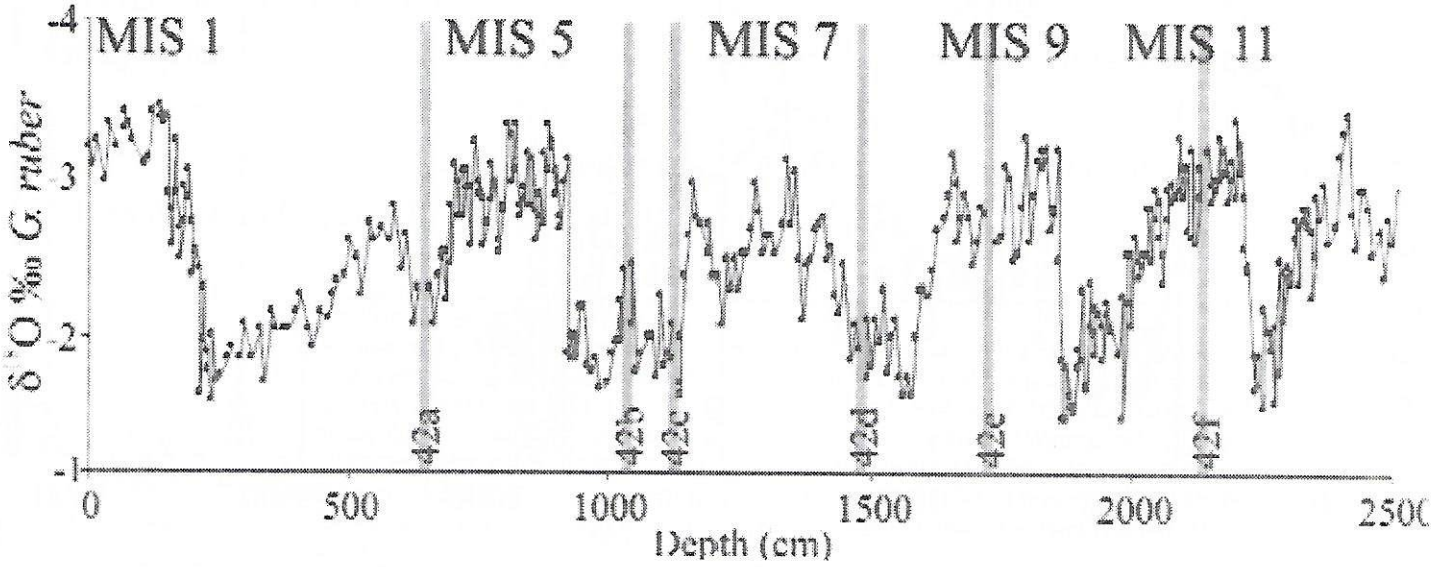


Fig. 2

Studied ash layers and stable oxygen isotope stratigraphy for core MD972142 (12°41.133'N, 119°27.90'E, 1,557 m water depth) from the South China Sea. Oxygen isotope stratigraphy based upon analysis of Globigerinoides ruber. MIS= Marine Isotope Stage.

The X-ray radiographs were produced according to standard methods (Bouma, 1964; Werner, 1967). Plastic boxes 8x4x1 cm (MD972142) and 15x8x1 cm (MD012388) 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 for exposure. The machine used was an ANDREX BW434 with 40 kV, 9.5 mA and exposure time 4 minutes and 30 seconds. The developed radiographs were studied directly against a light source or through paper positives.

tephra layers and immediately adjacent sediment. Nevertheless, these samples offer some insight into the reworking of discrete marker horizons in a low accumulation slope setting. In the two cases where the lower boundary between tephra and sediment could be observed (42a and 42f) it was found to be relatively sharp (Fig. 4). The upper boundaries, however, vary from rather sharp to gradual transitions. In layer 42a, which is only about 2 cm thick, little upwards dispersion of the tephra material can be observed although the sediment above is intensely bioturbated. In layers 42b, 42d,

