GEOLOGICA CARPATHICA, OCTOBER 2008, 59, 5, 395–409

New methods for ichnofabric analysis and correlation with orbital cycles exemplified by the Baden-Sooss section (Middle Miocene, Vienna Basin)

PETER PERVESLER[1], ALFRED UCHMAN[2] and JOHANN HOHENEGGER[1]

[1]Department of Paleontology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria;
peter.pervesler@univie.ac.at; johann.hohenegger@univie.ac.at
[2]Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, 30-063 Kraków, Poland; alfred.uchman@uj.edu.pl

(Manuscript received December 13, 2007; accepted in revised form June 12, 2008)

Abstract: A two step cluster analysis based on log-likelihood measures for categorial variables using 'Schwarz's Bayesian Criterion' for grouping allows the automatic detection of ichnofabric categories from a large data set. Preferred successions of these ichnofabrics were tested by 'Embedded Markov Chains'. This leads to the following ichnofacies interpretation: Alternating periods of higher/lower accumulation rates with higher/lower inputs of particulate food and higher/lower oxygen contents in pore waters led to sequential colonization of the substrate. The trace fossils *Phycosiphon* and *Nereites* represent opportunistic colonization of oxygenated sediments rich in particulate organic matter (POM) by deposit-feeding animals, quickly after an increased sediment input. A further stage of colonization caused by the decrease of POM induced by consumption and oxidation forced the animals to search for food on sediment surfaces and from the water column. The open burrows *Thalassinoides*, *Chondrites*, *Trichichnus* and *Zoophycos* indicate stable-bottom conditions in periods of low accumulation rates. *Zoophycos*, *Phycosiphon*, *Nereites* and *Teichichnus* suggest the *Zoophycos* ichnofacies for the lower section of the core; a transition to the distal part of the *Cruziana* ichnofacies is suggested for the upper section of the core with the appearance of *Thalassinoides.* The changes between stable and unstable bottom conditions significantly correlate with periods in magnetic susceptibility and calcium carbonate content, both forced by orbital cycles.

Key words: Miocene, Badenian, Vienna Basin, statistical analysis, orbital cycles, trace fossils, ichnofabrics.

Introduction

Trace fossil and ichnofabric analysis is a powerful tool in the recognition of ecological parameters such as energy level, oxygen content, food supply, salinity or stability of the environment. Several ichnological researches refer to the Badenian of the Central Paratethys (e.g. Abel 1928; Kühnelt 1931; Kleemann 1982; Hohenegger & Pervesler 1985; Pervesler & Uchman 2004; Pervesler & Zuschin 2004), but almost all of them concern littoral sandy sediments or rocky shores.

By drilling close to the Badenian stratotype (Middle Miocene) near the western margin of the southern Vienna Basin, a continuous 102 m section of mostly fine-grained sublittoral Badenian deposits was obtained. Biostratigraphy, paleoecology, sedimentology, geochemistry, magnetostratigraphy and magnetic climate proxies such as magnetic susceptibility (Khatun et al. 2006; Hohenegger et al. 2008) of the core were studied in FWF-Project P13743 — BIO. The main aim of this paper is to present the results of the ichnological analysis.

Geological setting

The drill site is situated near the western margin of the southern Vienna Basin (Fig. 1). The basin formed during the Neogene lateral extrusion within the Eastern Alps (Ratschbacher et al. 1991), is situated at the junction of the Eastern Alps and the Western Carpathians (e.g. Decker 1996; Hamilton et al. 2000). The scientific borehole at Baden-Sooss penetrated a succession of Badenian (Langhian, Middle Miocene) deposits, below the type section of the Badenian stage, the old Baden-Sooss brickyard near Baden (Papp et al. 1978). The "Badener Tegel" is placed into the Baden Group which is subdivided into the Jakubov Formation and the Lanžhot Formation (e.g. Kováč et al. 2004). The part of the Badenian within the Baden-Sooss borehole can be correlated to the Lanžhot Formation.

Material and methods

Preparation and documentation

After the core was split longitudinally and the cross-section was smoothed, it was scanned and photographed digitally. The image series was used for ichnological analyses. Trace fossils were detected from 8 to 102 meters of the core depth. Additional cuts were made parallel to bedding. The contrast obtained by moistening the core sections was further improved by graphic software elaboration of the images.

Statistical methods

The core was divided into 25 cm intervals and ichnofossils were determined for each interval as present/absent, resulting

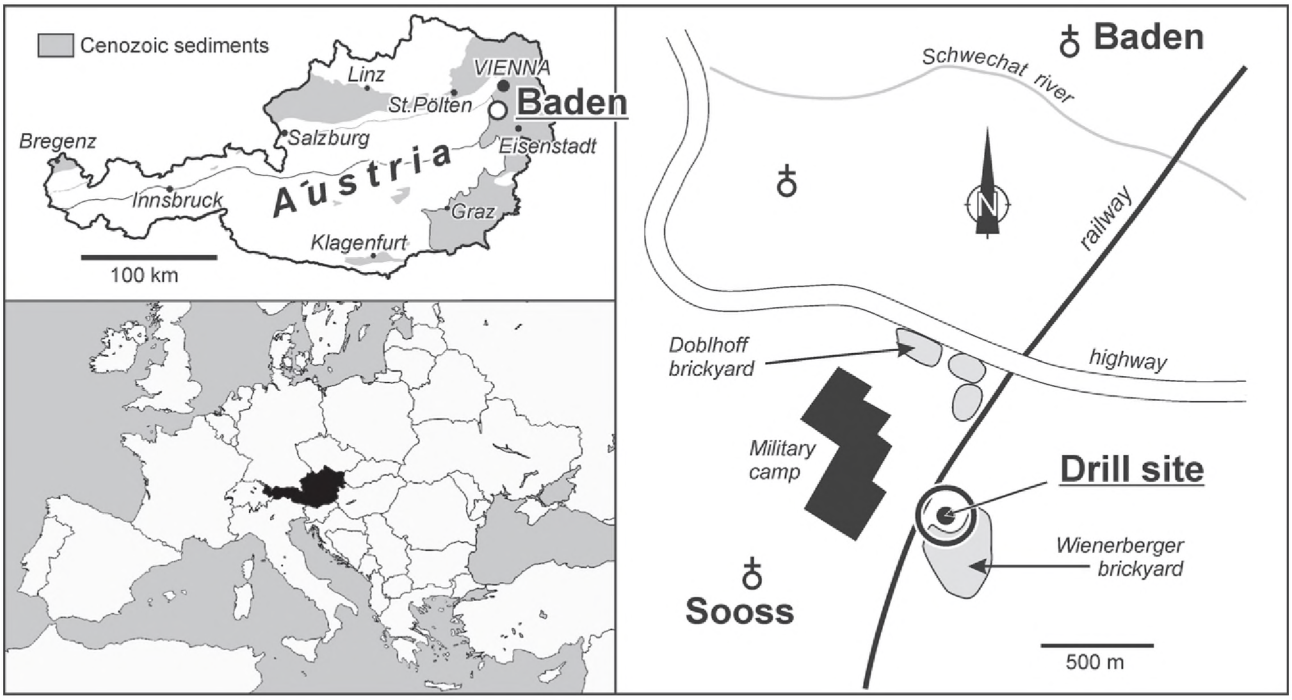

Fig. 1. Location map.

in a data matrix of 376 samples by 12 ichnospecies. Lamination was included as a further qualitative character. Samples were clustered using the 'Two Step Cluster Analysis' designed to handle very large data sets (SPSS 2006; Zhang et al. 1996). Log-likelihood measures appropriate to categorical variables functioned as distances between samples. 'Schwarz's Bayesian Criterion' was used for cluster finding with an automatic determination of cluster numbers (SPSS 2006).

Preferred successions of clusters were tested by 'Embedded Markov Chains' (Davis 2002), thus excluding self-transformations. General tendencies in ichnofabric composition along the core were shown in percentages of ichnofabric types calculated over an interval of 3 meters with intervals moving in 25 cm steps ('moving percentages').

Finally, correlations of each ichnospecies with quantitative environmental data were tested using the 'Point-Biserial Correlation' (Gibbons 1976). Statistical analyses were performed with EXCEL (for Markov Chains) and the program packages SPSS 15.0 and PC-ORD (McCune & Mefford 1999) for complex analyses.

Systematic ichnology

Except for several layers with primary lamination, the core is completely bioturbated.

Trace fossils of the ichnogenera *Asterosoma*, *Chondrites*, *Nereites*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon*, *Scolicia*, *Siphonichnus*, *Teichichnus*, *Thalassinoides*, *Trichichnus* and *Zoophycos* were distinguished in cross-sections and occasionally on surfaces parallel to bedding. Their distribution in the core is shown in Fig. 2.

Asterosoma von Otto, 1854
Asterosoma isp.
Fig. 3D

Description: In cross-section, clusters of variably oriented ovals, with faint concentric lamination around a central lumen. The ovals are 7–18 mm wide and 15–45 mm long. Locally, the lumen is oval, 5 mm in diameter, and in some cases filled with slightly coarser and darker sediment than in surrounding laminae. In many cases the centre is poorly outlined and seen as a dark dot.

Remarks: The ovals are cross-sections of vertical to inclined elongated bulbs tapering at both ends, with concentric internal lamination. Clusters of such bulbs form tree-like structures spread out from a common vertical or inclined shaft. The morphology of such cross-sections is typical of *Asterosoma* (e.g. Bromley & Uchman 2003; Pervesler & Uchman 2004). *Asterosoma* is interpreted as a selective-feeding burrow of a worm (Pemberton et al. 2001). It occurs in soft (mostly siliciclastic, rarely carbonate) substrates (e.g. Gibert 1996), typically in various shallow-marine settings, especially in the upper lower shoreface (Pemberton et al. 2001).

Chondrites von Sternberg, 1833
Chondrites isp.
Fig. 3A

Description: In cross-section, clusters of straight, locally branched, light bars and dots, 1.5–2 mm wide.

