JAHRBUCH DER GEOLOGISCHEN BUNDESANSTALT
Jb. Geol. B.-A. | ISSN 0016–7800 | Band **144** | Heft 2 | S. 233–251 | Wien, Oktober 2004

Trace Fossils, Ichnofabrics and Sedimentary Facies in the Shallow Marine Lower Miocene Molasse of Upper Austria

ALFRED UCHMAN[*] & HANS GEORG KRENMAYR[**]

20 Text-Figures and 1 Table

Oberösterreich
Molasse
Miozän
Ottnangium
Vöckla-Schichten
Atzbacher Sande
Robulus-Schlier
Innviertler Serie
Ichnologie
Spurenfossilien

Österreichische Karte 1 : 50.000
Blätter 47, 48, 49

Content

Spurenfossilien, Ichnogefüge and sedimentäre Fazies in der flachmarinen untermiozänen Molasse von Oberösterreich

Zusammenfassung

In untermiozänen, siliziklastischen Sedimenten des flachen Subtidals bis Offshore-Bereiches wurde die Spurenfossilverbreitung in Abhängigkeit von der sedimentären Fazies untersucht. Die verschiedenen sedimentären Faziestypen können anhand des Energieniveaus (i.e. der Strömungsintensität) zur Zeit ihrer Bildung charakterisiert und gereiht werden. Die hochenergetischen Faziestypen sind durch eben laminierte bis massige Rinnensande, pelitische Slumpingmassen und subaquatische Dünen mit Bündelstrukturen gekennzeichnet. Die Spurenfossilien beschränken sich in dieser Fazies auf vereinzelte Exemplare von *Rosselia* und seltene Anzeichen von biogener Verwühlung in Pelitlagen. Die Faziestypen des mittleren Energieniveaus bestehen aus dezimetermächtigen, subaquatischen Dünen, Flaserschichtung und welliger Wechselschichtung sowie aus sandigen bis pelitischen Sedimentpaketen, deren Gefüge durch die intensive Bioturbation teilweise homogenisiert wurde. *Cylindrichnus* und *Macaronichnus* treten hier in

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[*] ALFRED UCHMANN, Institute of Geological Sciences, Jagiellonian University, Oleandry 2a; 30-063 Kraków, Poland.
fred@ing.uj.edu.pl.
[**] HANS GEORG KRENMAYR, Geologische Bundesanstalt, Rasumofskygasse 23, A-1031 Wien, Austria.
hgkrenmayr@cc.geolba.ac.at.

großer Häufigkeit auf und bilden charakteristische Spurengefüge. Echinidenspuren wie *Scolicia* und *Bichordites* sind in den sandigen Sedimentanteilen mancher Aufschlüsse vertreten. Außerdem konnten in den Faziestypen des mittleren Energieniveaus *Planolithes*, ? *Alcyonidiopsis, Skolithos, Ophiomorpha* und *Rosselia* identifiziert werden. Die Faziestypen der relativ niedrigsten Energieniveaus werden von laminierten Peliten mit feinen Sandlaminae und völlig oder teilweise durch die Bioturbation homogenisierten Pelitpaketen unterschiedlicher Mächtigkeit aufgebaut. Diese Faziestypen zeigen im Allgemeinen eine insgesamt höhere Bioturbationsrate. Vertreten sind die Ichnogenera *Teichichnus, Cylindrichnus, Planolithes, Macaronichnus, Rosselia, Ophiomorpha, Skolithos, Thalassinoides* und stellenweise *Scolicia*. Ausgenommen *Rosselia* sind alle vorhandenen Spurentypen auf die Faziestypen des mittleren bis relativ niedrigen Energieniveaus beschränkt. *Rosselia* scheint vom Energieniveau und der Art des Substrates weitgehend unabhängig zu sein. Generell weisen die auftretenden Spurenfossilassoziationen die größte Ähnlichkeit zur Cruziana-Ichnofazies auf. Nur in einem Aufschluss, mit einem Faziestypus des mittleren Energieniveaus, ist die Skolithos-Ichnofazies vertreten. Die meisten Spurenfossilien zeigen eine opportunistische, r-selektive Besiedelung des Sediments, ohne ausgereiften Stockwerksbau an. Die Ursachen dafür könnten der hohe Umweltstress durch das tidale Strömungsregime, hohe Sedimentationsraten und die möglicherweise eutrophen Bedingungen sein. Die bathymetrische Interpretation der Foraminiferenassoziation deutet auf ein tiefneritisches Environment und weicht damit markant vom sedimentologischen und ichnologischen Befund ab.

Abstract

The distribution of trace fossils in relation to sedimentary facies was studied in Lower Miocene (Ottnangian) siliciclastic sediments that accumulated in shallow subtidal to offshore environments. The sedimentary facies can be arranged according to their environmental energy level. The high-energy facies are characterized by evenly laminated and massive channel fill sands, slump deposits, and sand dunes with bundle structures. Trace fossils in this facies are restricted to isolated *Rosselia* and local biogenic disturbances of mud drapes. The moderate-energy facies consist of cross-bedded sand dunes at decimetre-scale, flaser bedding, wavy bedding as well as sandy and muddy beds, which are partly homogenized by bioturbation. *Cylindrichnus* and *Macaronichnus* occur in great abundance and form characteristic ichnofabrics. Echinoids, represented by trace fossils like *Scolicia* and *Bichordites*, ploughed sandy sediments in some localities. Also *Planolithes*, ?*Alcyonidiopsis, Skolithos, Ophiomorpha*, and *Rosselia* could be identified in the moderate energy facies. The relatively low energy facies are dominated by finely laminated mud with very thin sandy laminae and muddy layers of varying thickness, which are partly to totally homogenized by bioturbation. Generally these facies display an increased overall intensity of bioturbation and contain *Teichichnus, Cylindrichnus, Planolithes, Macaronichnus, Rosselia, Ophiomorpha, Skolithos, Thalassinoides*, and locally *Scolicia*. All identified ichnotaxa, except for *Rosselia*, are restricted to the moderate to relatively low-energy facies. *Rosselia* appears to be fairly independent of energy level and substrate. Generally all these trace fossil assemblages display most similarities to the Cruziana ichnofacies. Locally, the Skolithos ichnofacies occurs in moderate-energy facies. Most trace fossils indicate opportunistic, r-selected colonization of the sediment, lacking mature tiering. A reason for this might be environmental stress caused by the tidal regime, high depositional rates, and probable eutrophy. The bathymetric interpretation of microfossil assemblages suggests deep neritic environments, which differs drastically from the sedimentologic and ichnologic approach.

1. Introduction

Trace fossils and ichnofabrics are widely applied as a tool in palaeoenvironmental reconstructions. Nevertheless, relationships between their distribution and changes in facies are still not well understood. In shallow-marine siliciclastics, where only the *Skolithos* and *Cruziana* ichnofacies are distinguished, the classic models are often insufficient for the description of trace fossil distribution, mainly because of the great variety of both depositional facies and ichnofossil assemblages preserved therein (GOLDRING, 1993; BROMLEY, 1996). A more refined model, with distinguishing of the *Macaronichnus* assemblage and the proximal, archetypal and distal Cruziana ichnofacies is based on the Cretaceous deposits of the Western Interior Seaway of North America (PEMBERTON & MACEACHERN, 1995; PEMBERTON et al., 2001).

All the trace fossils described in this paper can be attributed to the Cruziana ichnofacies, but their distribution in several shallow marine facies types displays significant variations. These facies types can be arranged according to an increasing environmental energy level on the basis of their sediment textures and sedimentary structures. This gives us the opportunity to consider the relationship between ichnological features and the environmental energy level. We also compare our data to recent and fossil environments.

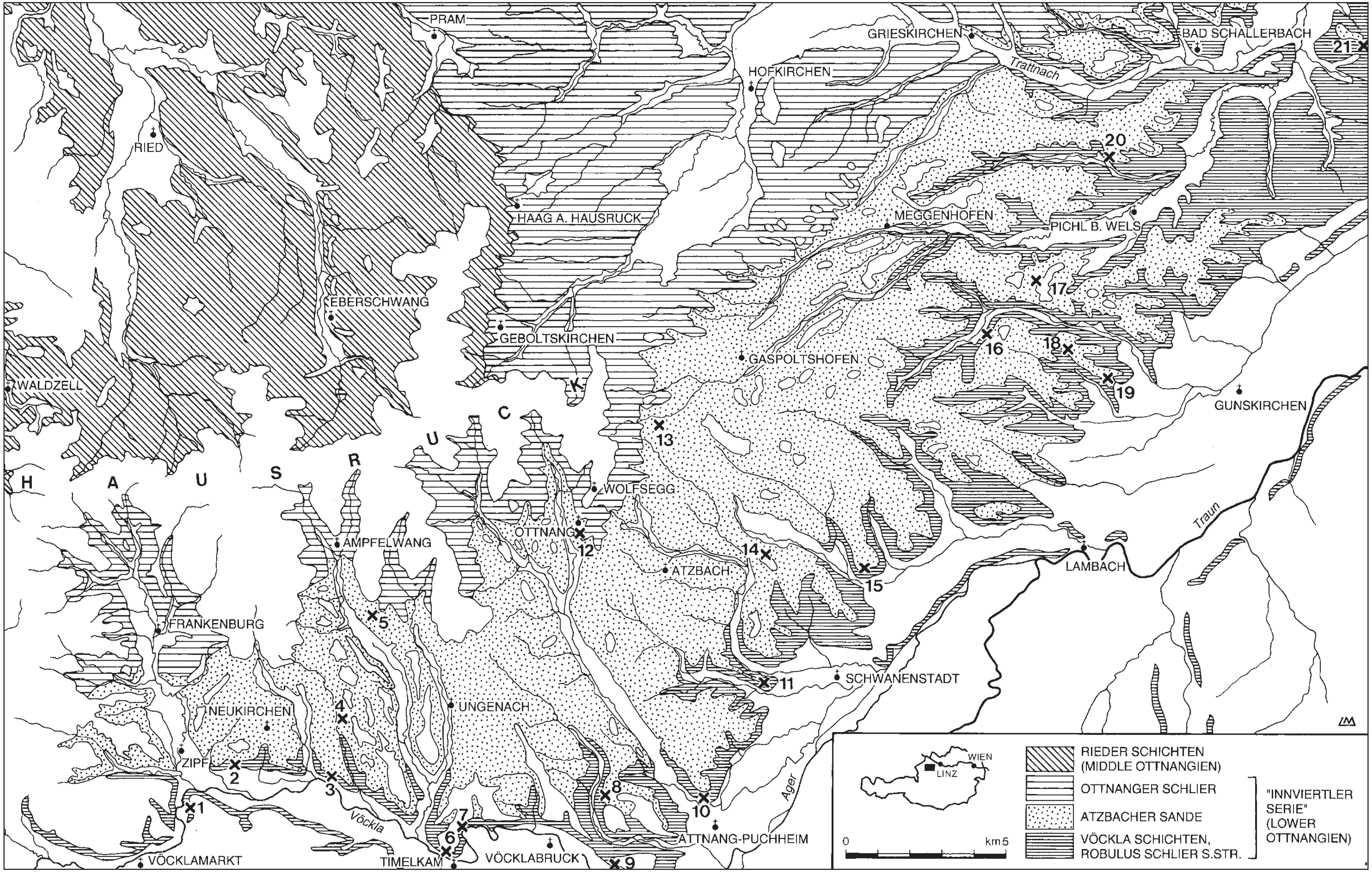
More than 50 outcrops were investigated in the study area (Text-Fig. 1). Coordinate-pairs of mentioned outcrops are given in the appendix. The sediments are poorly cemented facilitating observation of trace fossils in three dimensions. A systematic ichnology of these deposits was provided by UCHMAN & KRENMAYR (1995). The sedimentological part of the study was contributed by H.G. KRENMAYR, partly following the convention of FAUPL & ROETZEL (1987). The ichnological research was carried out by A. UCHMAN. Some of the illustrated specimens are housed in the Institute of Geological Sciences of the Jagiellonian University (acronym 150P). The foraminiferal data were provided by Ch. RUPP (Geologische Bundesanstalt, Austria).