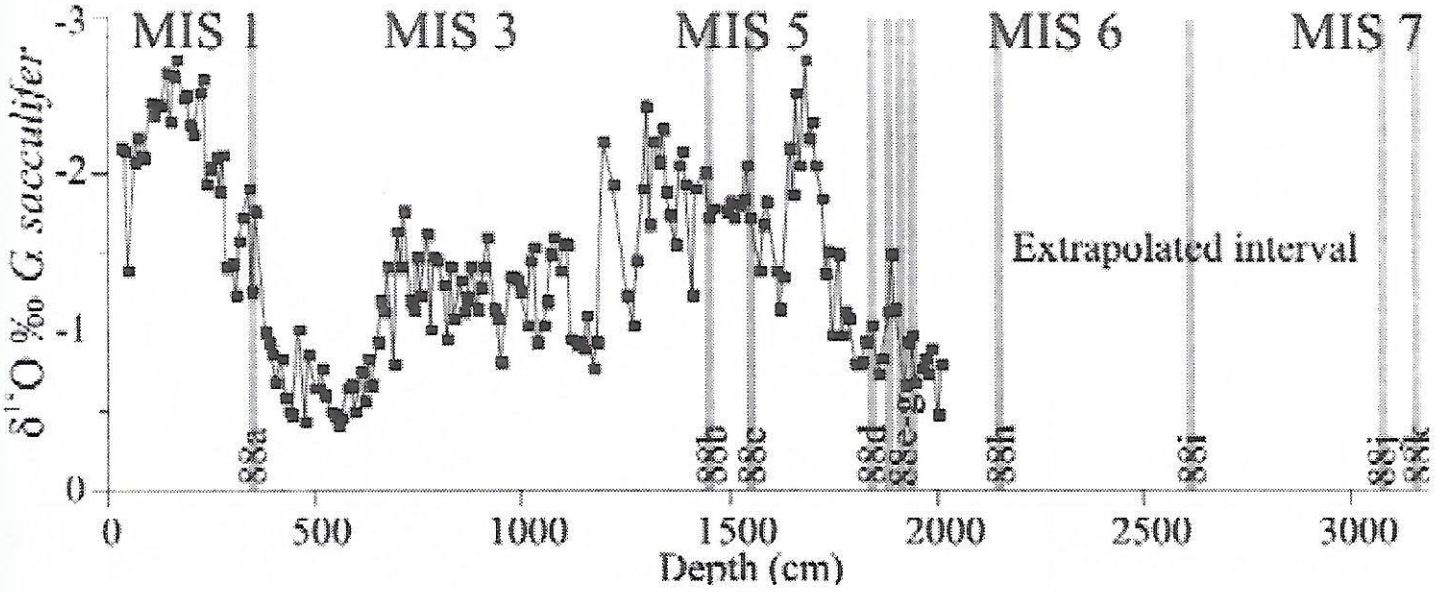


Fig. 3

Studied ash layers and stable oxygen isotope stratigraphy for core MD012388 (6°43,52'N, 122°55,91'E, 3340 m) from the Celebes Sea. Oxygen isotope stratigraphy based upon analysis of Globigerinoides sacculifer. Age model in the lower part is based on the average sedimentation rate in the upper part of the core. MIS= Marine Isotope Stage.

Results and discussion

Core MD972142 consists of homogeneous, completely bioturbated olive gray hemipelagic sediments with numerous discrete tephra layers. The 36m long core comprises ca. 860 ka, resulting in an average sedimentation rate of about 4 cm ka^{-1} (Wei et al., 2003). Because of the limited core material available, the X-ray radiographs from this core only allow observations to be made on the

and 42e, the upper boundary of the tephra is close to the top of the X-ray radiographs, limiting the observations on the upwards dispersion of ash material, but in 42c and 42f, a gradual transition over a few cm between tephra and overlying sediment can be clearly observed (Fig. 4). In contrast to this relatively minor remixing of tephra material upwards into the sediment column resulting from homogeneous mixing, the

redistribution resulting from discrete, single burrows penetrating into the ash layers is significant. In layer 42b, 42c, and 42e, 1-2cm thick burrows filled with hemipelagic sediment pierce the ash layers, and in 42f the right hand side of the layer seems truncated by a burrow. On top of layer 42d, a *Scolicia* like burrow plow through the top of the ash layer. These discrete burrows actually may constitute up to more than 50% of the material in a given cross section.