Remarks: The described cross-section morphology is typical of *Chondrites* (compare e.g. Werner & Wetzel 1981; Ekdale & Bromley 1991; Wetzel & Uchman 1998), which in three dimensions is a branched tunnel system ramifying at

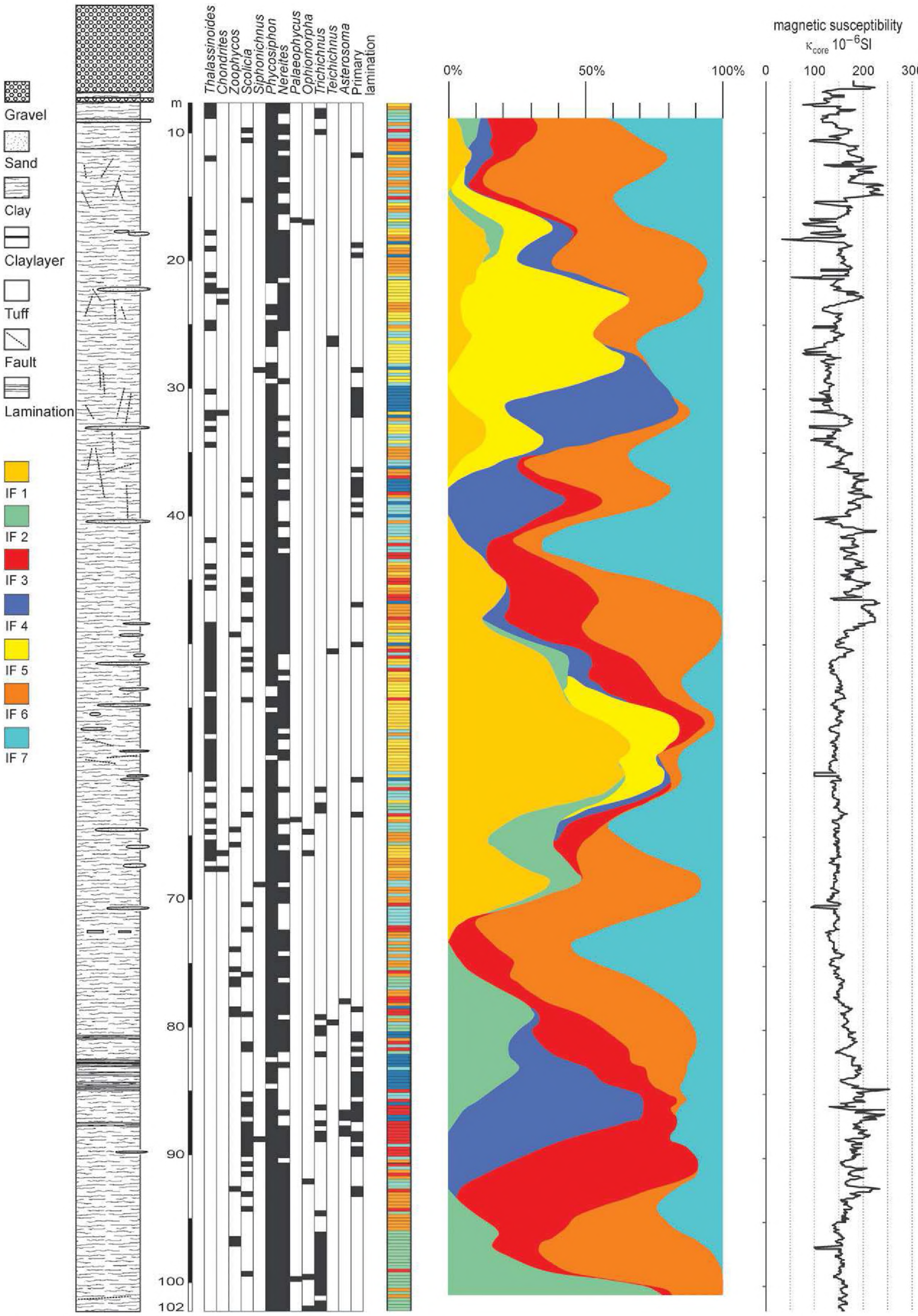

Fig. 2. Section of the core, distribution of ichnotaxa and ichnofabrics.

depth from a master shaft in a dendritic manner. *Chondrites* is interpreted as a chemosymbiotic feeding structure (Fu 1991; Uchman 1999, and references therein).

Nereites MacLeay, 1839
Nereites isp.
Fig. 3C, E–H

Description: Horizontal to subhorizontal, rarely oblique, winding subcylindrical structures seen rarely on surfaces of parted rocks parallel to the bedding as winding or loosely meandering dark ribbons bounded by lighter side zones. The ribbon is 3.5–4.0 mm wide and the bounding zone is 1.0–1.5 mm wide. Locally, the ribbon displays scalariform menisci. Much more commonly this trace fossil is seen in cross-section, where it appears as clusters of elongated dark, oval spots surrounded by a lighter halo (Fig. 3C,E,F,G). Some of the dark spots are asymmetric and pointed from one side. They are 1.2–2.0 mm high and mostly 3–10 mm wide. Some of them are more elongated as bars up to 30 mm long, with local meniscate structure. The lighter halo is 1.0–2.5 mm wide. The clusters are commonly as much as 60 mm wide and as much as 40 mm high.

Remarks: The ribbons, visible in cross-section as dark spots, are faecal strings having locally meniscate filling. The bounded lighter zones seen in cross-section as the light halo represents a reworking zone around the faecal string. These features are typical of *Nereites*, which is interpreted as a pascichnion made just above the redox boundary (Wetzel 2002). For discussion of this ichnogenus see Chamberlain (1971), Benton (1982), Uchman (1995, 1999) and Mángano et al. (2002). The described trace fossil, by its relatively narrow reworking zone and local scalariform menisci, resembles *Nereites missouriensis* (Weller 1899) (see also Conkin & Conkin 1968).

Ophiomorpha Lundgren, 1891
Ophiomorpha isp.

Description: Vertical or oblique, curved tubes, whose lumen diameter ranges from 5 to 10 mm, and whose wall thickness ranges from 3 to 6 mm. The lumen diameter and thickness of the wall are more or less constant in each specimen. The wall is built of a material that is slightly lighter than the host rock. The outer margin of the wall is poorly expressed or slightly lobate in cross-section.

Remarks: Size, orientation and thick wall suggest that this trace fossil belongs to *Ophiomorpha*. The lobate outer margin of the wall corresponds to the knobby wall exterior typical of this ichnogenus. *Ophiomorpha nodosa* is one of the most common shallow-marine trace fossils and is produced mostly by thalassinoid shrimps (Frey et al. 1978; Ekdale 1992). It is most typical of the *Skolithos* ichnofacies (Frey & Seilacher 1980; Pemberton et al. 2001), but also occurs in deeper shelf tempestites (Frey 1990; Frey & Goldring 1992).

Palaeophycus Hall, 1847
Palaeophycus tubularis Hall, 1847

Description: Horizontal to oblique simple tubes, 3–5 mm in diameter, with a thin, light wall.

Remarks: *Palaeophycus tubularis* is a facies-crossing form produced by carnivorous or omnivorous animals, mostly polychaetes (Pemberton & Frey 1982). For discussion of *Palaeophycus* see also Keighley & Pickerill (1995).

Phycosiphon Fischer-Ooster, 1858
Phycosiphon incertum Fischer-Ooster, 1858
Fig. 3A,C,E–H

Description: In cross-section, clusters of curved dark bars and spots surrounded by lighter halo. The dark spots and bars are up to 1mm thick and the bars are up to 6 mm long. Most of the bars and spots are parallel or sub-parallel to the bedding. The clusters are commonly as much as 35 mm wide and as much as 25 mm high. This trace fossil commonly occurs in the filling of larger burrows.

Remarks: The described structures are typical of poorly expressed *Phycosiphon incertum* Fischer-Ooster (Wetzel & Bromley 1994). It is seen on bedding planes as horizontal, curved small repeated lobes encircled by thin marginal tunnels. *Phycosiphon incertum* is a feeding structure (fodinichnion) (e.g. Ekdale & Mason 1988).

Scolicia de Quatrefages, 1849
Scolicia isp.
Fig. 3C

Description: Horizontal subcylindrical structures with a complex meniscate backfill. In cross-section, they are seen as oval structures with slightly concave top and concave bottom. The bottom concavity is bounded by two oval protrusions, which are about 5 mm in diameter. The structures are 20–35 mm high and 35–75 mm wide. In some cross-sections, the structures are dissected obliquely or along their course and in such cases the meniscate backfill is highly visible.

Remarks: The oval protrusions at the bottom are cross-sections of basal strings (see Uchman 1995). *Scolicia* is a fossil locomotion and feeding structure (pascichnion) produced by irregular echinoids (e.g. Bromley & Asgaard 1975; Smith & Crimes 1983).

Siphonichnus Stanistreet, Le Blanc Smith & Cadle, 1980
Siphonichnus isp.

Description: *Siphonichnus* is a steeply oblique structure, in the studied section about 9 mm wide and at least 107 mm long. It displays a thin margin, concave-down menisci and a central, straight vertical shaft crossing the menisci. The shaft 1 mm wide is distinctly darker than the surrounding sediment.

Remarks: *Siphonichnus* is interpreted as a bivalve burrowing structure, where menisci related to the burrowing action are crosscut by the shaft produced by the siphon (Stanistreet et al. 1980).