2. Geological Setting

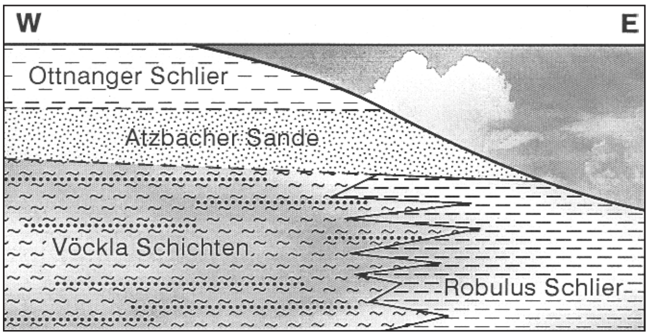
The Upper Austrian molasse basin is situated between the young orogen of the Eastern Alps in the south and the Variscian Bohemian Massif in the north. The basin was a part of the Paratethys, which intermittently extended from the Rhone valley to the Caspian Sea (RÖGL & STEININGER, 1983).

The studied outcrops lie within three lithological units of Lower Ottnangian age. All three units are mapable and can be equated to formations, which belong to the so-called “Innviertler Serie” (ABERER, 1961). The Robulus Schlier (“Schlier” is a regional expression for marly, sometimes fine-sandy, silt-rich sediments of the circum-Alpine molasse basins), Vöckla Schichten (“Vöckla beds”), and Atzbacher Sande (“Atzbach sands”) are all fully marine deposits. They correspond to the middle part of the “Obere Meeresmolasse” of the Western Paratethys (e.g., STEININGER et al., 1985). The interplay of subsidence, sedimentation rate and eustatic sea-level rise at that time (third-order cycle Tejas B 2.1; HAQ et al. [1987]) allowed the propagation of tides from the Mediterranean through the long and narrow seaway of the Paratethys, which can be concluded from sedimentary structures (SZTANÓ, 1994).

The Vöckla Schichten are 250–280 m thick, but only the uppermost 100 m crop out at the surface. The transition to the overlying Atzbacher Sande is gradational in the western part of their occurrence and more erosive towards the east, where the Robulus Schlier starts to replace the Vöckla Schichten (Text-Fig. 2). The Atzbacher Sande are 60–80 m thick and their transition to the overlying Ottnanger Schlier seems to be gradational. To the northeast the Atzbacher Sande are connected with comparatively coarse-grained shallow marine sediments which reflects the increasing influence of the Bohemian Massif as sediment source. There is no reliable information about the north(west)ward continuation of the Atzbacher Sande, where they plunge below the Ottnanger Schlier. The western continuation of the Vöcklaschichten and Atzbacher Sande is also covered by younger sediments, however



Text-Fig. 1.
Geological sketch map of the Lower to Middle Ottnangian (Lower Miocene) molasse sediments of the Hausruck area.
Compiled after Aberer (1958) and unpublished geological maps of Braumüller (1979), Krenmayr (1989, 1993), Roetzel (1984–1990), and Rupp (1984-1990).
Numbers refer to outcrop localities, see Appendix.



Text-Fig. 2.
General lithostratigraphic scheme of the study area.

they are supposed to interfinger with the sandy-gravelly fan delta facies of the "Sand-Schotter-Gruppe" in the surroundings of Salzburg (Aberer, 1961). The eastward continuation of the Atzbacher Sande is missing due to erosion, whereas the Robulus Schlier extends further to the east displaying no significant changes in lithology.

Unfortunately no precise information exists about the lateral and vertical relationships of the described lithological units as well as their internal facies organisation. The study area is covered by dense vegetation, outcrops are widely spaced and relatively small, and seismic or other subsurface data are not available. For that reason no sequence stratigraphic framework can be offered, where our observations could be integrated. There might exist, for example, a number of parasequences in the described sediment succession and their boundaries presumably run across the lithostratigraphic boundaries, however they cannot be traced in the field.

The Lower Ottnangian sediments of the southward basin margin, which supposedly rested upon the northernmost Alpine nappes, are eroded due to Upper Miocene to Pliocene uplift. The same is also true for the sediments of the northern nearshore facies, which must have rested upon the Bohemian Massif. In the study area the northward movements of the Alpine nappes largely ceased in the Early Miocene Eggenburgian stage. The younger, Ottnangian sediments are tectonically undisturbed and their present position in the centre of the basin seems to reflect the original palaeogeographic situation. Such conditions, with shallow marine sediments in the centre of a basin (i.e. a long and narrow seaway), are not known from any modern environment. Thus the comparison with common actualistic shore-offshore models is problematic.

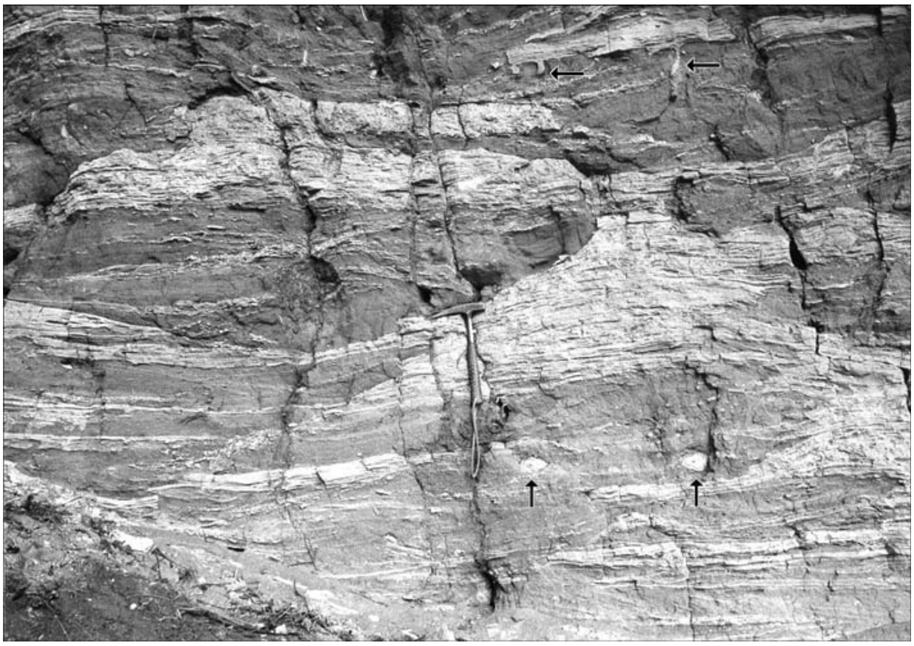
3. Sedimentology

A detailed sedimentological description of the Vöckla Schichten and Atzbacher Sande can be found in Krenmayr (1991) and Faupl & Roetzel (1987), respectively.

The Vöckla Schichten consist of silty marls, which are interbedded with small- and large-scale (beds up to 50 cm thick), cross-bedded, fine- to medium-grained, glauconitic sands. The marls occur as finely laminated intervals of varying thickness, as single or grouped mud drapes on foreset laminae of sand dunes, as reworked mud clasts, as flaser, lenticular, and wavy bedding, or as massive, sandy marlstone bodies and layers, which were partly or totally homogenized by bioturbation (Krenmayr, 1991).

The Atzbacher Sande are a distinct, sand-dominated unit between the marl-dominated sediments below (Vöckla Schichten and Robulus Schlier) and above (Ottnanger Schlier). In addition to the bedding types reported for the Vöckla Schichten they contain also larger bedforms, such as sand dunes (up to 150 cm thick) with bundle structures (Text-Fig. 17A), and thick, massive or clast-bearing, as well as evenly laminated channel-fill sands. The glauconitic sands are mostly fine- to medium-grained but coarse sand and fine gravels also occur. The facies of sand waves and channel-fill sands can be followed as a two kilometres wide, and more than 15 kilometres long, northeastward-trending zone across the whole area of distribution of the Atzbacher Sande. Within this zone also thick bodies of slumped, in places purely pelitic sediments occur which are thought to be derived from collapsed channel edges. No in situ equivalents of a comparable pelitic sediment type could yet be observed in a lateral position of their occurrence. In addition, there occur sandy gravity-flow deposits, containing partly sharp-edged rip-up clasts, which derived from eroded mud drapes of the sandwave facies. These flows were most probably also triggered by the undercutting of channel edges.

Tidal influence in the Vöckla Schichten and Atzbacher Sande is documented by herringbone cross-bedding, bundle structures, reactivation surfaces, and mud drapes and mud clasts on foreset laminae (Text-Fig. 3). Cross-bed measurements vary (Faupl & Roetzel, 1987; Krenmayr, 1991), but a bi-directionality is evident, which can be interpreted in terms of a strongly dominating flood-tidal current towards the ENE and a subordinate ebb-tidal current towards the WNW.



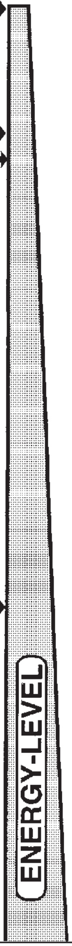
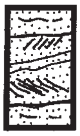
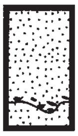
Text-Fig. 3.
Outcrop photograph from the Atzbacher Sande, Humpelberg.
Facies 3 and 4 (see Table 1 and Text-Fig. 15).
Nearly unbioturbated, laminated to lenticular-bedded muddy sediments, as well as muddy beds with the *Cylindrichnus* ichnofabric occur as erosional relicts within a "matrix" of deeply eroding, cross-bedded sand units. Several examples of *Ophiomorpha* are visible near the upper edge of the picture (horizontal arrows). To the lower right of the hammer are two cross-sections of *Rosselia* (vertical arrows). Hammer is 35 cm long.

All these features clearly indicate rather shallow-water conditions above fair-weather wave base in a mesotidal current regime. For hydrodynamic reasons it seems impossible that comparable sedimentary structures could develop under other than shallow water conditions. However, there are no indications that intertidal deposits exist in these strata. Calculations of the stability interval of symmetrical wave ripples based on grain size data and geometrical parameters of the wave ripples, resulted in a maximum palaeo water-depth of wave-ripple formation between 4 and 25 meters (FAUPL & ROETZEL, 1987). Wave-induced sedimentary structures are very rare in the Vöckla Schichten and Atzbacher Sande, although, for example, such structures constitute the dominant features of the sediment surface until about 10 m water depth in the mesotidal, modern environment of the North Sea (B. FLEMMING, pers. comm., 1998). Symmetrical wave ripples are extremely rare in the described sediments and hummocky cross-stratification is completely missing. This means that no storm deposits are known in the Vöckla Schichten and Atzbacher Sande. Probably their preservation potential is lower than commonly assumed in specific shallow marine environments, where continuously operating currents (i.e. tidal currents) might be able to immediately rework the sedimentary imprint of high-energy events. The only, however ubiquitous features of the submarine dune facies, which can be attributed to the influence of (storm)waves are the E1-surfaces (sensu ALLEN, 1980) or master beds and maybe as well the more prominent E2 or reactivation surfaces. E1 surfaces can generally be traced throughout the given outcrops, which generally extend over some tenths of meters.