The 3402-cm-long core MD012388 consists of olive green to gray nanno fossil oozes and numerous ash layers. Average sedimentation rate based on the upper 20 m of the core is about 15 cm ka^{-1}. The X-ray radiographs reveal that the tephra layers of core MD012388 are much stronger bioturbated than in core MD972142. Several layers have been so severely reworked that neither upper nor lower boundaries can be clearly recognized. In some cases the mixing has been so thorough that only fragments of the tephra layer can be observed in a cloud of ash particles. The thin white streaks and lines seen in the X-ray radiographs are pyritized *Trichichnus*-burrows (Table 1). *Trichichnus* are often very frequent in deep-sea cores but represent very little sediment transport due to their minute diameters. A common feature is 1-2 cm thick *Thalassinoides*-like burrows (Table 1) piping either hemipelagic sediment into the tephra layers or ash material into the surrounding sediment. Today, similar burrows are made by different types of suspension feeding crustaceans, which pump water through their burrow system. These burrows may be inhabited by several individuals living

TABLE

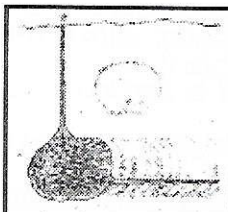
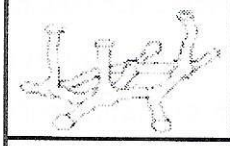
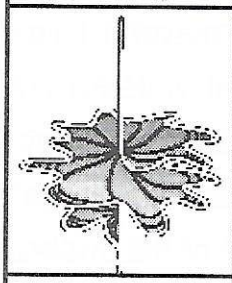
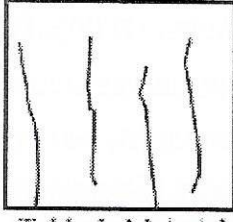
 After Bromley (1996)	***Scolicia* De Quatrefages 1849** *Scolicia* is a 2-5 cm thick, unbranched, and mostly horizontal burrow characterized by a thick meniscate backfill in longitudinal view and oval outline often with a pair of ridges at the base in transverse view (Wetzel, 1991; Fu and Werner, 2000). *Scolicia* occupies the tier directly below the mixed layer at a sediment depth seldom exceeding 10 cm (Wetzel, 1981; Bromley, 1996). Irregular echinoids have been found to be the producers of modern Scolicia (e.g. Reineck, 1968; Bromley and Asgaard, 1975). The producers show a pronounced preference for well-sorted coarse silts to fine sands and rather high sedimentation rates (Wetzel, 1991; Fu and Werner, 2000).
	***Thalassinoides* Ehrenberg 1944** Regularly branching cylindrical burrows forming horizontal networks connected to the surface through ventilation shafts. Diameter of the trace may vary between less than 1cm up to more than 20 cm. Presumably dwelling burrows of filter feeding crustaceans (Hantzschel, 1975; Bromley, 1996).
	***Zoophycos* Massalongo 1855** Consists of a 1-20 mm thick spreite that is helically coiled around a central axis. A marginal tube borders the spreite and the whole trace is connected to the sediment surface through a vertical shaft. In most cases, the spreiten are more or less horizontal and the outline may vary from semi-circular to highly lobate. The modern *Zoophycos* may reach a vertical extension of more than one meter and probably represents a combination of surface detritus-feeding and cache-behavior, where food is collected during episodic food flux events and is stored away for later use deep in the sediment (Löwemark and Schäfer, 2003).
	***Trichichnus* Frey 1970** *Trichichnus* typically are vertically oriented cylindrical, thread-like, and sometimes branched burrows, up to several tens of cm in length and with diameters normally less than 1 mm (Häntzschel, 1975). In modern marine sediments generally pyritized below a sediment depth of 10-20 cm, and are therefore particularly well discernible in radiographs. *Trichichnus* does not contribute significantly to sediment transport due to its minute tube thickness but is a conspicuous and abundant trace especially in MD012388

Table 1. Main ichnogenera in the studied cores.