Teichichnus Seilacher, 1955
Teichichnus isp.
Fig. 3B

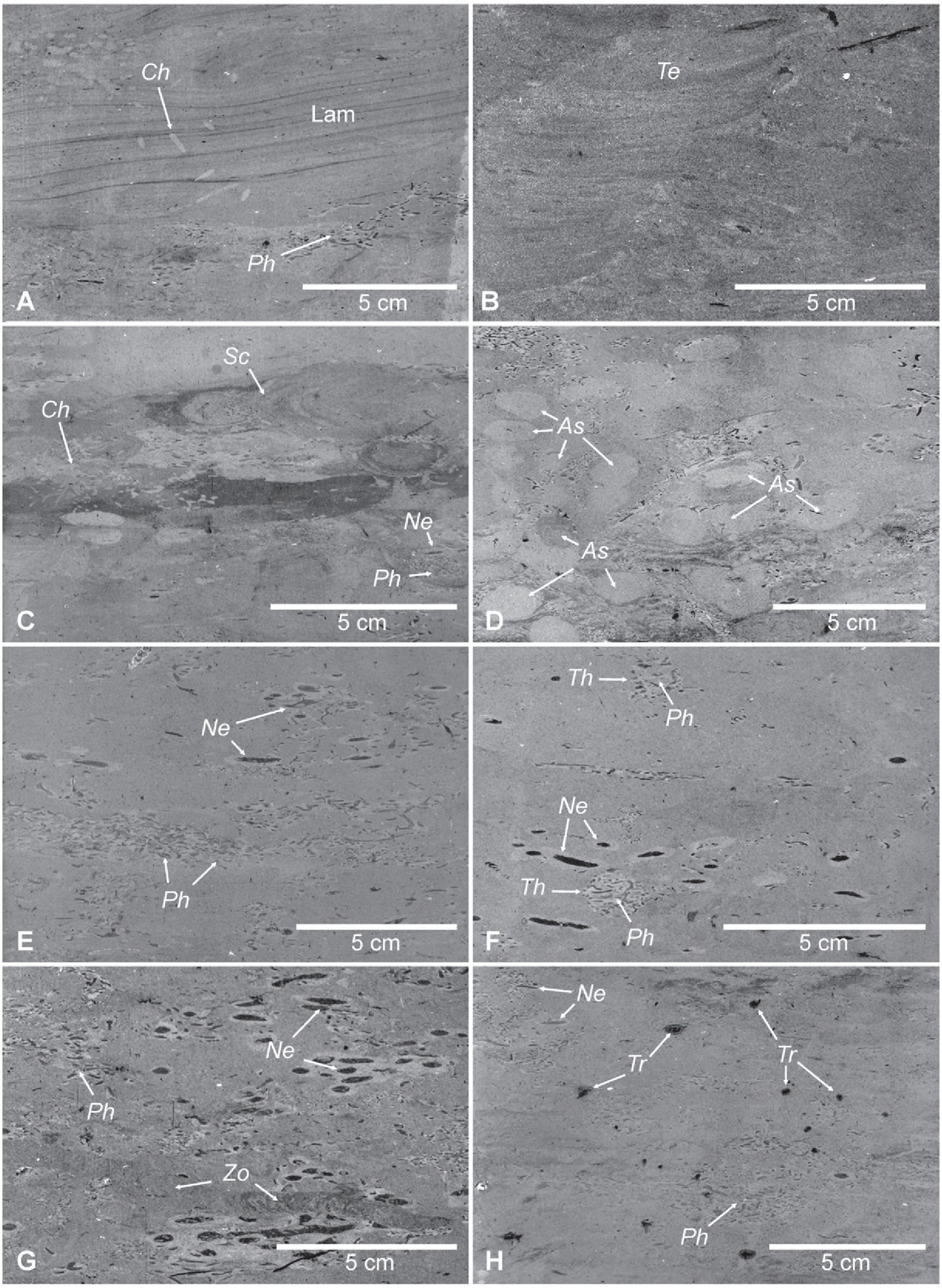

Fig. 3. Trace fossils from the Baden-Sooss core. **A** — Ichnofabric 4 with *Phycosiphon* (*Ph*) and primary lamination (Lam) penetrated by *Chondrites* (*Ch*). Meter 87.14–87.24. **B** — Ichnofabric 5_4 with *Teichichnus* (*Te*). Meter 26.43–26.53. **C** — Ichnofabric 3 with *Phycosiphon* (*Ph*), *Nereites* (*Ne*), *Scolicia* (*Sc*) and *Chondrites* (*Ch*). Meter 42.26–42.35. **D** — Ichnofabric 3 with *Asterosoma* (*As*). Meter 86.56–86.67. **E** — Ichnofabric 6 with *Phycosiphon* (*Ph*) and *Nereites* (*N*). Meter 95.47–95.57. **F** — Ichnofabric 1 with *Nereites* (*Ne*) and *Thalassinoides* (*Th*) filled with *Phycosiphon* (*Ph*). Meter 46.20–46.29. **G** — Ichnofabric 2 with *Phycosiphon* (*Ph*), and *Nereites* (*Ne*) cut by *Zoophycos* (*Zo*). Meter 96.44–96.54. **H** — Ichnofabric 2 with *Phycosiphon* (*Ph*), *Nereites* (*Ne*) and *Trichichnus* (*Tr*). Meter 85.83–85.93.

Description: Oblique or vertical, structure without wall consisting of dense, parallel or sub-parallel convex down spreite. The structure is about 100 mm high and about 50 mm wide, however the width can easily be overestimated because this trace fossil is observed in oblique cross-section. Side margins of the structure are uneven. The causative burrow at the top shows concentric lamination (Fig. 3B).

Discussion: *Teichichnus* is a typical feeding structure. For discussion of this ichnogenus see e.g. Fillion & Pickerill (1990) and Schlirf (2000).

Thalassinoides Ehrenberg, 1944
Thalassinoides isp.
Fig. 3F

Description: In cross-section, variably oriented, branching 6–18 mm wide bars and spots. They are filled with sand from the overlying bed and are surrounded by mudstone and siltstone. They represent a system of a boxwork burrow system without wall. Density of the burrows increases in proximity of the overlying sand bed. The lowest part of the system is located 165 mm below the base of the sand bed.

Remarks: *Thalassinoides* is characterized as a system of tunnels and shafts produced by crustaceans, mostly decapods in many marine environments (Fürsich 1973; Frey et al. 1984; Ekdale 1992; Bromley 1996; Schlirf 2000).

Trichichnus Frey, 1970
?*Trichichnus linearis* Frey, 1970
Fig. 3H

Description: Variably oriented, very thin (sub-millimetric), rarely branched cylinders. They are filled with ferruginous material and commonly surrounded by a yellowish halo.

Remarks: *Trichichnus* occurs mostly in fine-grained, shallow-water deposits (e.g. Frey 1970) as well as deep-sea deposits (e.g. Kennedy 1975; Wetzel 1981). A strong tendency to pyritization is typical of this form (e.g. Werner & Wetzel 1981). It is a deep-tier trace fossil produced by opportunistic organisms in poorly oxygenated sediments (McBride & Picard 1991), which may belong to the chemosymbiotic meiobenthos (Uchman 1999).

Zoophycos Massalongo, 1855
Zoophycos isp.
Fig. 3G

Description: Spreite structures seen in core cross-sections as horizontal or oblique, rarely steeply inclined stripes, filled with spreites, 4–9 mm thick, which in cross-section look like densely packed menisci. In oblique cross-sections, the spreite laminae can be seen (Fig. 3G). They contain very small, sub-millimetric pellets. In some specimens the stripes converge in the axial part, where they are strongly wrapped up forming inverted V-structures.

Remarks: *Zoophycos s.l.* is generally regarded as a structure produced by some as-yet undiscovered deposit-feeder, which has been referred to sipunculids (Wetzel & Werner 1981), polychaete annelids, arthropods (Ekdale & Lewis 1991), and echiurans (Kotake 1992). The feeding strategy is, however, controversial (e.g. Bromley 1991; Locklair & Savrda 1998; MacEachern & Burton 2000). Bromley & Hanken (2003) suggested that the upper helical part of a large Pliocene *Zoophycos* from Rhodes, Greece, is a deposit-feeding structure, and lateral lobes developing from its lower part are sulphide wells for chemosymbiotic bacteria. The same interpretation refers to a similar but smaller *Zoophycos* from the Miocene of Austria (Grund Formation), which displays very steep lobes in its lowermost part (Pervesler & Uchman 2004).

Results

'Ichnofabric' types

The cluster analysis of ichnofabrics resulted in seven automatically determined groups, which can be interpreted as 'ichnofabric' types. Six clusters are homogeneous in their composition possessing one or two dominant species, while the seventh cluster (Type 5) is heterogeneous, consisting either of a single species that is not found or underrepresented in the other types, or none.

Type 1

All samples are characterized by the concurrence of *Thalassinoides* (in all samples of the cluster = 100 %) and *Phycosiphon* (in all samples of the cluster = 100 %) with an important proportion of *Nereites* (in 61 % of the samples within the cluster; Table 1).

Type 2

This is the most heterogeneous group, where *Phycosiphon* again is represented in all samples. The major concurrent species are *Trichichnus* (72 %) and *Nereites* (65 %), followed by minor proportions of *Zoophycos* (26 %), *Thalassinoides* (14 %) and *Ophiomorpha* (12 %).

Type 3

This is similar to the former with identical proportions of *Phycosiphon* (100 %) and *Nereites* (65 %). *Trichichnus* is less important (10 %), while its position as the second important species is overtaken by *Scolicia* (92 %). *Trichichnus*, *Asterosoma* (both 10%), *Chondrites* (8 %) and *Thalassinoides* (6 %) are rare; *Zoophycos*, *Siphonichnus* and *Teichichnus* have extremely low proportions (2 % each). The relatively high percentage of lamination within this type (24 %) demonstrates the close relationship to the following ichnofabric type.

Type 4

This is characterized by the predominance of lamination (100 %) in combination with a high proportion of *Phycosiphon* (92 %). *Nereites* (18 %) and *Thalassinoides* (8 %) are of minor importance and a very few *Chondrites*, *Zoophycos*, *Siphonichnus*, *Trichichnus* and *Asterosoma* (all 3 %) can be found.

Type 5

The 5th group is heterogeneous according to the low number or lack of ichnospecies and thus must be divided into several homogeneous sub-types:

Type 5_1: Although bioturbated, no distinct ichnofossil could be identified in this ichnofabric type.

Type 5_2: Only *Nereites* (100 %) is represented in this type.

Type 5_3: *Nereites* (100 %) and *Thalassinoides* (100 %) are the concurrent ichnofossils.

Type 5_4: *Teichichnus* is the single ichnofossil here.

Type 5_5: Only *Thalassinoides* can be found.

Type 6

Nereites (100 %) is combined with *Phycosiphon* (100 %, Table 1).

Type 7

Phycosiphon dominates (100 %), accompanied by very few *Teichichnus* (3 %).

Regarding proportions of ichnofabric types in the core, Type 6 (*Nereites* and *Phycosiphon*) is the most abundant (24.7 %) followed by Type 7 (19.7 %). The remaining types show similar proportions from 10.4 to 13 %, while the insignificant group 5 with different singular or lacking major ichnofossils (8.5 %) is less important (Fig. 4).

Figure 4 demonstrates the importance of ichnofossils to ichnofabric types. While *Phycosiphon* is characteristic for all types (except the heterogeneous group 5), *Nereites* and *Thalassinoides* follow with decreasing proportions (Fig. 4). *Scolicia* is a marker species for Type 3, while *Trichichnus* is abundant in Type 2 and less important for Types 3 and 4. All remaining ichnofossils are of low importance in all ichnofab-

Table 1: Ecological interpretation of ichnofabric types.