The most "distal" deposits of the basin are represented by the Robulus Schlier. This unit consists of centimetre-to-decimetre thick layers of finely laminated silty marls with very thin laminae and lenses of fine sand to silt. Typically, these layers are regularly interbedded with layers of muddy sediment of similar thickness, which have been partly or totally bioturbated. The Robulus Schlier can be regarded as a basinal facies which was deposited close to or below the storm-wave base. This can be concluded from rarely occurring, very thin, erosive sandy layers in which shell-debris from molluscs and coarse glauconite grains are concentrated. These layers are interpreted as tempestites.

Table 1 gives a detailed description of six sedimentary facies types, which have been identified in the sediments described above. Their arrangement, according to the relative environmental energy level (i.e. the current velocity as most important variable but also the influence of waves) during deposition, is based upon detailed grain size investigations, set height and geometry of cross-bedded sand units, sand/mud ratios, size of erosive structures (reactivation surfaces, channels, major sub-horizontal erosional sur-

Table 1.
Sedimentological characteristics and interpretation of environment of facies types 1–6, arranged according to their interpreted environmental energy level.
In previous studies by FAUPL & ROETZEL (1987) and KRENMAYR (1991) a different facies classification was used, which is not directly related to environmental energy-level and referred to a restricted study area.
The corresponding facies-codes (Ax, Bx, Cx) of these studies are also given in the table. For key see Text-Fig. 15.

	Type of facies	Typical locality	Assoc. facies	Texture, (sand/mud ratio)	Sedimentary structures	Interpretation (and corresp. facies types in Krenmayr, 1991)
ROBULUS SCHLIER 	 1	Silbers-berg		Silty marl, fine sand and silt in thin laminae and lenses (< 1:10).	Finely laminated silty marls with very thin laminae and lenses of fine sand to silt, intercalated with layers of muddy sediment which have been totally homogenized by bioturbation.	Muddy outer shelf facies, influenced by weak bottom currents depositional depth approximating the storm-wave-base.
VÖCKLA SCHICHTEN	 2	Vöckla-bruck - Ager		Fine- to medium-grained sand, layers of silty marl, massive silty marl-beds with subordinate admixture of fine- to medium-grained sand (~1:10).	Wavy bedding, flaser bedding, lenticular bedding, intercalated with cm-to-m-thick muddy beds, which are totally homogenized by bioturbation.	Shallow subtidal, mud-rich deposits which generally occur in dense intercalation with facies 3 and 4; in case of coocurrence with facies 4 muddy sediments tend to dominate (C_2-partly, C_3-partly, C_5).
ATZBACHER SANDE	 3	Attnang		Fine- to medium-grained sand, layers of silty marl, massive silty marl-beds with subordinate admixture of fine- to medium-grained sand (~1:4).	Wavy bedding, flaser bedding, lenticular bedding, intercalated with cm-to-dm-thick muddy beds, showing the characteristic *Cylindrichnus*-ichnofabric; there occur transitional beds with sparse to nearly-complete reworking by *Cylindrichnus*.	Shallow subtidal, mud-rich deposits which generally occur in dense intercalation with facies 2 and 4; in case of coocurrence with facies 4 sand tends to dominate (C_2-partly, C_4).
	 4	Puch-kirchen		Fine- to medium-grained sand, layers and clasts of silty marl (~9:1).	Planar-, rarely festoon-shaped, cross-bedded sand-units, 10-70 cm thick, sometimes with mud-drapes and muddy clasts on the lee-side-laminae, ripple bedding in or near the bottom-sets, water-escape-structures, reactivation surfaces, cross-lamination frequently obliterated by biological activity, small channel structures.	Subtidal sand-fields with small sand-waves and ripples, intricately interfingering with the lower-energy facies 2 and 3 in a broad transition-zone, which is cross-cut by small channel-structures (C_3-partly, B_1, B_2).
	 5	Ottnang - Fischer		Fine- to medium-grained sand, fine gravel, layers and clasts of silty marl, plant detritus, pieces of wood (>9:1).	Planar- or festoon-shaped, cross-bedded sand-units, 30-150 cm thick, mud-drapes and muddy clasts on the lee-side laminae, bootom-sets form mud-rich intervalls, sometimes bundle-structures, reactivation surfaces, water-escape-structures.	Subtidal sand-waves, with dominating flood-tidal current towards the ENE, situated within a major channel-structure parallel to the flood-tidal current (A_1-partly, A_3, A_4).
	 6	Burgstall		Medium-grained sand, partly fine- to coarse-grained gravel, clasts of silty marl, plant detritus; slumped sediment-bodies: mainly silty marls, partly with sandy lenses and layers.	Several meters thick, massive sandbodies with intervalls of evenly laminated sand (upper-plane bed), bounded by major erosional surfaces, broad channel-structures, muddy clasts and gravel as channel-lag, slump-folds in mud-rich sediment-bodies, sediment-gravity-flow deposits with mud-clasts.	Subtidal channel-fill sands in the same major channel-structure as facies 5, with slumped sediment-bodies from collapsed channel-edges and high-density sediment-gravity-flows (A_1-partly, A_2, A_5).

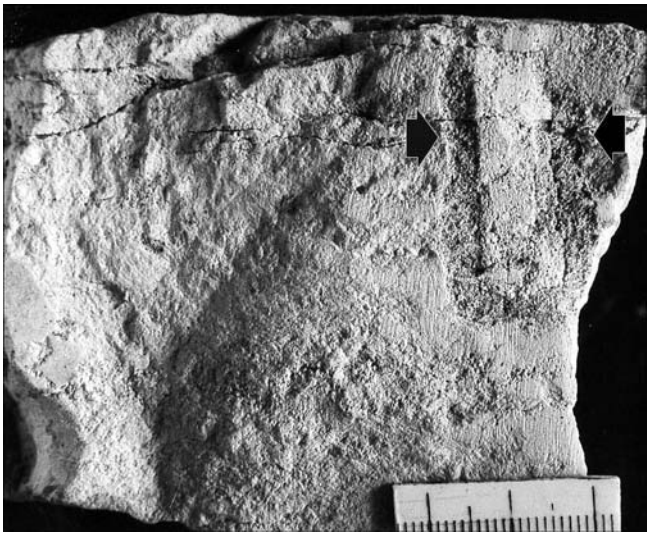
faces), bedding-types (e.g. occurrence of upper plane bed), position of the facies in the lithostratigraphic framework, and calculated current velocities, based upon grain size and geometric parameters of cross-bedded sand units (see FAUPL & ROETZEL, 1987). In some outcrops only one sedimentary facies type occurs (e.g. in most of the "typical localities" given in Table 1). However, in many outcrops particular facies types are intricately interfingering (e.g. Text-Fig. 3), which demonstrates that the environmental energy level fluctuated within narrow limits of time and space. Those facies types, which have been observed in outcrops in close lateral and vertical interrelationship, are indicated as "associated facies" in Table 1. As mentioned above, it is not possible to appreciate the spatial extent, geometry and internal arrangement of the sedimentary facies bodies more accurately because of outcrop conditions.

4. Synopsis of Ichnotaxa

A more extensive description and discussion of most of the following ichnotaxa was provided by UCHMAN & KRENMAYR (1995). As a result of further field research, the ichnotaxa *Macaronichnus segregatis*, ? *Alcyonidiopsis* isp., *Arenicolites* isp., *Ancorichnus* isp., *Teichichnus* isp., and *Thalassinoides* isp. have now been recognized.

? *Alcyonidiopsis* isp. is a small, winding, or helically coiled (KRENMAYR, 1991, Fig. 9), cylindrical, unbranched trace fossil, 1–2 mm in diameter. The filling is pelitic and the surface displays distinct pelletal structure. If preservation of the pelletal filling is poor, it can be mistaken for *Planolites*. For literature on *Alcyonidiopsis* see UCHMAN (1999).

Arenicolites isp. (Text-Fig. 4) is a vertical U-shape trace fossil having parallel limbs. The limbs are 4–5 mm in diameter, 10–11 mm apart and the structure is 35 mm deep. This form is very rare and was observed only in the Robulus Schlier at Silbersberg (locality 20, Text-Fig. 1) in a marly siltstone bed, which is overlain by a sandy bed. *Arenicolites* is interpreted as a dwelling and feeding burrow of suspension feeding annelids (e.g., HAKES, 1976) or small crustaceans (GOLDRING, 1962). It occurs in different environments, but is typical of shallow-marine settings (MÁNGANO et al., 2002).



Text-Fig. 4.
Arenicolites isp. in marly siltstone, filled with poorly cemented sandstone (between the arrows); vertical cross section.
Robulus Schlier, Silbersberg. UJ179P1. Scale in mm.

Ancorichnus isp. (Text-Fig. 5) is a horizontal to oblique meniscate cylindrical trace fossil possessing a discontinuous mantle sensu KEIGHLEY & PICKERILL (1994). It is 5–8 mm in diameter. This is a very rare form, which was found in the Robulus Schlier in Hartberg (locality 21, Text-Fig. 1) in a silty marlstone bed.

Text-Fig. 5.
Ancorichnus isp. in marly mudstone.
Horizontal section, polished and oiled surface.
Robulus Schlier, Hartberg. UJ179P2. Scale in mm.

Bichordites monastiriensis PLAZIAT & MAHMOUDI 1988 (Text-Fig. 11C) is a horizontally oriented, winding, more or less cylindrical trace fossil 3–5.5 cm in diameter, indistinctly bilobate along the lower side and distinctly bilobate along its upper side, and containing a distinct internal, central, heart-shaped core. For a discussion about this trace fossil see UCHMAN (1995).

Cylindrichnus concentricus HOWARD 1966 (Text-Fig. 6) is a concentrically layered, cylindrical, mainly horizontal or oblique trace fossil, 5–8 mm in diameter. *Cylindrichnus* was discussed by GOLDRING (1996) and GOLDRING et al. (2002). Nevertheless, several problems of its formation and ichnotaxonomy need further explanation.