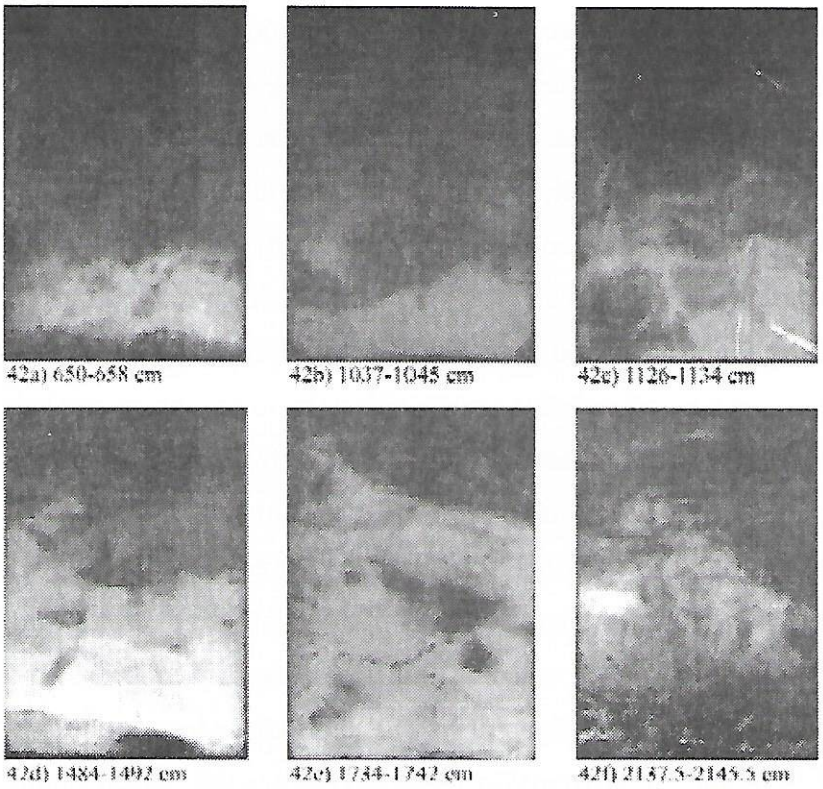


Fig. 4

X-ray radiographs showing tephra layers 42a to 42f from core MD972142. 42a) Some ash is dispersed upwards but the layer is essentially intact. 42b) Thalassinoides-like burrows introduce hemipelagic mud into the ash layer. 42c) Upper part of tephra layer gradually mixed into above material. Thalassinoides-like burrow filled with darker material. 42d) Upper boundary cut by Scolicia in transverse view; some small Thalassinoides-like traces. 42e) Sharp upper boundary and some Thalassinoides-like burrows in the ash layer. 42f) Large Thalassinoides above ash layer; left side cut by burrow.

communally in a continuous burrow system (Bromley, 1996). In the intertidal zone, *Thalassinoides*-like burrows constructed by callianasid crustaceans can reach down several meters into the sediment. In contrast, *Thalassinoides* burrows in the deep-sea normally reach some tens of centimeters into the sediment (Wetzel, 1991). Excavation of this type of burrow leads to the upwards-directed transport of sediment over significant distances. The burrow system may then be actively or passively filled with material from higher stratigraphic levels. This type of burrows filled with foraminifer-rich sediment is sometimes erroneously referred to as "foraminifer nests". Especially in intervals otherwise depleted in foraminifer abundance, they may represent a tempting but precarious source of sample material (T. Hanebuth, pers. comm.). In tephra layers 42b, 42e (Fig 4), and 88b (Fig. 5), *Thalassinoides*-like burrows pipe hemipelagic sediment, presumably from a higher level, into the tephra. A transport of ash material out of the tephra and into the adjacent sediment is best demonstrated by the traces in association with layers 88c and 88i (Fig. 6), where several discrete, oval to semi-circular burrows filled with lighter tephra material can be observed.

Another trace that is also relatively abundant in association with several of the ash layers is *Scolicia* (Table 1). The typical meniscate backfill lamellae of *Scolicia* are clearly visible in layer 88c (Fig. 5) where the lower boundary is partially obliterated by a *Scolicia* trace seen in longitudinal view. The lamellae are formed when sediment particles are moved around the sea urchin's body by the spines as the animal moves through the sediment (Bromley, 1996). This manipulation results in a gravitational separation of the grains in the matrix, the heavier grains accumulating in the lower half of the meniscae, behind the animal (Fu and Werner, 2000). The accumulation of coarse, heavy grains is especially clearly visible in the sediment surrounding ash layer 88h (Fig. 6). Here the sediment is completely dominated by *Scolicia* traces in transverse view.