Ichnofabric type	Presence of trace fossils and lamination in the measured intervals	Opportunistic colonization (number of ichnotaxa)	Stable colonization (number of ichnotaxa)	Remarks
Type 1	*Thalassinoides* 100 % *Phycosiphon* 100 % *Nereites* 61 %	2	1	opportunistic colonization, followed by stabilization phase
Type 2	*Phycosiphon* 100 % *Trichichnus* 72 % *Nereites* 65 % *Zoophycos* 26 % *Thalassinoides* 14 % *Ophiomorpha* 12 %	3	3	high organic matter content
Type 3	*Phycosiphon* 100 % *Scolicia* 92 % *Nereites* 65 % *Trichichnus* 10 % *Asterosoma* 10 % *Thalassinoides* 6 % *Zoophycos* 2 % *Siphonichnus* 2 % *Teichichnus* 2 % lamination 24 %	3	5	high sediment input
Type 4	*Phycosiphon* 92 % *Nereites* 18 % *Thalassinoides* 8 % *Chondrites* 3 % *Zoophycos* 3 % *Siphonichnus* 3 % *Trichichnus* 3 % *Asterosoma* 3 % lamination 100 %	3	6	less food
Type 5_1	bioturbated 100 %			shallow bioturbation
Type 5_2	*Nereites* 100 %	1		
Type 5_3	*Nereites* 100 % *Thalassinoides* 100 %	1	1	
Type 5_4	*Teichichnus*			lowered salinity?
Type 5_5	*Thalassinoides*			discontinuity surface
Type 6	*Phycosiphon* 100 % *Nereites* 100 %	2		only opportunistic colonization
Type 7	*Phycosiphon* 100 % *Teichichnus* 3 %	1		opportunistic colonization, less food

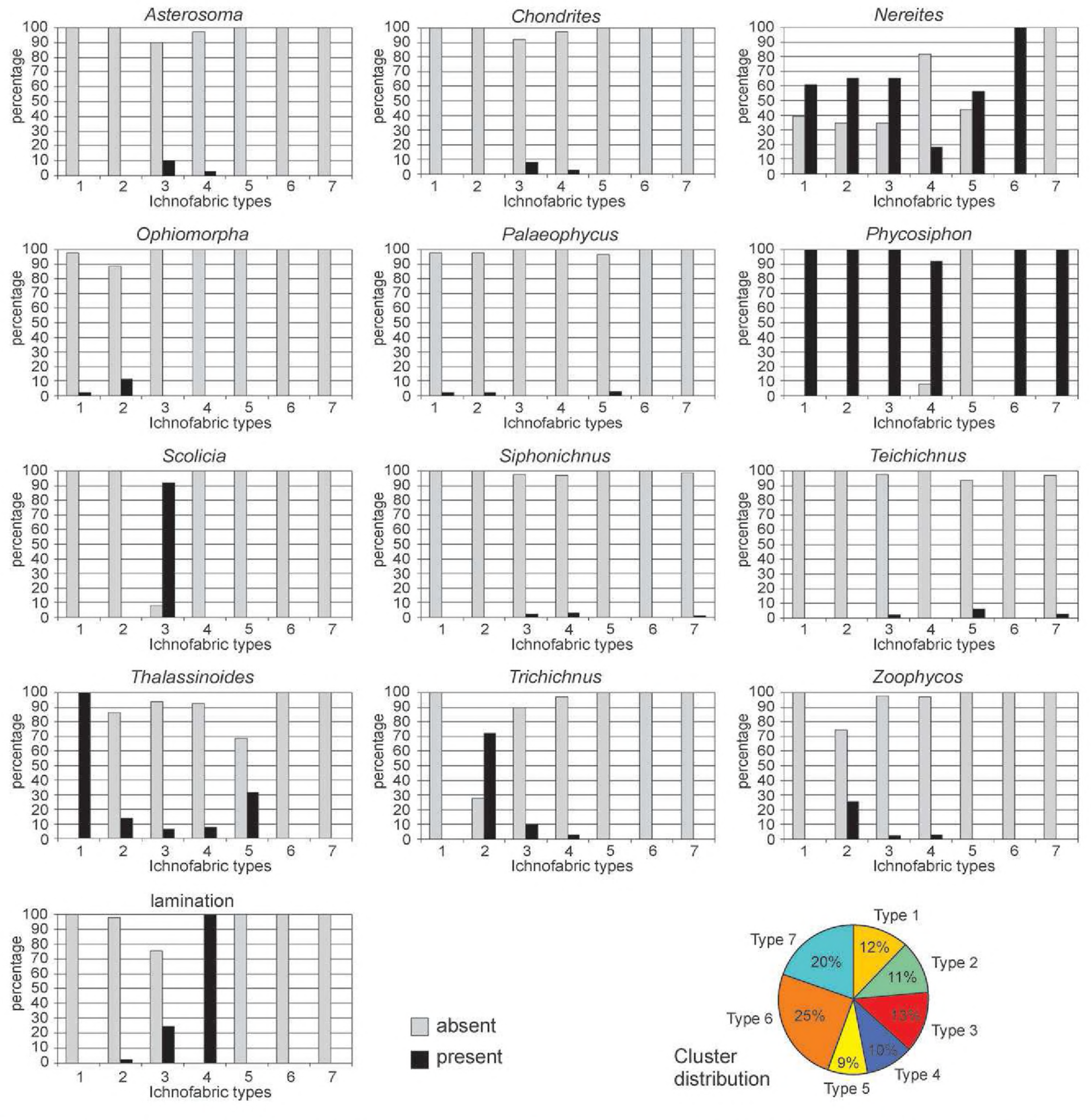

Fig. 4. Percentages of ichnofabric types in the core (pie-diagram) and percentages of ichnogenera in these ichnofabric types (bar-diagram).

ric types. Lamination signalizing lack of bioturbation is characteristic for Type 4, being only of minor importance in Type 3 and rare in Type 2.

Transition between ichnofabric types

Transitions from one into another ichnofabric type could be random, then characteristic for rather stable environments with minor alterations. Otherwise, preferred transitions demonstrate significant reactions to monotonously or periodically changing environments. Proving these transitions by embedded Markov Chains resulted in significant transitions at the 5% error probability level (Table 2). The representation of transitions between ichnofabric types and their intensities are represented as a directed graph (Fig. 5). Within this figure, preferred transition from the heterogeneous Type 2 to the homogeneous Type 6 that combines dominating *Phycosiphon* and *Nereites* is more frequent (46 % of all transitions starting from Type 2) than the reverse transition (only 9 % of transitions starting from Type 6). Similar preferred transitions can be found from Type 4 (with predominant laminations) to Type 7 (23 % of transitions versus 7 % reverse transitions) and in weaker form to Type 3 (31 % of transitions versus 14 % reverse transitions). Similar types of transitions, where the one direction is of a two-fold intensity than the opposite can be found in relations from Type 3 to Type 6 (25 % of tran-

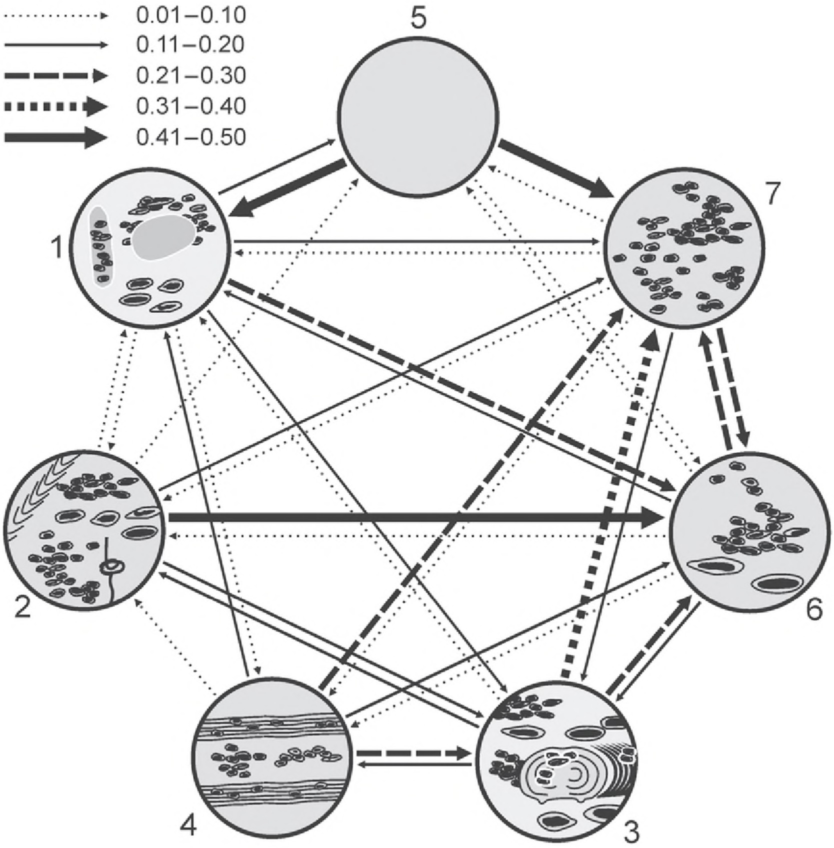

Fig. 5. Transitions between ichnofabric types represented as directed graphs.