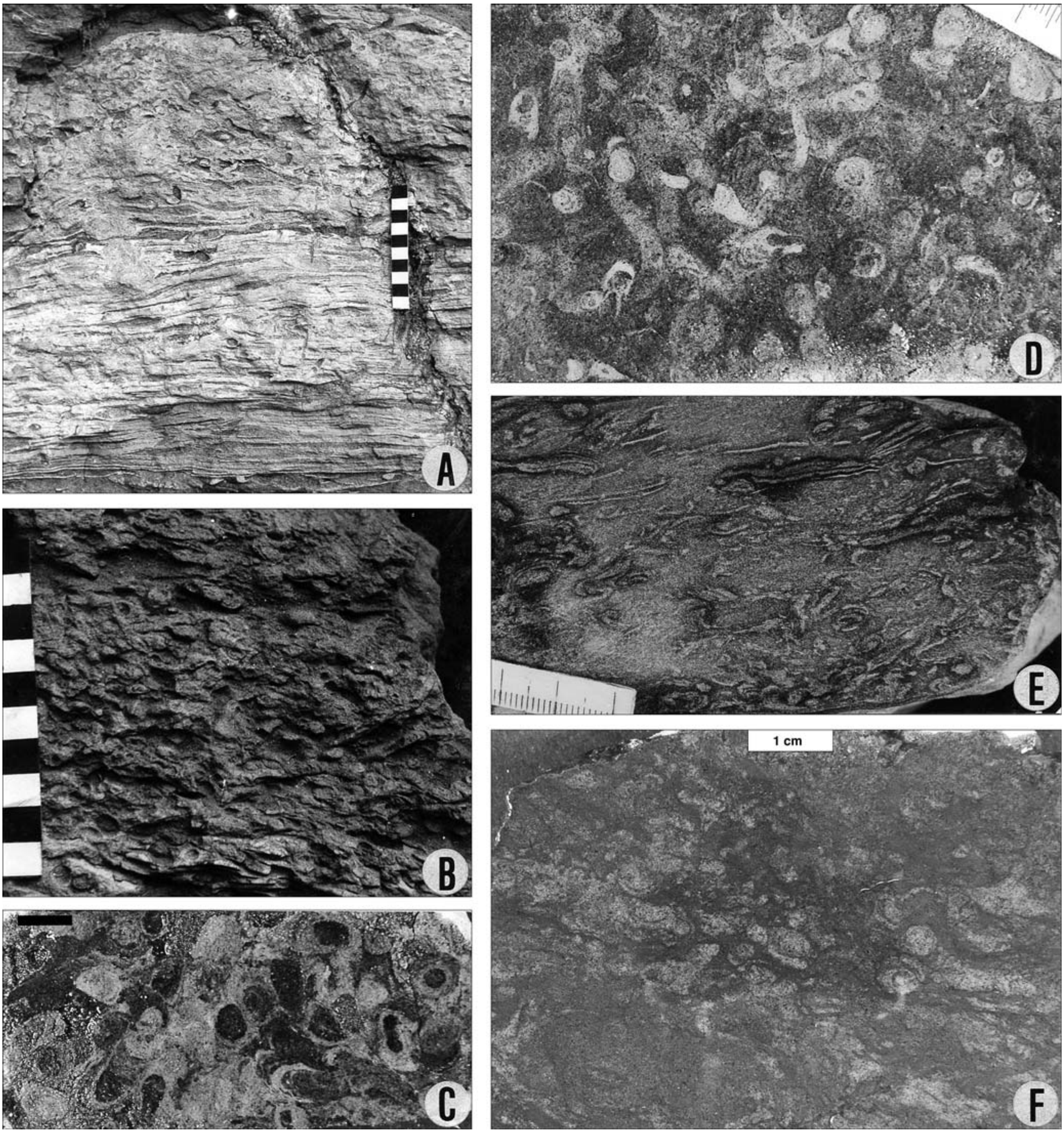
Macaronichnus segregatis CLIFTON & THOMPSON 1978 (Figs. 7, 20). Variably oriented, but mostly horizontal or sub-horizontal cylindrical trace fossils, 2–3 mm in diameter, filled with lighter sediment than the host rock. It occurs gregariously. The filling is devoid of biotite flakes and glauconite grains, which can be present in the host rock and concentrated along the margin of the trace fossil. An active segregation of the grains and flakes is typical of this ichnotaxon. In those cases, where the flakes or heavy minerals are scarce, the segregation is poorly visible and separation of this form from *Planolites* may be problematic. The tracemakers of *Macaronichnus* (mostly polychaetes) are believed to feed on epigranular bacterial films deeply, even several metres, within well-oxygenated foreshore sands (SAUNDERS & PEMBERTON, 1990; MACEACHERN & PEMBERTON, 1992, p. 68; PEMBERTON et al., 2001, p. 126-132).

Ophiomorpha annulata (KSIĄŻKIEWICZ, 1977). Variably oriented simple cylindrical trace fossils, 3–6 mm (smaller form) and 10 mm (larger form) in diameter. Their exterior is covered with densely packed elliptical pellets perpendicularly arranged to the course of the trace fossil.

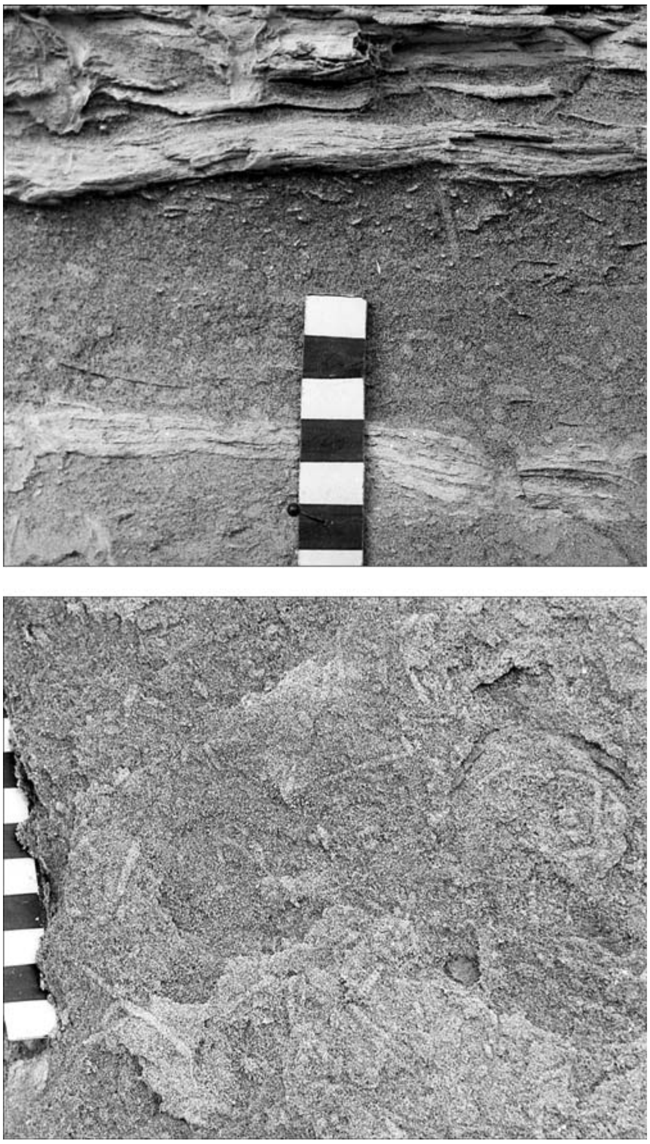
Ophiomorpha nodosa LUNDGREN 1891 (Text-Figs. 8, 20). Variably oriented, but mainly vertical, walled and rarely branched tubes, 10–25 mm in diameter, the exterior of which is densely covered with ovoid pellets.

Planolites ? *beverleyensis* BILLINGS 1862 (Text-Figs. 9, 10B). Cylindrical, horizontal to oblique, unlined structures, filled with sediment different in lithology and colour from the host rock. They are 1–2 mm (smaller forms) or 3–6 mm (larger forms) in diameter.

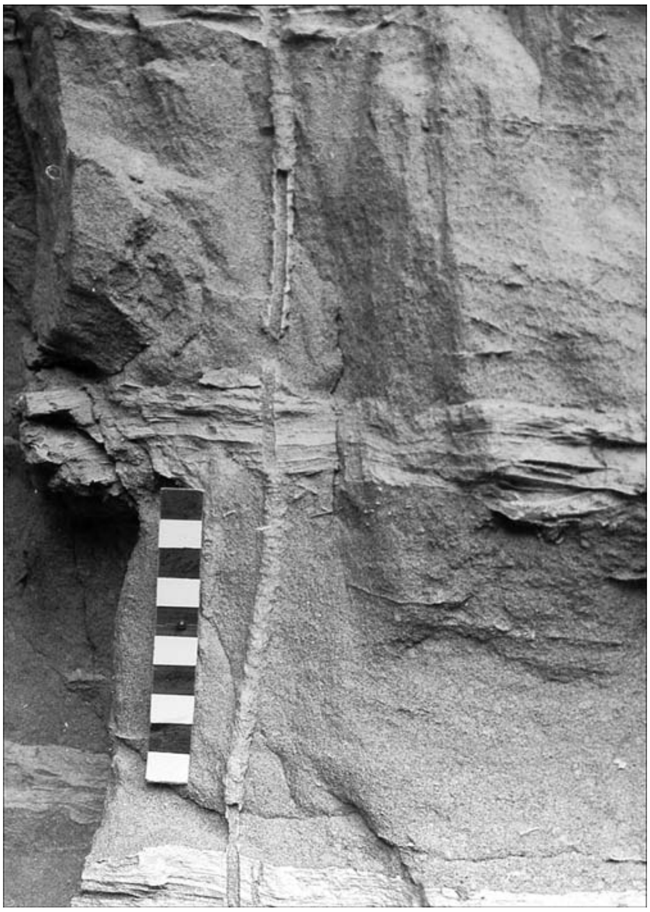
Rosselia socialis 1937 (Text-Fig. 10) is a concentrically layered, horn-shaped, obliquely oriented, simple or rarely



Text-Fig. 6.
Cylindrichnus concentricus HOWARD.
A) Sandy marly mudstone bed containing *Cylindrichnus* in the upper part and laminated marly mudstone in the lower part.
Atzbacher Sande, Humpelberg.
Field photograph.
B) Appearance of *Cylindrichnus* ichnofabrics on weathered surface of sandy marly mudstone bed.
Vertical section, Atzbacher Sande, Hinterschützing.
Field photograph.
C–D. Appearance of the *Cylindrichnus* ichnofabrics on polished and oiled surfaces in sandy marly mudstones.
Atzbacher Sande, Winkl.
C = vertical cross-section, UJ179P3.
D = horizontal section, UJ179P4.
E) *Cylindrichnus* ichnofabric in marly mudstone. Cross-section view, polished and oiled surface.
Robulus Schlier, Hartberg, UJ179P5.
Note the deformed contours of the trace fossils.
F) *Cylindrichnus* ichnofabric in sandy mudstone. Cross-section view, polished and oiled surface .
Vöckla Schichten, Vöcklabruck-Ager, UJ179P6.
Note the deformed contours of the trace fossils.
Scale in cm for A–B; scale bar = 1 cm in C; scale in mm in D–F.



Text-Fig. 7.
Macaronichnus segregatis CLIFTON & THOMPSON in sandstone beds in the Atzbacher Sande.
A) Vertical section of bed. Offenhausen.
B) Bedding plane. Kasberg.
Transition Vöcklaschichten/Atzbacher Sande.
Field photographs. Scale in cm.