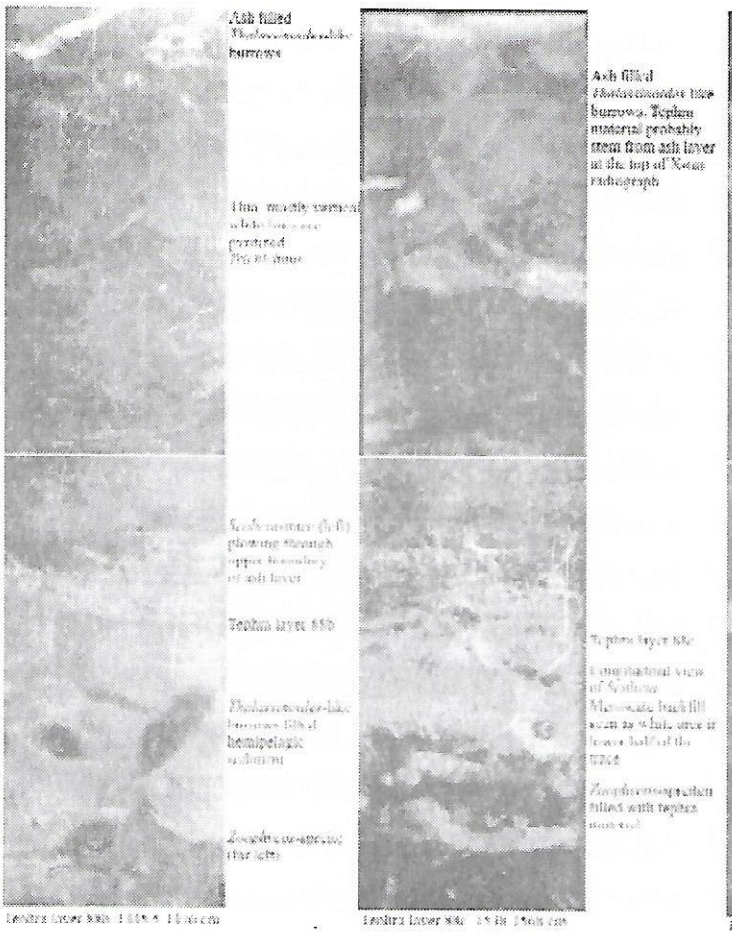


Fig. 5

X-ray radiographs showing tephra layers 88b (left) and 88c (right) from core MD012388.