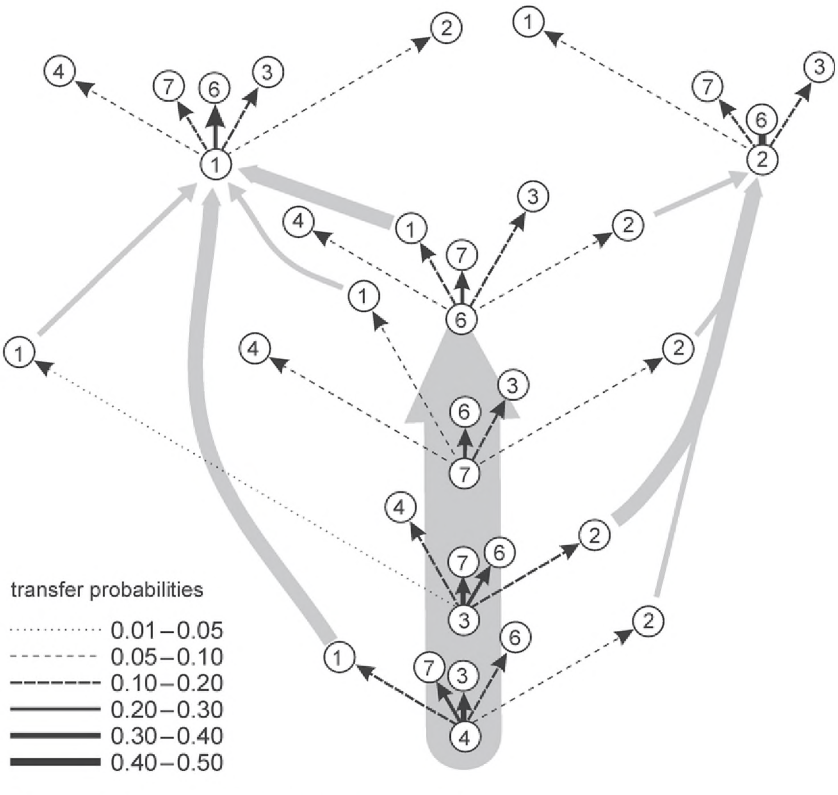

Fig. 6. Transition probabilities between ichnofabric types.

sitions versus 12 % reverse transitions) and from Type 3 to Type 7 (34 % of transitions versus 17 % reverse transitions). The closest transitions without preferred directions are between Types 6 and 7 (24 % versus 26 %).

Ichnofabric Type 5 must be separately treated and is thus excluded from this analysis, because it represents an inhomogeneous group. Therefore, normal Markov Chains were calculated, since self-transformations within the 25 cm intervals are rare in these subtypes (Table 3). Characteristic transitions are from Subtype 5_1 (no visible macro-burrows) to Type 7 (dominated by *Phycosiphon*) with 30 % forward versus 2 % reverse transitions, and from Subtype 5_3 (*Nereites* and *Thalassinoides* exclusively) and Subtype 5_5 (*Thalassinoides* solely) to Type 1 (*Thalassinoides* and *Phycosiphon*), both with 33 % versus 5 % reverse transitions. Both transitions are of similar intensity between Subtypes 5_2 (only *Nereites*) and 5_3 (16.7 % in both directions), while no visible burrows (Subtype 5_1) mainly overlay Subtypes 5_3 (16.7 %) and 5_2 (8 %).

Embedded Markov Chains allow the detection of preferred transitions starting from non-bioturbated (laminated) core segments (Fig. 6). After the period with laminated (undisturbed) sediments, the *Phycosiphon* as a pioneer species reaches a high proportion, accompanied by a few *Nereites*. Preferred transitions from Type 4 to Type 3 (probability 0.32) that shows less lamination and the addition of abundant *Scolicia* follow this pioneer stage. Type 7 with dominance of *Phycosiphon* can also be directly derived from Type 4 (probability 0.24), while transitions to Type 6 (*Phycosiphon* and *Nereites*) are less important (probability 0.16).

Type 1 (*Thalassinoides* additional to both former species) mainly derives from Type 4 (probability 0.12) and from Type 6 (probability 0.17; Figs. 5, 6).

Type 3 as the main derivative from the laminated type mostly transforms to Type 7 (probability 0.34) and Type 6 (probability 0.25), with additional reverse transitions to the laminated Type 4 (probability 0.14) or to the most heterogeneous Type 2 (probability 0.11). It is important that the latter as the 'climax' community type mainly derives from Type 3, although *Scolicia* is completely lacking here.

Type 7 and Type 6 shows the closest connections as mentioned before with transition probabilities of 0.26 from Types 7 to 6 and 0.27 for the reverse. Transitions to Type 3 are more abundant from Type 7 (probability 0.17) than from Type 6 (probability 0.12) confirming the non-directed transitions between Types 3, 6 and 7.

Types 1 and 2 are not easily derived from the other types. After verification, Type 1 intensively changes to Type 6 (probability 0.22), Type 3 (probability 0.16) and Type 7 (probability 0.22). The most intensive transitions are from Type 2 to Type 6 (probability 0.46) meaning a restriction of the heterogeneous ichnofossils of Type 2 to *Phycosiphon* and *Nereites* in Type 6. Further important transitions are from Type 2 to Type 7 (solely *Phycosiphon*; probability 0.18) and to Type 3 (probability 0.14).

General tendencies in ichnofabrics along the core could be shown in percentages calculated over an interval of 2.75 m, whereby this interval moves in 25 cm steps (Figs. 2, 7). The results of 'moving percentages' demonstrate core segments preferred by special ichnofabric types and confirms the transitions between types explained above. Climax Type 2 dominates in the deepest core (95 to 100 m), only accompanied by a few Type 3 and Type 6 ichnofabrics. After vanishing around 90 m, Type 6 dominates, accompanied from 90 m upward by Types 3 and 7 (Figs. 2, 7). Type 4 with lamination becomes abundant between 78 and 87 m getting its maximum around

Table 2: Transformation matrix between ichnofabric types (diagonal calculated for embedded Markov Chains) and matrix of transition probabilities.

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	sum
Type 1	3.7	2	5	3	5	7	6	31.7
Type 2	2	1.8	3	0	1	10	4	21.8
Type 3	1	4	4.7	5	0	9	12	35.7
Type 4	3	2	8	2.4	0	4	6	25.4
Type 5	7	0	0	0	1.1	1	8	17.1
Type 6	11	6	8	6	3	16.2	16	66.2
Type 7	6	5	12	5	6	19	19.4	72.4
sum	33.7	20.8	40.7	21.4	16.1	66.2	71.4	270.3

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	sum
Type 1	0.12	0.06	0.16	0.09	0.16	0.22	0.19	1.0
Type 2	0.09	0.08	0.14	0.00	0.05	0.46	0.18	1.0
Type 3	0.03	0.11	0.13	0.14	0.00	0.25	0.34	1.0
Type 4	0.12	0.08	0.32	0.09	0.00	0.16	0.24	1.0
Type 5	0.41	0.00	0.00	0.00	0.06	0.06	0.47	1.0
Type 6	0.17	0.09	0.12	0.09	0.05	0.25	0.24	1.0
Type 7	0.08	0.07	0.17	0.07	0.08	0.26	0.27	1.0
sum	1.0	0.5	1.0	0.5	0.4	1.7	1.9	7.0

$\chi^2 = 55.1$; $df = 36$; $p(H_0) = 0.022$

Table 3: Transformation matrix between ichnofabric subtypes of group 5 treated as normal Markov Chains and matrix of transition probabilities.

	Type 5.1	Type 5.2	Type 5.3	Type 5.4	Type 5.5	Type 1	Type 2	Type 4	Type 6	Type 7	sum
Type 5.1	5			1				1		3	10
Type 5.2	1	6	2			1			1	1	12
Type 5.3	1	1	2			2					6
Type 5.4				1						1	2
Type 5.5						1				2	3
Type 1		1	2		2	17	2	3	7	6	40
Type 2						2	23		10	4	40
Type 4	1					3	2	17	4	6	33
Type 6	1	2				11	6	6	42	16	84
Type 7	1	2	1	1	1	6	5	5	19	23	64
sum	11	12	7	3	3	43	38	32	83	62	294

	Type 5.1	Type 5.2	Type 5.3	Type 5.4	Type 5.5	Type 1	Type 2	Type 4	Type 6	Type 7	sum
Type 5.1	0.500			0.100				0.100		0.300	1.0
Type 5.2	0.083	0.500	0.167			0.083			0.083	0.083	1.0
Type 5.3	0.167	0.167	0.333			0.333					1.0
Type 5.4				0.500		0.000				0.500	1.0
Type 5.5						0.333				0.667	1.0
Type 1		0.025	0.050		0.050	0.425	0.050	0.075	0.175	0.150	1.0
Type 2	0.025					0.050	0.575	0.000	0.250	0.100	1.0
Type 4	0.030					0.091	0.061	0.515	0.121	0.182	1.0
Type 6	0.012	0.024				0.131	0.071	0.071	0.500	0.190	1.0
Type 7	0.016	0.031	0.016	0.016	0.016	0.094	0.078	0.078	0.297	0.359	1.0
sum	0.833	0.747	0.566	0.616	0.066	1.541	0.835	0.840	1.426	2.532	10.0

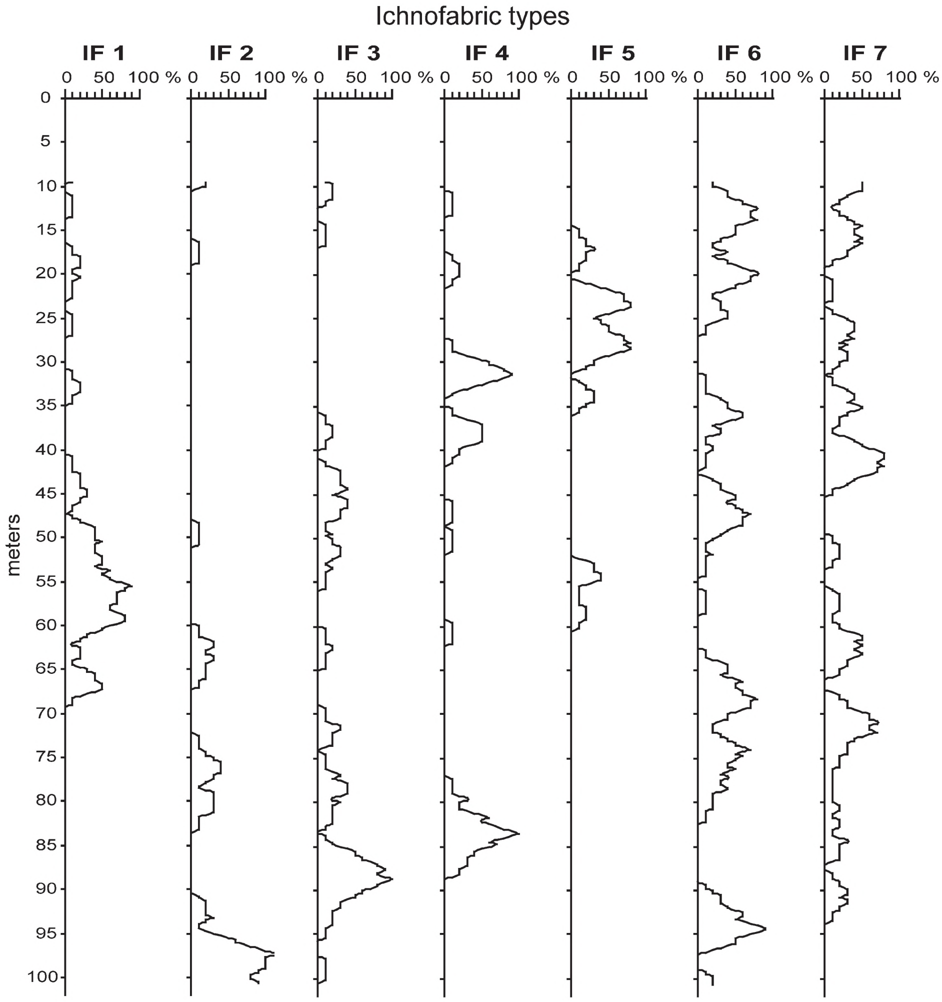

Fig. 7. General tendencies in ichnofabrics along the core shown in percentages calculated over an interval of 2.75 m moving in 25 cm steps.