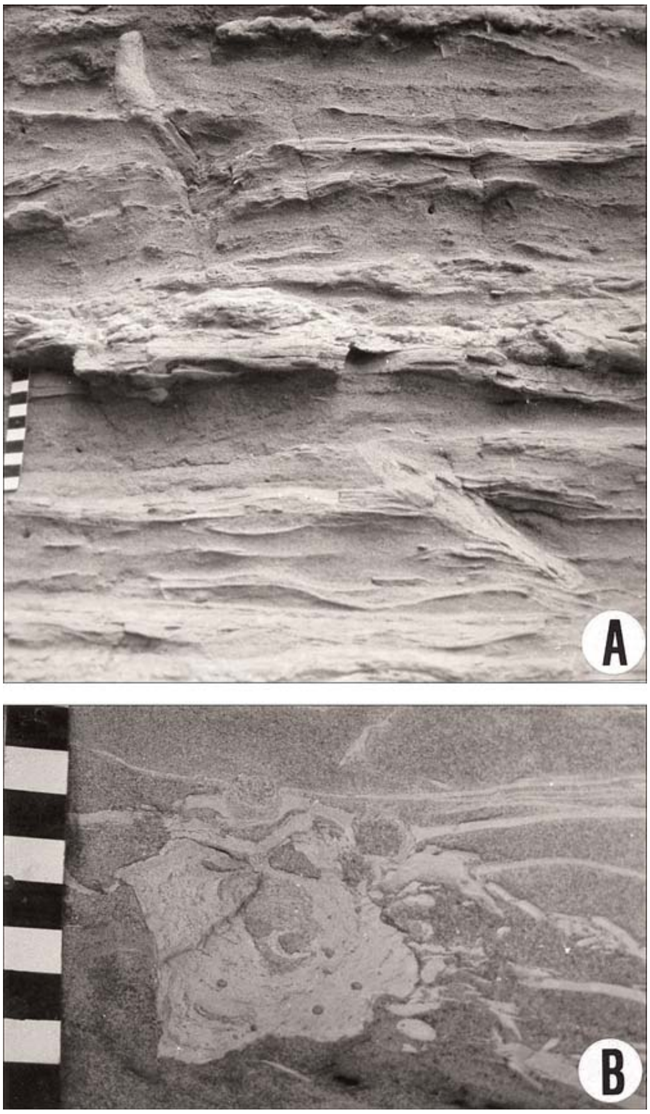
Text-Fig. 8.
Ophiomorpha nodosa LUNDGREN penetrating through a few sedimentary cycles.
Atzbacher Sande, Offenhausen.
Note lack of the knobbly wall structure within muddy intervals.
Field photograph. Scale in cm.

branched, endichnial trace fossil, which is swollen at the proximal part. It is up to 75 cm long and 2.5–8.5 cm in diameter at the swellings.

NARA (1995) described a *Rosselia* from Pleistocene deposits of Japan as a dwelling structure of terebelloid polycheates and determined it as *R. socialis*. This form differs distinctly from our *Rosselia* by its exclusively vertical orientation, cone-in-cone stacked pattern, and crowded occurrence. For this reason the Japanese material should be described under another ichnospecies.

Scolicia isp. (Text-Fig. 11A–B) is a horizontal, straight to winding, more or less subcylindrical, backfilled structure, 3–4 cm wide and 5–8.5 cm high, which displays a distinctly bilobate lower (ventral) side and a slightly concave upper (dorsal) side of the trace fossil.

Text-Fig. 9.
Planolites ? *beverleyensis* BILLINGS.
Hypichnial form in thin sandy bed.
Robulus Schlier, Hartberg, UJ179P7.
Scale in mm.

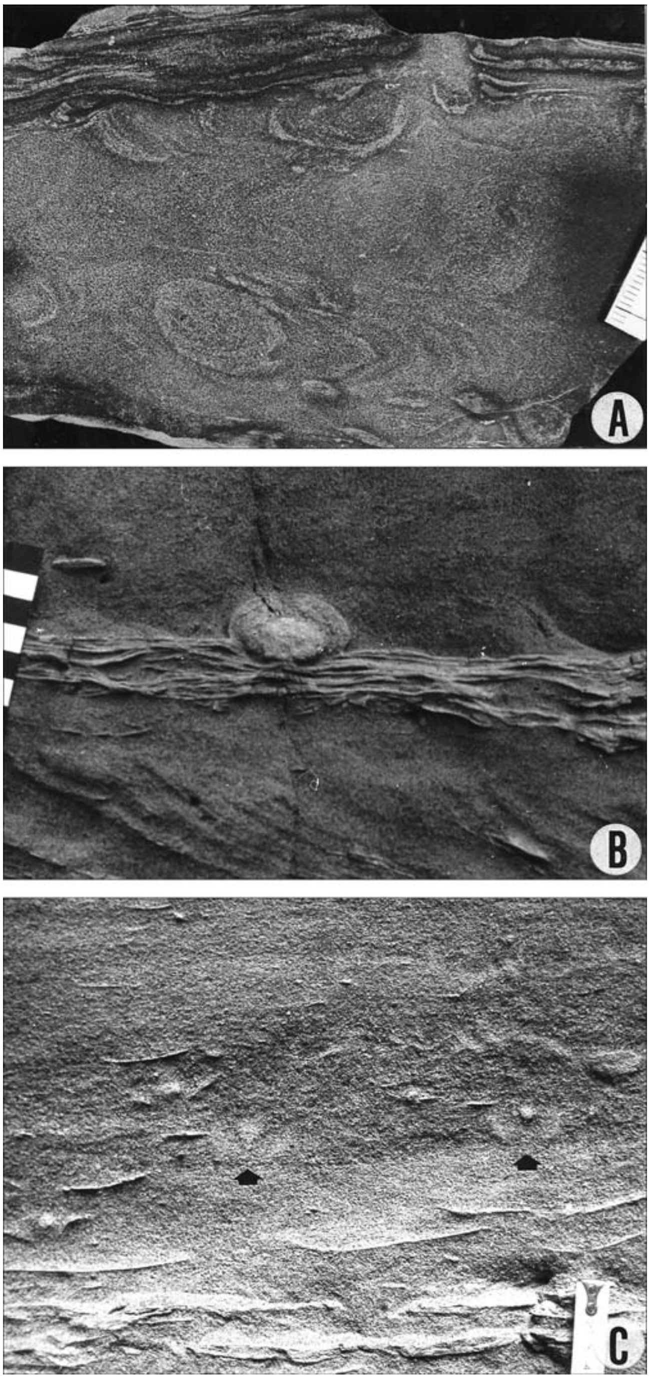


Text-Fig. 10.
Rosselia socialis DAHMER in Atzbacher Sande.
A) Specimen in lower right of the picture is in cross section; that at upper left is a weathered-out specimen.
Holzing.
B) Horizontal section view, the burrow is cross-cut by *Planolites* ? *beverleyensis* BILLINGS.
Hinterschützing.
Field photographs. Scale in cm.

Skolithos isp. (Text-Fig. 12). At least a few centimetres long, vertical to subvertical tubes, 2–4 mm in diameter. The tubes are filled with coarser sandy material and occur in patches. Exceptionally, in one outcrop of the moderate-energy facies, we traced a near-vertical tube along 105 cm.

Teichichnus isp. (Text-Fig. 13). In perpendicular cross sections it is a vertically arranged zone composed of arcuate, convex down, stacked laminae. The zone is about 10 mm wide. The laminae form wide, convex-down arcs in longitudinal sections. This morphology indicates a protrusive character of this trace fossil. For a discussion of *Teichichnus* see PEMBERTON et al. (2001, p. 324) and MÁNGANO et al. (2002).

Thalassinoides isp. (Text-Fig. 14). Horizontally oriented cylinders, which display Y-shaped, rarely T-shaped branchings. They are 10 to 25 mm in diameter. *Thalassinoides* was produced by crustaceans, mostly decapods (FREY et al., 1984). For further discussion of this ichnogenus see EKDALE (1992).

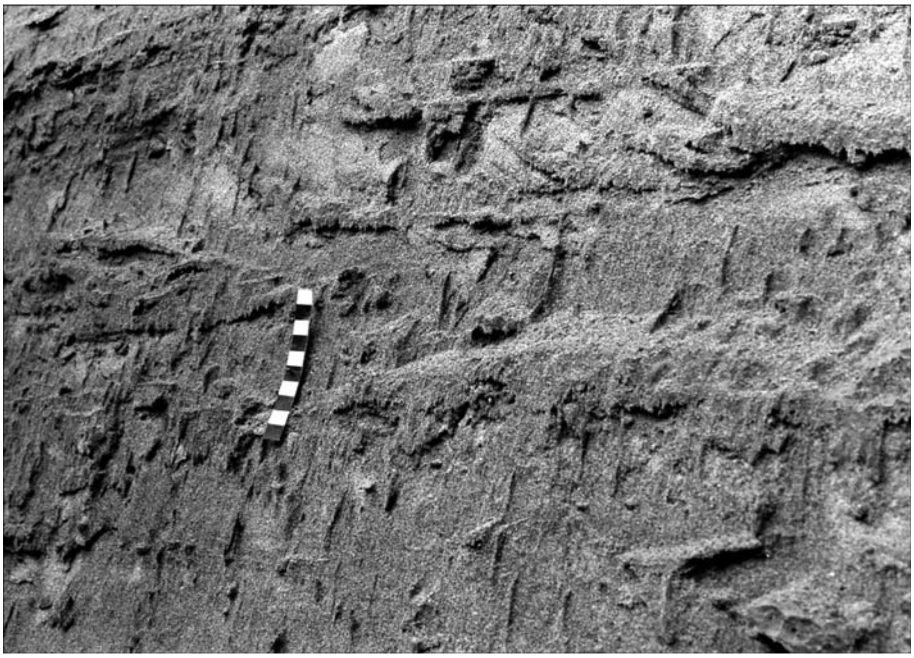


Text-Fig. 11.
Ichnofabrics and trace fossils produced by echinoids.
A) *Scolicia* ichnofabric in the Robulus Schlier, Hartberg.
Marly mudstone, cross section view of polished and oiled surface, UJ179P8. Burrows at the top are truncated by wavy laminae.
B) *Scolicia* isp. in the Atzbacher Sande, Holzing.
Cross-section view. Field photograph.
C) *Bichordites monastiriensis* PLAZIAT & MAHMOUDI in the Atzbacher Sande, Puchkirchen-Berg. The central, heart-shaped core of *Bichordites* is the most prominent structure (above the arrows).
Cross-section view. Field photograph.
Scale in mm for A; scale in cm for B–C.

5. Distribution of Trace Fossils, Ichnofabrics, and Degree of Bioturbation

5.1. Distribution of Trace Fossils

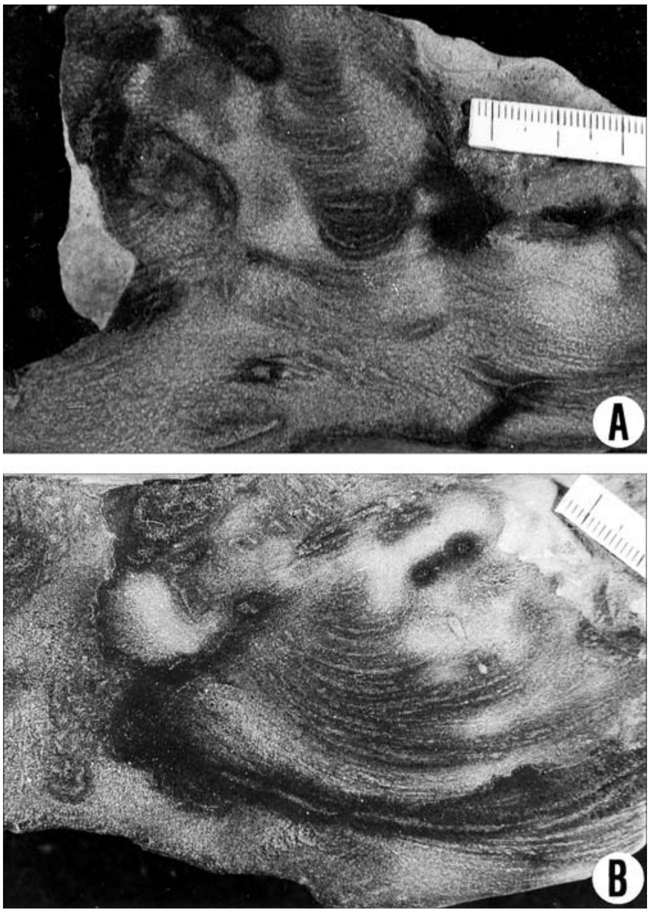
Trace fossil distribution and abundance distinctly vary in the examined facies as depicted in Text-Fig. 15.