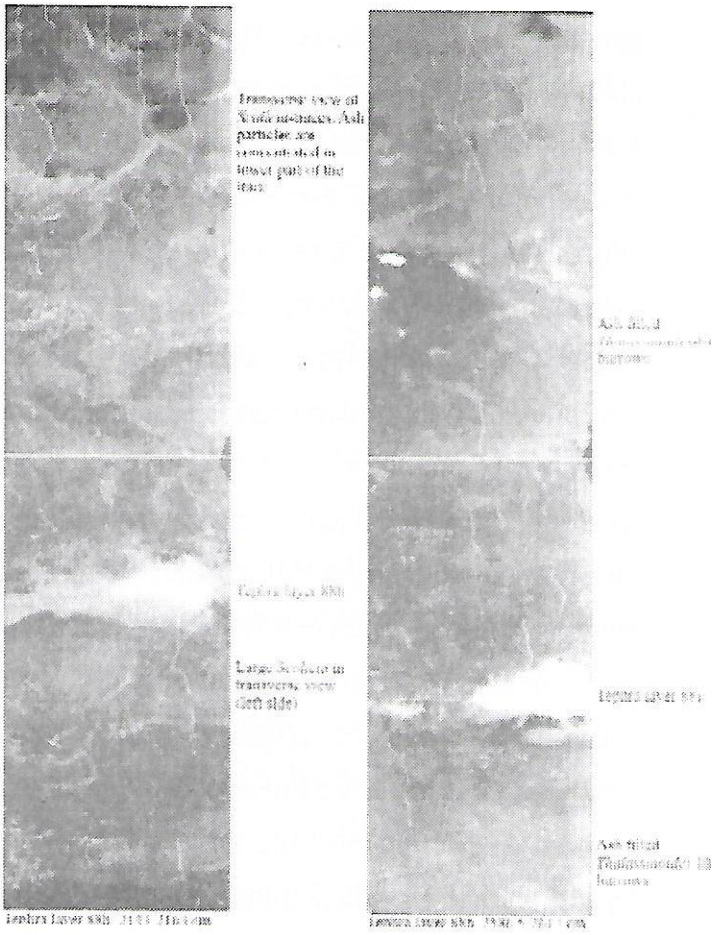


Fig. 6

X-ray radiographs showing tephra layers 88h (left) and 88i (right) from core MD012388.

Coarse ash particles are concentrated in the lower part of the trace and the upper parts are typically destroyed by later *Scolicia*. The ash particles likely originate from the remains of a now completely obliterated ash layer rather than from the underlying ash layer 88h (Fig. 6). At the top of ash layers 42d (Fig. 4) and 88b (Fig. 5), the typical grooves of large *Scolicia* can be seen cutting ca. 1-cm deep trenches into the tephra layers. Fossil *Scolicia* are often preserved in a similar way at the interface between muddy and silty/sandy sediment (Uchman, 1998). The producers of the *Scolicia*-trace in late Quaternary marine sediment have been found to show a pronounced preference for well sorted coarse silts to fine sands and rather high sedimentation rates (Wetzel, 1991; Fu and Werner, 2000). This may explain the increased occurrence of *Scolicia* in association with tephra layers, as they represent a considerable input of coarser material in an otherwise relatively muddy environment. Due to its shallow burrowing depth, the preservation of *Scolicia* strongly depends on the amount of deep-reaching bioturbation. Thus, where *Scolicia* is still present it can be taken to indicate that little deep-reaching bioturbation has affected the sediment. In contrast, where deep-reaching burrows have destroyed *Scolicia*, caution is advisable since these burrows may have introduced foreign material.

In several cases *Zoophycos*-spreiten (Table 1) containing ash particles were observed, (Fig. 5). Just at the base of ash layer 88b, a spreite composed of light (ash) and dark (host sediment)

lamellae can be observed. The darker lamellae containing hemipelagic sediment probably stem from the sediment above the ash layer. Ash particles in *Zoophycos* spreiten were first described from Upper Pliocene turbidite sequences in Japan (Kotake, 1989). The ash particles stemmed from higher stratigraphic levels and Kotake (1989) interpreted the introduced surface material to be the result of a surface detritus feeding behavior where the feces are excreted as spreiten deep in the sediment. Radiocarbon studies on the spreiten material in Late Pleistocene-Holocene *Zoophycos* from the North Atlantic (Löwemark and Werner, 2001) and the Arabian Sea (Leuschner et al., 2002) clearly show a massive introduction of surface material deep (>50 cm) into the sediment. This type of trace is especially treacherous because of its sheet like shape and deep penetration. However, the *Zoophycos*-spreiten visible below ash layer 88c contain ash that presumably originated from the tephra layer directly above, indicating that vertical transport is not always that long.