84 m. After this period with abundant lamination, Type 3 briefly becomes important, but is suddenly replaced by Type 6 interchanging with Type 7 (Figs. 2, 7). These abundance changes between Types 6 and 7 are characteristic for the core from 87 m upwards, except the interval between 42 and 67 m, where Type 1 characterized by *Thalassinoides* additional to *Phycosiphon* and *Nereites* disturb these alterations. Further disturbance can be found in the upper core by temporal occurrence of laminated core intervals (Type 4) and by the indefinite group 5 with different subtypes or no visible macro-burrows. The latter is mainly restricted to the core interval between 16 and 34 m with two maxima around 27 and 22 m (Figs. 2, 7). While the 'climax' Ichnofabric Type 2 dominates the deepest core parts, it is rare between 47 and 82 m and completely lacking between 18 and 47 m.

Correlations and dependencies from the parameters of lamination and magnetic susceptibility were tested using the complete core, while relations to calcium carbonate and organic carbon could be tested only for the deeper part (40 m to 102 m). *Phycosiphon* is significantly positively correlated with magnetic susceptibility, explaining its presence in almost all ichnofabric types (Table 4). *Nereites*, which is an equivalent partner in Ichnofabric Type 6 and less prominent — compared to *Phycosiphon* — in Types 3, 2 and 1, is significantly positively correlated with organic carbon and magnetic susceptibility, but highly negatively correlated with lamination (Table 4). This is surprising, because lamination is positively correlated with magnetic susceptibility. *Thalassinoides*, characteristic for Ichnofabric Type 1 and the Subtypes 5_3 (together with *Nereites*), and for 5_5 where it represents the only trace fossil, is negatively correlated with magnetic susceptibility and lamination, but highly positively correlated with calcium carbonate (Table 4). *Scolicia* as a typical component of Ichnofabric Type 3 is, contrary to *Thalassinoides*, highly positively correlated with both lamination and magnetic susceptibility. *Trichichnus* is the only abundant ichnofossil that is exclusively correlated with organic carbon, thus similar in demands to the rare *Zoophycos*; both are elements of the climax Type 2. The rare ichnofossils *Asterosoma* and *Chondrites* behave similarly in their positive relations to lamination and magnetic susceptibility, which are more intensive in *Asterosoma* compared to *Chondrites* (Table 4).

Discussion

Classification of ichnofabric types and their relations by statistical methods can be applied in ichnofabric analysis (Erba & Premoli Silva 1994). However, its limitations must be taken into account, since co-occurrence of trace fossils in ichnofabric types may result from overlapping of different horizons. For example for *Ophiomorpha* and *Zoophycos*, the colonization surface can be above the 25-cm observation interval taken as the basic unit of observation. Such trace fossils are more connected with the environment at the colonization surface than in the horizon at which they are observed. Such situations influence the source data.

Accumulation rate, trophic changes and bottom stability

The fill of some open burrows, mainly *Thalassinoides*, shows coarser grains than the surrounding, totally bioturbated

Table 4: Point-biserial correlation matrix between ichnogenera and the parameters lamination, magnetic susceptibility, $CaCO_3$ and organic carbon.

	Asterosoma	*Chondrites*	*Nereites*	*Ophiomorpha*	*Palaeophycus*	*Phycosiphon*	*Scolicia*	*Siphonichnus*	*Teichichnus*	*Thalassinoides*	*Trichichnus*	*Zoophycos*	lamination
	0.133 **0.010** 376	0.088 0.088 376	**−0.193** **0.000** 376	−0.051 0.324 376	−0.036 0.487 376	0.049 0.345 376	**0.137** **0.008** 376	0.051 0.327 376	−0.047 0.368 376	−0.128 0.013 376	−0.055 0.290 376	0.009 0.869 376	
	0.157 **0.002** 376	0.107 0.038 376	**0.172** **0.001** 376	−0.032 0.537 376	−0.094 0.068 376	**0.176** **0.001** 376	**0.227** **0.000** 376	−0.037 0.480 376	−0.129 0.012 376	**−0.175** **0.001** 376	−0.011 0.832 376	−0.013 0.796 376	**0.227** **0.000** 376
	−0.135 0.034 249	−0.048 0.451 249	−0.022 0.734 249	0.028 0.662 249	0.076 0.232 249	−0.082 0.196 249	−0.106 0.094 249	0.007 0.916 249	0.029 0.653 249	0.180 0.004 249	0.087 0.169 249	0.021 0.736 249	**−0.220** **0.000** 249
	0.033 0.603 249	−0.024 0.705 249	**0.217** **0.001** 249	0.117 0.065 249	0.067 0.289 249	0.092 0.149 249	−0.045 0.482 249	0.045 0.479 249	−0.004 0.953 249	−0.043 0.504 249	**0.320** **0.000** 249	0.142 0.025 249	**−0.272** **0.000** 249

Legend: black – highly significant positive correlation; light grey – highly significant negative correlation; dark grey – significant positive correlation; white – significant negative correlation.

rock. This suggests that deposition of coarser and finer sediments alternated but that the sediments were homogenized by bioturbation. The sediment of the original grain size avoided this process only in deep burrows. Thus, it can be supposed that accumulation rate of the finer and coarser sediments varied in periods of higher and lower accumulation rates. Probably, coarser sediments of higher accumulation rate derived from shallower zones and contained higher amounts of particulate food and better oxygenated pore waters than the finer sediments, which no doubt influenced ichnofauna.

Phycosiphon dominates the core, occurs in nearly all horizons, and is accompanied in many layers by *Nereites* (Ichnofabric Type 6). These two trace fossils are produced by deposit-feeding animals that have no permanent connection to the seafloor and use oxygen from pore waters. They use particulate organic matter by horizontal reworking. Their abundance suggests an opportunistic colonization. In turbiditic sediments, they are typical of the initial colonization of turbiditic muds, whose pore waters are oxygenated and which contain abundant food; *Nereites* usually crosscuts *Phycosiphon* (Wetzel & Uchman 2001). By analogy, these trace fossils represent opportunistic colonization of oxygenated sediment rich in particulate organic matter, probably quickly after increased sediment input.

In most cases, *Nereites* crosscuts *Phycosiphon* and both are crosscut by *Scolicia*, which is another horizontally reworking infaunal deposit-feeding and omnivorous trace fossil. This order of crosscutting relationships resulted rather from sequential colonization of sediment than from upward migration of steady tiers in sediment occupied by the trace makers, accord-

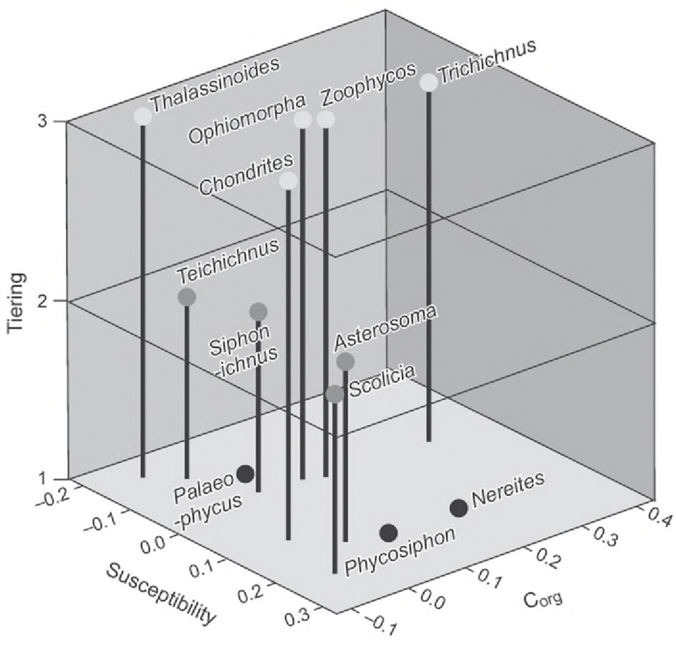

Fig. 8. Position of ichnofossils along environmental gradients based on correlation with magnetic susceptibility (related to accumulation rate and oxygenation) and organic carbon (related to particulate food content) (Table 1).

ing to sediment accumulation. *Nereites* followed *Phycosiphon*; *Scolicia* was produced later by irregular echinoids. Taking into account the size of these trace fossils, their trace makers were larger and probably more effective deposit feeders in their order of crosscutting. In turn, this can be correlated with decrease of particulate food in the sediment. It is intriguing that *Nereites* has a tendency to occur in sediments richer in TOC than *Phycosiphon* (Fig. 8). Probably, the *Nereites* stage of colonization is missing when the food content is lower in the colonized sediment. In such situations, *Phycosiphon* is always present as an unfailing opportunistic colonizer followed directly by ichnotaxa for which horizontal sediment reworking is less important.

When the sedimentation rate decreased, oxygen content gradually decreased in pore waters and the redox boundary migrated up. Particulate food also became less available due to consumption by deposit feeders and by oxidation. In such a situation, open and more stationary burrows were constructed, which allowed use of oxygen from the water column instead of pore waters. Intense sediment reworking for particulate food deeper in the sediment was replaced by searching for food at the sediment surface and from the water column. Some of the trace makers applied chemosymbiotic feeding, such as *Chondrites* or *Trichichnus* and partly *Zoophycos* (chemichnia *sensu* Bromley 1996). *Trichichnus* is present only in sediments rich in TOC (Fig. 8), mainly in Ichnofabric Type 2, where abundant particulate organic matter was buried below the redox boundary.