Text-Fig. 12.
Skolithos isp. in cross-laminated sands.
Atzbacher Sande in Bruck.
Scale in cm.

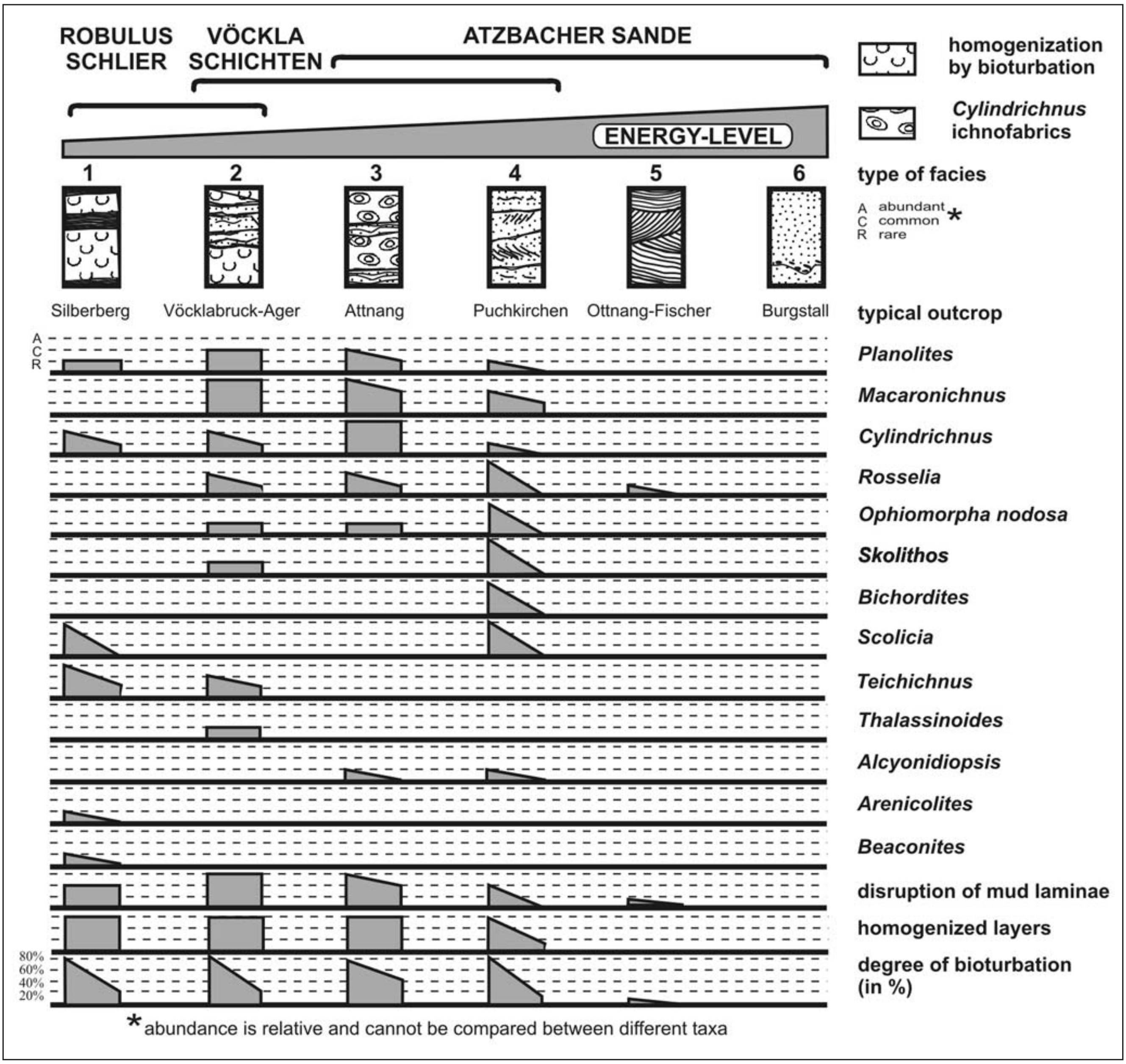
Scolicia isp. occurs in two different facies (types 1 and 4 in Text-Fig. 15). In the first case, *Scolicia* isp. occurs in low-energy marly-to-muddy sediments of the Robulus Schlier, interpreted as muddy outer shelf facies. It was found together with body fossils of irregular echinoids, which could be the potential tracemakers. In the second case, *Scolicia* isp. occurs in the moderate-energy facies of the Atzbacher Sande, interpreted as subtidal sand-fields. It has not been observed in the intermediate facies type 2 and 3. Most probably, *Scolicia* isp. in these two different facies was produced by different echinoids, living in different environments. However, no important morphological features were recognized, which could allow their ichnotaxonomical separation. The *Scolicia* from facies 1 occurs in a monotypic association. The *Scolicia* from facies 4 occurs together with *Bichordites monastiriensis*. *Bichordites* is always more abundant than *Scolicia* isp. Locally, sparse *Rosselia socialis* occurs with them. The highest abundance of *Bichordites* was observed in Puchkirchen-Berg (locality 4; Text-Fig. 1), where about 50 burrows are visible in 1 m^2 of the outcrop wall; *Scolicia* is less abundant with about 10 burrows/m^2.

Cylindrichnus concentricus occurs, commonly in high density, in moderate- to low-energy facies. It is most abundant in the shallow subtidal, mud-rich facies 3.



Text-Fig. 13.
Teichichnus ichnofabric in the Vöckla Schichten, Vöcklabruck-Ager.
A) Cross section perpendicular to the spreite.
Polished and oiled surface, UJ179P9.
B) Cross section along the spreite.
Polished and oiled surface, UJ179P10.
Scale in mm.

Text-Fig. 14.
Thalassinoides isp.
Hypichnial form from the Vöckla Schichten, Eiding.
UJ179P11. Scale in mm.



Text-Fig. 15.
Scheme of trace fossil distribution according to facies changes.
The typical outcrops illustrated are only examples of the sedimentary facies and do not necessarily preserve all ichnotaxa indicated. Nevertheless, all ichnotaxa are typical of the particular facies and have been observed in other outcrops of the same facies type.

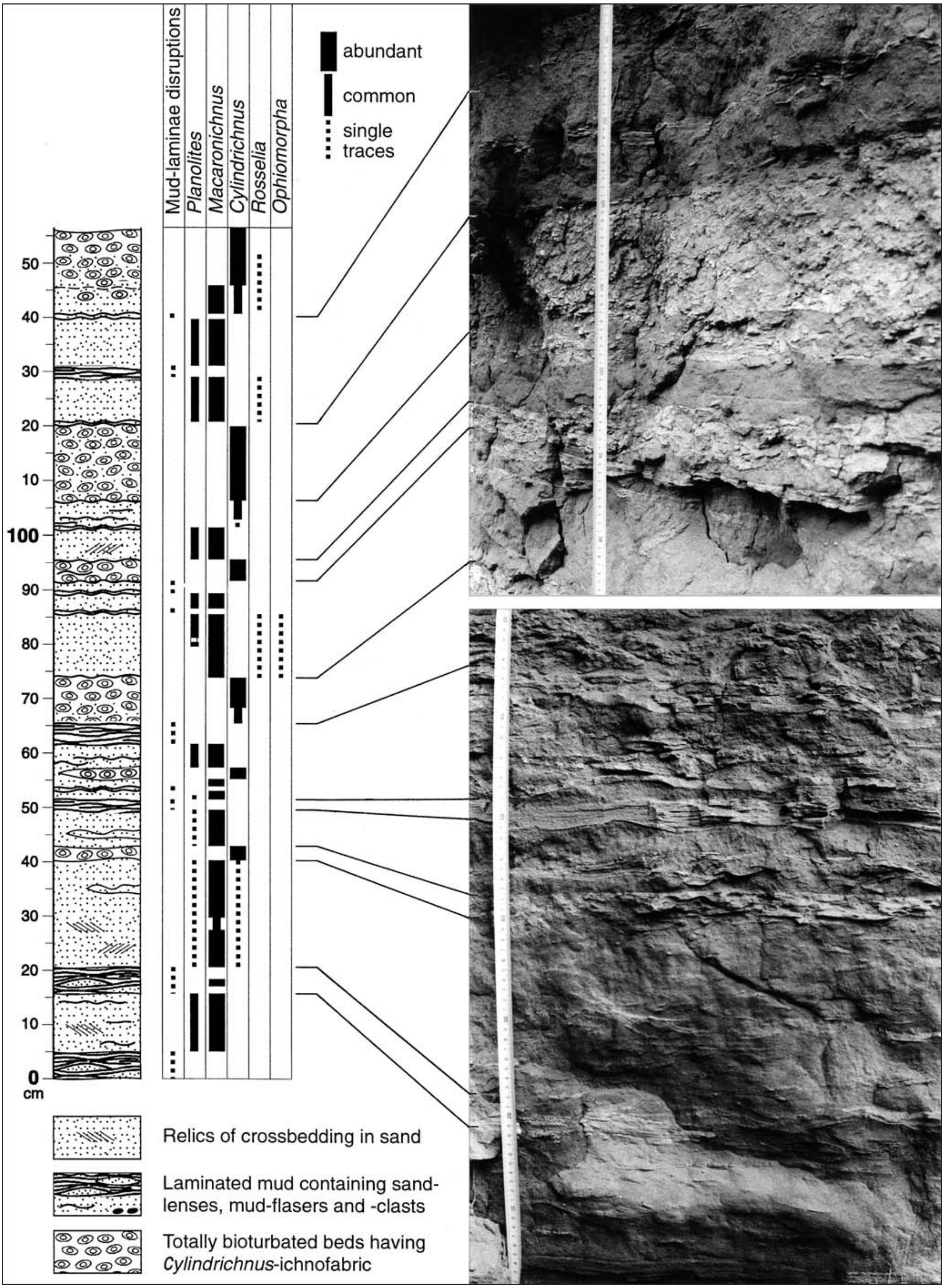
Macaronichnus occurs in high density in the sandy beds of the relatively low-energy facies (type 2, Text-Fig. 15) to the moderate-energy facies (types 3 and 4, Text-Fig. 15). It is most common in the intercalated sandy beds of facies types 2 and 3 (Figs. 7, 16). However, the recognizeability of *Macaronichnus* strongly depends on sediment composition (abundance of dark grains) and weathering conditions. This is especially true for facies type 4, where in many beds missing sedimentary structures of both physical and biogenic origin, make suspicious in terms of bioturbation by the *Macaronichnus* tracemaker.

Rosselia socialis occurs in sparse populations from relatively low-energy (facies 2) to moderate-energy facies (facies 3 and 4) and rarely is found in high-energy facies (facies 5). Its abundance is never higher than 10 individuals/m^2 of the outcrop wall, e.g. at Bruck (locality 5, Text-Fig. 1), where it occurs together with *Skolithos*.

Ophiomorpha nodosa and *O. annulata* occur in sparse populations in some of the relatively low- to moderate-energy facies 2, 3 and 4. The highest abundance of *O. nodosa*, about 50 structures/m^2 of the outcrop wall, was observed in Oberthumberg (locality 3, Text-Fig. 1), where it forms a characteristic ichnofabric of dense vertical structures, that penetrate a few sandy beds separated by thick muddy laminae (facies 2). At Ziegelwies (locality 8, Text-Fig. 1), the abundance reaches 10 structures/m^2 of the outcrop wall.