Using ash particles as a tracer to study bioturbation has some inherent weaknesses. Ash particles do not represent a food source and may therefore be selectively avoided by deposit feeders. The observed patterns of redistribution may therefore not be identical to the bioturbation of hemipelagic muds. Another problem is related to the difference in transport of different grain sizes. Artificial tracers such as luminophores illustrate that some organism, e.g. bivalves, show large differences in the transport of different grain sizes, whereas others, e.g. polychaetes, display only little selectiveness between the grain sizes (Mahaut and Graf, 1987). Only the larger grains have enough contrast to be observed separately in the X-ray radiographs. This means that grain sizes smaller than fine sand may display a partially different pattern of reworking, however, the grain sizes usually used for foraminiferal studies fall within the observable spectrum of the X-ray radiographs. Furthermore, the ash fall itself may affect the type of bioturbation dominating the fabric. First, as suggested by the association of *Scolicia*-traces with ash layers, the change in substrate may promote a change in the type of burrows due to change in substrate consistency or food content. Second, ash falls may cause destruction of the benthic fauna if the ash layer is too thick, and the opportunistic recolonization fauna responsible for the bioturbation of the upper boundary of the ash layer may not necessarily reflect normal conditions. In a study of modern *Nereites*-burrows in the South China Sea, Wetzel (2002) noted that where the 1991 Pinatubo ash fall exceeded 3 cm in thickness, no continued burrowing activity was observed. Although, studies on the recolonization of the benthic realm after an ash fall in the eastern Mediterranean Sea indicated a rapid repopulation with only minor effect on the benthic community structure (Cita and Podenzani, 1980). Thus, the thickness of the ash layer plays an important role in controlling the type of traces that are preserved in the historical layer. Where the ash layer is thick enough to prevent homogenizing bioturbation, the importance of deep-reaching discrete burrows might become overestimated compared to normal hemipelagic sediment.

Despite these shortcomings, X-ray radiograph observations made on the distribution of ash particles in gravity cores have the advantage of showing the final result of bioturbation on the sediment. While most modern tracer studies do

show a near perfect homogenization in the mixed layer, the X-ray radiographs show a palimpsest picture where generations of burrows have been superimposed on the sediment package as it passes through the different tiers of bioturbation. The differing ecological preferences of the endobenthos inhabiting the sediment lead to a vertical zonation of the traces, the so-called tiering (Reineck et al., 1967; Levinton and Bambach, 1975; Wetzel, 1981; Savrda and Bottjer, 1986). Typically, traces of oxygen dependent organisms such as *Scolicia* and *Planolites* are found in a tier directly below the mixed layer, whereas the middle tier is dominated by *Thalassinoides,* and the lowest tier, directly above the historical layer, is dominated by low-oxygen tolerant ichnospecies such as *Zoophycos* and *Chondrites* (Wetzel, 1981; Savrda and Bottjer, 1991). The vertical extent of the tiering influences the impact of bioturbation on high-resolution stratigraphy, the larger vertical extent, the larger the stratigraphic error. Enhanced sedimentation rates, food flux and bottom water oxygenation levels all lead to an increase in mixed layer and tiering depth (Wetzel, 1991; Tyson, 1995; Trauth et al., 1997). Thus, the enhanced resolution gained in high-sedimentation rate settings is partially offset by increased burrowing depth. However, strongly increased food flux may actually lead to a diminished extent of the vertical mixing. On the African margin, Wetzel (1981) found indistinct bioturbation to correspond to high nutrient content in the sediment. He interpreted this to be a behavioral response to surplus nutrients in the sediment, making specialized burrowing strategies superfluous, and consequently little vertical transport of the sediment.

Conclusions

The X-ray radiograph observations clearly show the importance of deep-reaching, discrete traces such as *Thalassinoides* and *Zoophycos* on the vertical transport of sediment, especially for coarser grain sizes. As demonstrated by ash material transported out of the tephra layers and into the hemipelagic mud, as well as by hemipelagic mud piped into the ash layers, distance and amount of sediment can reach considerable dimensions. The X-ray radiographs also reveal an often-dense occurrence of these traces. The material in these burrows can cause serious errors to high-resolution studies and AMS-^{14}C dating if inadvertently sampled.

Observations on the type of bioturbation can furthermore be used to estimate the intensity of vertical mixing. Where a well developed tiering sequence is present, or where traces such as *Thalassinoides* and *Zoophycos* dominate, extreme caution is recommended before sampling. In contrast, deposit feeders and shallow tier traces such as *Scolicia* or *Planolites* generate little vertical transport of the sediment, rendering the homogeneously-mixed-layer model a legitimate approximation of the influence of bioturbation on high-resolution records. It is therefore recommended that X-ray radiographs should routinely be made before sub-sampling the cores, especially before AMS-^{14}C dating.

Acknowledgments

We thank Chao-Kai Huang (NTU, Taiwan) for making the X-ray radiographs and paper positives. Financial support from NSC and the Taiwanese APEC-program is thankfully acknowledged.

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