The open burrows (*Thalassinoides*, *Chondrites*, *Trichichnus*, *Zoophycos*) indicate more specialized feeding related to lower trophic level above the redox boundary and competition for food, which are both probably caused by decreasing accumulation rate. Thus, they indicate more stable-bottom conditions. Based on such assumptions it is possible to interpret the ichnofabric types and to distinguish tendencies in bottom stability change in the core.

Ichnofabric Types 6 and 7 record opportunistic colonization (*Phycosiphon*, *Nereites*) of well-oxygenated sediments (Fig. 7), interrupted by stable-periods allowing construction of open burrows and their maintenance. In the Ichnofabric Type 2, the stable periods after opportunistic colonization were probably longer and characterized by some deficiency of food above the redox boundary, but still with high food content below the redox boundary. In such conditions, stationary chemosymbiotic feeding (*Trichichnus* and probably partly *Zoophycos*) was effective. *Ophiomorpha* can be related to shallowing or the effects of storms.

Ichnofabric Type 3 records the stabilized phase of colonization and work of vagrant, opportunistic, omnivorous bioturbators, namely irregular echinoids producing *Scolicia*. This was evidently caused by higher input of detritus and slightly coarser sediment.

The lamination in Ichnofabric Type 4 indicates a high rate of sedimentation. *Phycosiphon* is abundant and *Nereites* quite rare. The sediment was only shallowly reworked and the primary lamination partly destroyed. In the Ichnofabric Type 5_1, the sediment was reworked in a very shallow semifluid zone, in which discrete trace fossils cannot be produced. In Ichnofabric Type 5_2, only opportunistic colonization of oxygenated, moderately food-rich-sediment took place, without more stable-periods. In Ichnofabric Type 5_3, opportunistic periods of colonization (*Nereites*) were followed by more stable periods (*Thalassinoides*).

Bathymetry, salinity, oxygenation, deposition and consistency of the substrate

The presence of *Zoophycos* and associated *Zoophycos*, *Phycosiphon*, *Nereites* and *Teichichnus* suggests the Zoophycos ichnofacies for the deeper part of the core. Upcore, *Thalassinoides* is more common, suggesting a transition to the distal *Cruziana* ichnofacies. Such relations indicate shallowing up to the upper offshore zone (cf. Pemberton et al. 2001).

The trace fossil *Scolicia*, produced by stenohaline irregular echinoids, indicates fully marine conditions (e.g. Bromley & Asgaard 1975; Smith & Crimes 1983). The salinity-tolerant crustacean burrow *Thalassinoides* (Frey et al. 1984) replaces *Scolicia* in the higher parts of the core. *Teichichnus*, which is especially common in fine-grained brackish sediments (Pemberton et al. 2001), occurs infrequently in Ichnofacies Types 3, 5_4 and 7. Thus, lowering salinity is not excluded in the upper part of the core, especially in Ichnofacies Type 5_4, where *Teichichnus* occurs alone.

The horizons with primary horizontal lamination in fine-grained sediments can be related to anoxic conditions. The laminae are partly disturbed by trace fossils connected to subsequent improvement of oxygenation.

Commonly, *Thalassinoides* is filled with slightly coarser sediment (fine sandy siltstone) than the host rock (siltstone, mudstone). This suggests deposition of coarser sediment beds, maybe distal tempestites or other event deposits, which were later completely obliterated by bioturbation and the only less mixed sediment was trapped in open *Thalassinoides* burrows, similarly to the so-called tubular tempestites (Wanless et al. 1988; Tedesco & Wanless 1991). This is quite clear for the boxwork of *Thalassinoides* filled with sand from the overlying bed (Fig. 3F). Probably, rare *Ophiomorpha* isp. is connected with colonization of such event beds.

Small compaction of the *Thalassinoides* galleries indicates stiffground substrate sensu Wetzel & Uchman (1998), especially in Ichnofabric Type 5_5, where *Thalassinoides* marks a discontinuity surface (*Glossifungites* ichnofacies sensu Pemberton et al. 2001).

Periodicity

Occurrences of the ichnofabric types show some periodicity. Ichnofabric Types 6 and 7, related to opportunistic colonization and bottom instability, display maxima every 10–15 m (Figs. 2, 7). They are intercalated by ichnofabrics that show generally higher trace fossil diversity and are related to higher bottom stability. Periods of stability and instability are related to changes in sedimentation rate and resultant oxygenation and food availability changes. Changes of these factors, in turn, can be related to the precession cycles calculated for 11–15 m periods (Hohenegger et al. 2008). The other cycles, namely obliquity cycles with 20-m periods and the eccentricity cycles with around 40-m periods, are less distinct but still visible (Fig. 2). Thus, analysis of ichnofabric can help the recognition of orbital cycles in lithologically monotonous sections.

Conclusions

1. Trace fossil and ichnofabric analyses are powerful traditional tools in the recognition of ecological parameters such as energy level, oxygen content, food supply, salinity or stability of ancient environments.

2. Statistical classification analyses help us to distinguish types of recurrent ichnofabrics.

3. Calculation of transition probabilities between ichnofabric types allows the recognition of general tendencies in ichnofabric distribution along a section.

4. Correspondence of these general tendencies with environmental gradients like magnetic susceptibility and organic carbon results in detailed information on tolerance of burrowing organisms against accumulation rate, oxygenation and particulate food content.

5. Based on these correspondences the distribution of ichnofabrics significantly marks the influence of periods in orbital cycles.

Acknowledgments: The study was supported by the Austrian Science Fund (FWF, Projects P13743-BIO, P 13740, P 18203), the Austrian Oriental Society Hammer-Purgstall, and the OAD, Austrian Exchange Service. A. Uchman was supported additionally by the Jagiellonian University, Kraków (DS funds).

References

Abel O. 1928: Parasitische Balanen auf Stockkorallen aus dem Miozänmeer. *Paläobiologica* 1, 13–38.

Benton M.J. 1982: Trace fossils from Lower Palaeozoic ocean-floor sediments of the Southern Uplands of Scotland. *Trans. Roy. Soc. Edinburgh, Earth Sci.* 73, 67–87.

Bromley R.G. 1991: *Zoophycos*: strip mine, refuse dump, cache or sewage farm? *Lethaia* 24, 460–462.

Bromley R.G. 1996: Trace fossils. Biology, taphonomy and applications. 2nd ed. *Chapman and Hall*, London, 1–361.

Bromley R.G. & Asgaard U. 1975: Sediment structures produced by a spatangoid echinoid: a problem of preservation. *Bull. Geol. Soc. Denmark* 24, 261–281.

Bromley R.G. & Hanken N.-M. 2003: Structure and function of large, lobed *Zoophycos*, Pliocene of Rhodes, Greece. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 192, 79–100.

Bromley R.G. & Uchman A. 2003: Trace fossils from the Lower and Middle Jurassic marginal marine deposits of the Sorthat Formation, Bornholm, Denmark. *Bull. Geol. Soc. Denmark* 52, 185–208.

Chamberlain C.K. 1971: Morphology and ethology of trace fossils from the Ouachita Mountains, southeast Oklahoma. *J. Paleontology* 45, 212–246.

Conkin J.E. & Conkin B.M. 1968: *Scalarituba missouriensis* and its stratigraphic distribution. *Univ. Kansas Paleont. Contr.* 31, 1–7.

Davis J.C. 2002: Statistics and data analysis in geology. 3rd ed. *John Wiley & Sons*, NewYork, NY, XVI+1–638.

Decker K. 1996: Miocene tectonics at the Alpine-Carpathian junction and the evolution of the Vienna Basin. *Mitt. Gesell. Geol. Bergbaustud. Österr.* 41, 33–44.

Ehrenberg K. 1944: Ergänzende Bemerkungen zu den seinerzeit aus dem Miozän von Burgschleinitz beschriebenen Gangkernen und Bauten dekapoder Krebse. *Paläont. Z.* 23, 354–359.

Ekdale A.A. 1992: Muckraking and mudslinging; the joys of deposit-feeding. In: Maples C.G. & West R.R. (Eds.): Trace fossils. Short courses in paleontology 5. *Paleont. Soc.*, Knoxville, 145–171.

Ekdale A.A. & Bromley R.G. 1991: Analysis of composite ichnofabrics: an example in Uppermost Cretaceous chalk of Denmark. *Palaios* 6, 232–249.

Ekdale A.A. & Lewis D.W. 1991: The New Zealand *Zoophycos* revisited. *Ichnos* 1, 183–194.

Ekdale A.A. & Mason T.R. 1988: Characteristic trace-fossil association in oxygen-poor sedimentary environments. *Geology* 16, 720–723.

Erba E. & Premoli Silva I. 1994: Orbitally driven cycles in trace-fossil distribution from the Piobicco core (late Albian, central Italy). In: De Boer P.L. & Smith D.G. (Eds.): Orbital Forcing and Cyclic. *Int. Assoc. Sed. Spec. Publ.* 19, 211–225.

Fillion D. & Pickerill R.K. 1990: Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. *Palaeontographica Canadiana* 7, 1–119.

Fischer-Ooster C. 1858: Die fossilen Fucoiden der Schweizer-Alpen, nebst Erörterungen über deren geologisches Alter. *Huber*, Bern, 1–72.

Frey R.W. 1970: Trace fossils of Fort Hays Limestone Member of Niobrara Chalk (Upper Cretaceous), West-Central Kansas. *Univ. Kansas Paleont. Contr.* 53, 1–41.

Frey R.W. 1990: Trace fossils and hummocky cross-stratification, Upper Cretaceous of Utah. *Palaios* 5, 203–218.

Frey R.W. & Goldring R. 1992: Marine event beds and recolonization surfaces as revealed by trace fossil analysis. *Geol. Mag.* 129, 325–335.

Frey R.W. & Seilacher A. 1980: Uniformity in marine invertebrate ichnology. *Lethaia* 23, 183–207.

Frey R.W., Howard J.D. & Pryor W.A. 1978: *Ophiomorpha*: its morphologic, taxonomic and environmental significance. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 23, 199–229.

Frey R.W., Curran A.H. & Pemberton S.G. 1984: Tracemaking activities of crabs and their environmental significance: the ichnogenus *Psilonichnus*. *J. Paleontology* 58, 511–528.