Thalassinoides isp. occurs in some horizons of the relatively low-energy facies 2. *Teichichnus* isp. occurs exclusively in silty or sandy marlstones of the low-energy, outer-shelf facies 1 and the shallow-subtidal heterolithic facies 2. *Skolithos* isp. is most common in marly siltstone beds (facies 2), although never abundant, and is filled with overlying sand. Moreover, it occurs locally in moderate-energy sandy facies 4 (Text-Fig. 15).

Planolites ? *beverleyensis* also occurs in some sandy beds, presumably in moderate-energy facies and only partially disturbs primary sedimentary structures. ?*Alcyonidiopsis* isp. is not abundant and occurs in some horizons of facies 3



Text-Fig. 16.
Portion of section of the Atzbacher Sande and trace fossil distribution at Winkl.

and 4 at Humpelberg (locality 18, Text-Fig. 1) and Ziegelwies (locality 8, Text-Fig. 1). *Arenicolites* isp. and *Ancorichnus* isp. are very rare (single specimens) and occur in silty marlstone beds of facies 1.

Most trace fossils penetrate one sedimentary cycle. Nevertheless, *Rosselia* and *Ophiomorpha* can penetrate a few sedimentary cycles (Figs. 8, 10). These tracemakers probably kept pace with sedimentation and are examples of multilayer colonizers sensu UCHMAN (1995).

5.2. Ichnofabrics and Degree of Bioturbation

A few important trace fossils are responsible for the appearance of facies, forming typical ichnofabrics. *Cylindrichnus concentricus* forms a monotypic ichnofabric, which is restricted to marly-silty, originally heterolithic beds, with a small admixture of sand. The beds are partly to totally bioturbated, and in the latter case no evidence of physical sedimentary structures is left. *Cylindrichnus* is mostly horizontally oriented and densely packed. The beds are commonly 10–30 cm thick, with exceptional beds up to 120 cm thick (Text-Figs. 6, 16). *Cylindrichnus* ichnofabrics change their appearance according to the change of lithology and consistency of the sediment. In more clayey sediments, which probably were more water saturated, *Cylindrichnus* is more compacted and smeared (Text-Fig. 6E–F). Very rarely, the *Cylindrichnus* beds are cross cut by *Rosselia*.

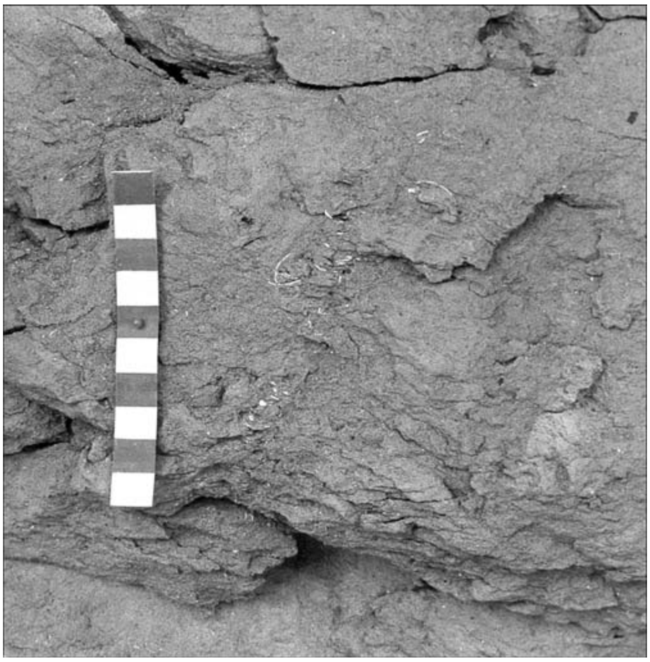
A commonly monotypic ichnofabric is formed by *Macaronichnus*, mainly in the sandy beds of the relatively mud-rich facies 2 and 3 (Text-Figs. 7, 16); it also occurs in facies 4. It is characterized by crowded and crossing-over *Macaronichnus* and totally or almost totally obliterates primary sedimentary structures. However, relict cross lamination is preserved in some beds. The cross cuttings of *Macaronichnus* can give the impression of branches, but they are false branches sensu D'ALESSANDRO & BROMLEY (1987). Locally, *Rosselia, Planolites*, and *Ophiomorpha* occur as constituents of the ichnofabric, and they cross-cut *Macaronichnus*.

Scolicia and *Bichordites monastiriensis* form ichnofabrics in some sandy horizons of facies 4. They obliterate primary sedimentary structures to different degrees, and in some horizons there is a total homogenization. The trace fossils are commonly poorly visible, especially *Bichordites*, which is commonly marked only by the central, heart-shaped core (Text-Fig. 11C).

Teichnichnus forms a monotypical ichnofabric in some silty or sandy marlstones of facies 1 and 2 (Text-Fig. 13). It totally, or almost totally, obliterates primary sedimentary structures in some one decimetre-thick horizons.

In some sections of the relatively low-energy facies (e.g., Vöcklabruck-Ager – locality 9, Text-Fig. 1), vertically or obliquely oriented, elongate nests of bivalve shell debris occur in totally bioturbated sediments (Text-Fig. 17). It is possible that they accumulated as fillings of large, open burrows, which were destroyed by subsequent burrowing.

The degree of bioturbation distinctly changes from high-energy to low-energy facies. In the high-energy facies, trace fossils are absent or extremely rare. Biogenic disturbances only occur in some mud drapes (Text-Fig. 18) and single structures of *Rosselia* can be observed in facies 5. Bioturbation increases towards the moderate- and low-energy facies. Commonly some beds are completely homogenized, lacking discrete trace fossils, while in other beds biogenic structures are still poorly visible. However, some of the completely bioturbated beds display recognizable trace fossils and characteristic ichnofabrics. This is especially true for the beds containing *Cylindrichnus*, and the echinoid trace fossils. Most sediments of the lower-energy facies are bioturbated. In the lowest-energy marly siltstone to mudstone of the Robulus Schlier, a special phenomenon can be observed: totally bioturbated beds, 5 to 15 cm thick, are intercalated with beds containing at least partially preserved, slightly wavy lamination.



Text-Fig. 17.
Nests of bivalve shells in thoroughly bioturbated sandy-muddy sediment of the Vöckla Schichten, Vöcklabruck-Ager.
Scale in cm.

6. Tiering

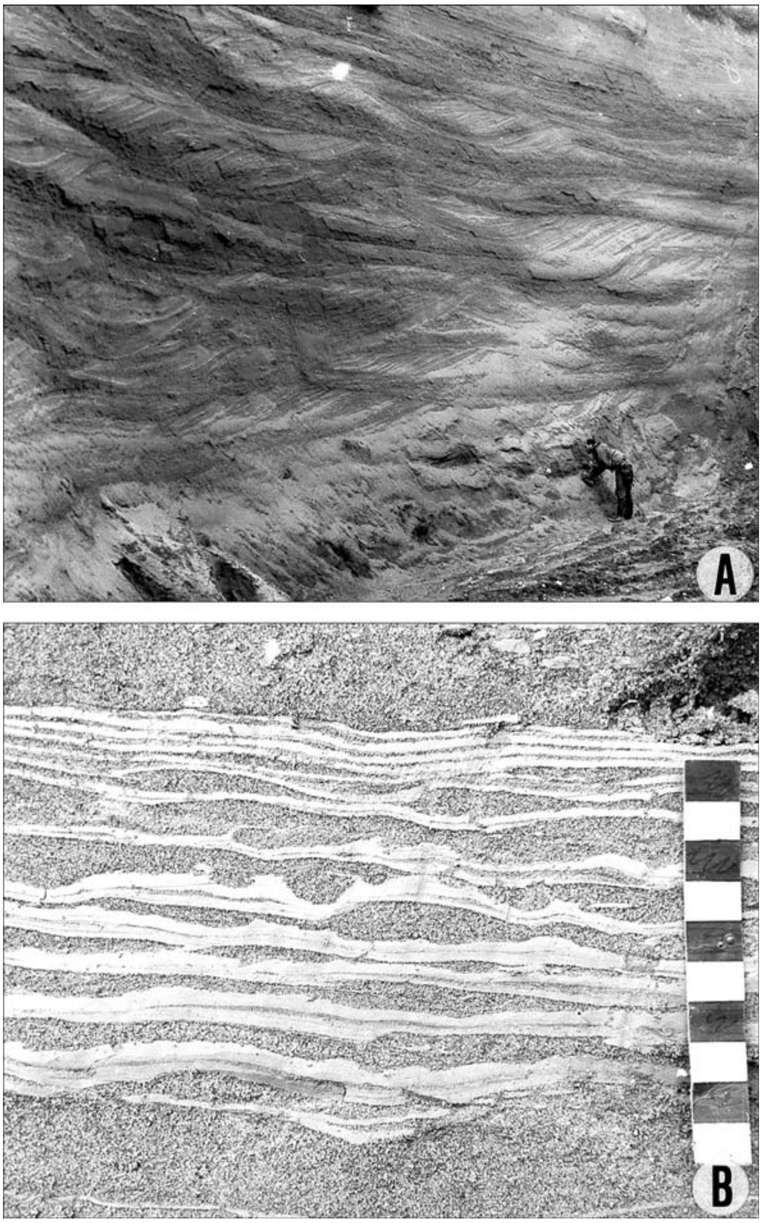
Spatial relationships of trace fossils can be studied in some beds, where the probability that they were primarily related is very high. For instance, at Winkl (locality 11, Text-Fig. 1), abundant *Cylindrichnus* occurs in the more muddy, upper part of beds above the more sandy part with abundant *Macaronichnus* (Text-Fig. 16). Locally, *Planolites ? beverleyensis* cross-cuts *Macaronichnus*. The structures within these beds are rarely cross-cut by *Rosselia* (Text-Fig. 19). At Ziegelwies (locality 8, Text-Fig. 8), some sandy beds homogenized by densely crowded *Macaronichnus* are cross-cut by *Ophiomorpha nodosa* (Text-Figs. 19–20). Cross-cutting relationships between the trace fossils are not common and not always clear. Nevertheless, the spatial relationships between the trace fossils can be expressed in simple spatial models (Text-Fig. 19). Probably, the spatial relationships resulted from primary tiering or community replacement.

In moderate-energy facies (Puchkirchen-Berg – locality 4, Text-Fig. 1), *Scolicia* isp. co-occurs with *Bichordites* and *Rosselia* in the same horizons. *Rosselia* there cross cuts *Scolicia* (Text-Fig. 19). In another case (Hinterschützing, locality 15, Text-Fig. 1), *Rosselia* is cross-cut by *Planolites* (Text-Fig. 10B).

7. Discussion

7.1. Comparison to the Classical Ichnofacies

The trace fossil assemblage of all facies as a whole most closely resembles the Cruziana ichnofacies, which occurs in poorly sorted, unconsolidated substrates of subtidal zones between fair-weather wave base and storm wave base (FREY & SEILACHER, 1980; FREY & PEMBERTON, 1985). However, FREY et al. (1990) and PEMBERTON et al. (1992b) noted that the Cruziana ichnofacies can also occur in tidal-



Text-Fig. 18.
High-energy facies of the Atzbacher Sande.
A) Sandwave facies with tidal bundles at the base, evenly laminated sands of the upper flow regime at the top, Ottnang-Fischer.
B) Biogenic disturbances in mud drapes from the lower part of the outcrop illustrated in A.
Scale in cm.

flat, lagoonal, or estuarine environments. The assemblages examined herein contain typical trace fossils of the Cruziana ichnofacies, such as *Teichichnus* (SEILACHER, 1967; PEMBERTON et al., 1992a, b), variably oriented *Ophiomorpha* and *Thalassinoides* (FREY & SEILACHER, 1980), *Rosselia*, and *Arenicolites* (FREY & PEMBERTON, 1985; PEMBERTON et al., 1992b). These trace fossils were produced by deposit feeders (e.g., *Teichichnus, Scolicia*) and suspension feeders (e.g., *Arenicolites, Skolithos, Rosselia* [?]). The presence of these two trophic groups characterizes the Cruziana ichnofacies (FREY & SEILACHER, 1980).