Fu S. 1991: Funktion, Verhalten und Einteilung fucoider und lophoctenoider Lebensspuren. *Cour. Forsch.-Inst. Senckenberg* 135, 1–79.

Fürsich F.T. 1973: A revision of the trace fossils *Spongeliomorpha*, *Ophiomorpha* and *Thalassinoides*. *Neu. Jb. Geol. Paläont., Mh.* 1972, 719–735.

Gibbons J.D. 1976: Nonparametric methods for quantitative analysis. *Holt, Rinehart and Winston*, New York, NY, XV+1–463.

Gibert J.M. de 1996: *Diopatrichnus odlingi* n. isp. (annelid tube) and associated ichnofabrics in the White Limestone (M. Jurassic) of Oxfordshire: sedimentological and palaeoecological significance. *Proc. Geologists Assoc.* 107, 189–198.

Hall J. 1847: Palaeontology of New-York. Volume 1. *C. van Benthuysen*, Albany, New York, 1–338.

Hamilton W., Wagner L. & Wessely G. 2000: Oil and gas in Austria. *Mitt. Österr. Geol. Gesell.* 92, 235–262.

Hohenegger J. & Pervesler P. 1985: Orientation of crustacean burrows. *Lethaia* 18, 323–339.

Hohenegger J., Ćorić S., Khatun M., Pervesler P., Rögl F., Rupp C., Selge A., Uchman A. & Wagreich M. 2008: Cyclostratigraphic dating in the Lower Badenian (Middle Miocene) of the Vienna Basin (Austria) — the Baden-Sooss core. *Int. J. Earth Sci.*, DOI 10.1007s00531-007-0287-7.

Khatun M., Wagreich M., Selge A., Stingl K., Hohenegger J. & Pervesler P. 2006: Cyclostratigraphy in the middle Badenian core

Sooß/Baden (Vienna Basin, Austria). *Geophys. Res. Abstr.* 7, 07993 (Abstr. EGU05).

Keighley D.G. & Pickerill R.K. 1995: The ichnotaxa *Palaeophycus* and *Planolites*: historical perspectives and recommendations. *Ichnos* 3, 301–309.

Kennedy W.J. 1975: Trace fossils in carbonate rocks. In: Frey R.W. (Ed.): The study of trace fossils. *Springer*, New York, 377–398.

Kleemann K.H. 1982: Ätzmuscheln im Ghetto? *Lithophaga* (Bivalvia) aus dem Leithakalk (Mittel-Miozän: Badenien) von Müllendorf im Wiener Becken, Österreich. *Beitr. Paläont. Österr.* 9, 211–231.

Kotake N. 1992: Deep-sea echiurans: possible producers of *Zoophycos*. *Lethaia* 25, 311–316.

Kováč M., Baráth I., Harzhauser M., Hlavatý I. & Hudáčková N. 2004: Miocene depositional systems and sequence stratigraphy of the Vienna Basin. *Cour. Forsch.-Inst. Senckenberg* 246, 187–212.

Kühnelt W. 1931: Über ein Massenvorkommen von Bohrmuscheln im Leithakalk von Müllendorf im Burgenland. *Paläobiologica* 4, 239–250.

Locklair R.E. & Savrda C.E. 1998: Ichnology of rhythmically bedded Demopolis chalk (Upper Cretaceous, Alabama): Implications for paleoenvironment, depositional cycle origins, and tracemaker behavior. *Palaios* 13, 423–438.

Lundgren S.A.B. 1891: Studier öfver fossilförande lösa block. *Geologiska Föreningens Stockholm Förhandlingar* 13, 111–121.

MacEachern J.A. & Burton J.A. 2000: Firmground *Zoophycos* in the Lower Cretaceous Viking formation, Alberta: A distal expression of the *Glossifungites* ichnofacies. *Palaios* 15, 387–398.

MacLeay W.S. 1839: Note on the Annelida. In: Murchison R. (Ed.): The Silurian System. Part II. Organic remains. *J. Murray*, London, 699–701.

Massalongo A. 1855: *Zoophycos,* novum genus plantorum fossilium. *Antonelli*, Verona, 1–52.

Mángano M.G., Buatois L., West R.R. & Maples C.G. 2002: Ichnology of a Pennsylvanian equatorial tidal flat — the Stull Shale Member at Waverly, eastern Kansas. *Kansas Geol. Surv., Bull.* 245, 1–133.

McBride E.F. & Picard M.D. 1991: Facies implications of *Trichichnus* and *Chondrites* in turbidites and hemipelagites, Marnoso-arenacea Formation (Miocene), northern Apennines, Italy. *Palaios* 6, 281–290.

McCune B. & Mefford M.J. 1999: PC-ORD. Multivariate analysis of ecological data. Version4. *MjM Software Design*, Gleneden Beach, Oregon, USA, 1–237.

Otto E. von 1854: Additamente zur Flora des Quadergebirges in Sachsen. Part 2. *G. Mayer*, Leipzig, 1–53.

Papp A., Cicha I., Seneš J. & Steininger F. (Eds.) 1978: Chronostratigraphie und Neostratotypen: Miozän der Zentralen Paratethys. Bd. VI. M_4 Badenien (Moravien, Wielicien, Kosovien). *VEDA SAV*, Bratislava, 1–594.

Pemberton G.S. & Frey R.W. 1982: Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma. *J. Paleontology* 56, 843–881.

Pemberton G.S., Spila M., Pulham A.J., Saunders T., MacEachern J.A., Robbins D. & Sinclair I.K. 2001: Ichnology and sedimentology of shallow to marginal marine systems. *Geol. Assoc. Canada Short Course Notes* 15, 1–343.

Pervesler P. & Uchman A. 2004: Ichnofossils from the type locality of the Grund Formation (Miocene, Lower Badenian) in northern Lower Austria (Molasse Basin). *Geol. Carpathica* 55, 103–110.

Pervesler P. & Zuschin M. 2004: A lucinoid trace fossil *Saronichnus abeli* igen. nov. et isp. nov. from the Miocene (Lower Badenian) molasse deposits of Lower Austria, and its environmental significance. *Geol. Carpathica* 55, 111–115.

Quatrefages M.A. de 1849: Note sur la *Scolicia prisca* (A. de Q.) annélide fossile de la Craie. *Ann. Sci. Natur., 3 série Zoologie* 12, 265–266.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O. 1991: Lateral extrusion in the Eastern Alps. 2. Structural analysis. *Tectonics* 10, 257–271.

Schlirf M. 2000: Upper Jurassic trace fossils from the Boulonnais (northern France). *Geologica & Palaeont.* 34, 145–213.

Seilacher A. 1955: Spuren und Fazies im Unterkambrium. In: Schindewolf O.H. & Seilacher A. (Eds.): Beiträge zur Kenntnis des Kambriums in der Salt Range (Pakistan). *Akad. Wiss. Liter. Mainz, Math.-Nat. Kl., Abh.* 10, 11–143.

Smith A.B. & Crimes T.P. 1983: Trace fossils formed by heart urchins — a study of *Scolicia* and related traces. *Lethaia* 16, 79–92.

SPSS 15.0 for Windows, 2006: Release 15.0.0. SPSS Inc.

Stanistreet I.G., Le Blanc Smith G.K. & Cadle A.B. 1980: Trace fossils as sedimentological and palaeoenvironmental indices in the Ecca Group (Lower Permian) of the Transvaal. *Trans. Geol. Soc. South Africa* 83, 333–344.

Sternberg G.K. von 1833: Versuch einer geognostisch-botanischen Darstellung der Flora der Vorwelt. IV Heft. *C.E. Brenck*, Regensburg, 1–48.

Tedesco L.P. & Wanless H.R. 1991: Generation of sedimentary fabrics and facies by repetitive excavation and storm infilling of burrow networks, Holocene of South Florida and Caicos Platform, B.W.I. *Palaios* 6, 326–343.

Uchman A. 1995: Taxonomy and palaeoecology of flysch trace fossils: The Marnoso-arenacea formation and associated facies (Miocene, Northern Apennines, Italy). *Beringeria* 15, 3–115.

Uchman A. 1999: Ichnology of the Rhenodanubian Flysch (Lower Cretaceous-Eocene) in Austria and Germany. *Beringeria* 25, 65–171.

Wanless H.R., Tedesco L.P. & Tyrrell K.M. 1988: Production of subtidal tubular and surficial tempestites by hurricane Kate, Caicos Platform, British West Indies. *J. Sed. Res.* 58, 739–750.

Weller S. 1899: Kinderhook faunal studies. I. The fauna of the vermicular sandstone at Northview, Webster County, Missouri. *Trans. Acad. Sci. St. Louis* 9, 9–51.

Werner F. & Wetzel W. 1981: Interpretation of biogenic structures in oceanic sediments. *Bull. Inst. Géol. Bassin Aquitaine* 31, 275–288.

Wetzel A. 1981: Ökologische und stratigraphische Bedeutung biogener Gefüge in quartären Sedimenten am NW-afrikanischen Kontinentalrand. *"Meteor" Forschungen-Ergebnisse, Reihe C* 34, 1–47.

Wetzel A. 2002: Modern *Nereites* in the South China Sea — Ecological association with redox conditions in the sediment. *Palaios* 17, 507–515.

Wetzel A. & Bromley R.G. 1994: *Phycosiphon incertum* revisited: *Anconichnus horizontalis* is its junior subjective synonym. *J. Paleontology* 68, 1396–1402.

Wetzel A. & Uchman A. 1998: Biogenic sedimentary structures in mudstones — an overview. In: Schieber J., Zimmerle W. & Sethi P.S. (Eds.): Shales & Mudstones. I. Basin studies, sedimentology, and paleontology. *E. Schweizerbart*, Stuttgart, 351–369.

Wetzel A. & Uchman A. 2001: Sequential colonization of muddy turbidites: examples from Eocene Beloveža Formation, Carpathians, Poland. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 168, 171–186.

Wetzel A. & Werner F. 1981: Morphology and ecological significance of *Zoophycos* in deep-sea sediments of NW Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 32, 185–212.

Zhang T., Ramakrishnan R. & Livny M. 1996: BIRCH: An efficient data clustering method for very large databases. *Proc. ACM SIGMOD Conf. on Management of Data*, Montreal, Canada, 103–114.