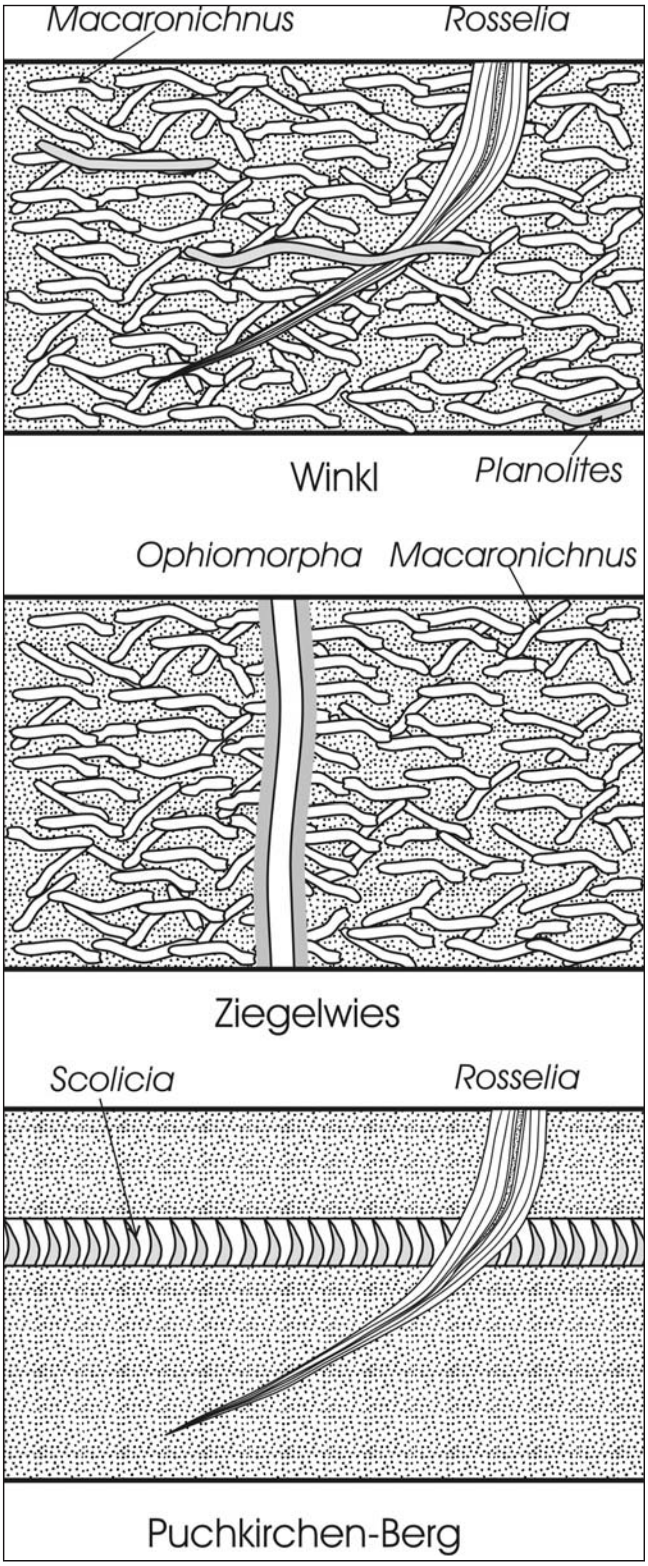
In contrast to the typical range of environments ascribed to the Cruziana ichnofacies, most facies in the study area are supposed to be deposited above the fair-weather wave base, with the exception of facies type 1 (Text-Fig. 15, Robulus Schlier). This interpretation is based mainly on the presence of typical shallow water sedimentary structures, which can be related to tidally driven currents. The Skolithos ichnofacies, dominated by vertical burrows of suspension feeders, is to be expected in such facies, but is very rare here. It occurs only at Bruck (locality 5, Text-Fig. 1), in cross-laminated sands of facies 4, where it is represented by *Rosselia* and *Skolithos*. This is a peculiar Skolithos ichnofacies, because *Rosselia* is commonly included in the Cruziana ichnofacies, and indeed it occurs presumably in this ichnofacies in the investigated deposits. Nevertheless, the vertical to oblique structure of *Rosselia* most probably was produced by suspension feeders (see discussion in Chapter 7.5). Thus, if *Rosselia* occurs together with *Skolithos* in cross-laminated sands, it can be regarded as a typical component of the *Skolithos* ichnofacies, which should be dominated by vertical trace fossils attributed to suspension feeders.

PEMBERTON et al. (2001) distinguished between a proximal, an archetypal and a distal Cruziana ichnofacies. The proximal Cruziana ichnofacies is typical of lower shoreface settings above the fair-weather wave base, the archetypal ichnofacies of the transition-upper offshore settings, and the distal Cruziana ichnofacies of the lower offshore settings. In the investigated deposits, the proximal Cruziana ichnofacies can be distinguished where in sands trace fossils related to suspension feeders (*Ophiomorpha, Rosselia*) occur together with forms related to deposit feeders (e.g., *Scolicia, Bichordites*), for instance at Puchkirchen-Berg (locality 4, Text-Fig. 1). Trace fossil assemblages from most remaining localities can be ascribed to the archetypal Cruziana ichnofacies. Trace fossils from the Silbersberg section (locality 20, Text-Fig. 1), where silty marls prevail, probably represent a transition from the archetypal to the distal Cruziana ichnofacies. Small grazing trace fossils (e.g., *Phycosiphon, Chondrites*), typical of the distal Cruziana ichnofacies, are not present, but *Teichichnus* could be their equivalent.

Trace fossils do not occur in the highest-energy facies, and there is no transition to the expected Skolithos ichnofacies. This can be explained by a wider range of the Cruziana ichnofacies towards the higher-energy facies and the resulting trophic-group amensalism (cf. RHOADS & YOUNG, 1970). Probably the deposit feeders that produced the Cruziana ichnofacies traces were more successful in the environment and eliminated smaller suspension feeders, maybe in periods of standstill. The small suspension feeders, which produce *Skolithos* and *Arenicolites*, were rarely successful in colonizing the sea-floor, and their burrows had little chance of being preserved after further burrowing of deposit feeders. Moreover, common deposition of muddy sediment, which can be easily resuspended, was unfavourable for colonization by suspension feeders. SAUNDERS & PEMBERTON (see MALE, 1992) were of the opinion that suspension feeders are absent in high-energy facies because of strong wave-induced stress.

7.2. Problem of Environmental Interpretation of *Macaronichnus*

Literature on the environmental interpretation of *Macaronichnus* is confusing. According to CLIFTON & THOMPSON (1978) this ichnotaxon



Text-Fig. 19.
Examples of cross-cutting relationships of trace fossils.

occurs in the foreshore zone. Similar data were presented by NARA (1994). According to PEMBERTON in MALE (1992, p. 47), *Macaronichnus* is common at high-energy shorelines and, according to SAUNDERS in MACEACHERN & PEMBERTON (1992, p. 66), it "appears to be more common near the upper shoreface-foreshore contact". CURRAN (1985) regarded *Macaronichnus* as typical of middle shoreface bars as does POLLARD et al. (1993), who suggested that subtidal bars or sand waves are the environments of *Macaronichnus*. MAPLES & SUTTNER (1990) placed it in an offshore environment. PEMBERTON et al. (2001) distinguishes the *Macaronichnus* assemblage in foreshore settings of moderate energy situations and in foreshore-middle shoreface settings of high-energy situations. They pointed out that the colonization window for *Macaronichnus* can occur in lower shoreface settings after storm deposition, when oxygenation of the sediment is increased. In the deposits examined herein, *Macaronichnus* occurs within moderate to relatively low-energy facies and even exists in thin sandstone beds of mud-dominated sections. It is not excluded that these beds are related to storm events.

7.3. Comparison to Other Trace Fossil Assemblages

A comparison of the molasse trace fossil assemblages to the classical ichnofacies is insufficient for the description of the changes we observed: all assemblages are grouped in a single ichnofacies (except for the Skolithos ichnofacies at Bruck; locality 5, Text-Fig. 1). A few authors have considered shallow-water trace fossils in relation to energy-level/bathymetry trends in more detail, but only some of the proposed models can be related to the analysed deposits. In the model of FÜRSICH (1975) for the Corallian of England, *Teichichnus* co-occurs with *Cylindrichnus concentricus, Thalassinoides* and *Planolites* in an intermediate situation between intertidal and offshore-subtidal environments. These are argillaceous or silty calcareous muds or sands of low-energy subtidal environments, or protected lagoons with a relatively stable substrate. This ichnoassemblage corresponds to our low-energy facies. The intermediate position of *Teichichnus* co-occurring with *C. concentricus* is also noted in the Upper Jurassic siliciclastic-carbonate deposits of Portugal (FÜRSICH, 1981). Despite these similarities, in both cases described by FÜRSICH, the typical Skolithos ichnofacies occurs in the higher-energy facies. MARTIN & POLLARD (1996) interpreted silty to fine grained sandstones from the Jurassic of the North Sea containing large *Teichichnus* as deposits of the lower shoreface to offshore zone. POLLARD et al. (1993) studied shallow-water occurrences of *Ophiomorpha* in Jurassic and Eocene deposits of NW Europe. They recognized *Macaronichnus-Ophiomorpha* ichnofabrics, which resemble ichnofabrics from the Atzbacher Sande in Ziegelwies (Text-Figs. 19–20) and Offenhausen (Text-Fig. 8), and related these to subtidal sand wave facies.

HOWARD & FREY (1984), FREY & HOWARD (1982, 1985, 1990), FREY (1990), and MACEACHERN & PEMBERTON (1992) studied trace fossil distributions in different Upper Cretaceous shallow water, storm-influenced, siliciclastic deposits of the Western Interior Seaway in North America. They recognized that *Teichichnus, R. socialis*, and *C. concentricus* occur mainly in the middle shoreface to upper offshore facies. However, sections in which the nearshore, high-energy facies are preserved were only rarely and incompletely studied (MACEACHERN & PEMBERTON, 1992). Therefore, a more detailed comparison with the molasse facies is impossible. Moreover, *Schaubcylindrichnus* and *"Terebellina"*, which do not occur in the studied deposits, are present in the Cretaceous of North America. A very similar pattern of trace fossil distribution is provided by PEMBERTON et al. (2001) on the basis of Cretaceous deposits on the Atlantic shelf of Canada. They related *Rosselia* mostly to the lower shoreface, *Scolicia* to lower shoreface and deeper settings, and *Teichichnus* and *Thalassinoides* to lower shoreface-offshore settings.

According to GOLDRING (1996), *Cylindrichnus* occurs in middle to lower shoreface ichnofabrics in the Jurasssic of the North Sea. In the studied molasse deposits, *Cylindrichnus* has a wider facies range up to offshore sediments of facies 1, like in the Cretaceous of North America.

Text-Fig. 20.
Ophiomorpha nodosa Lundgren (large spots and elongate forms) cross-cut *Macaronichnus segregatis* Clifton & Thompson (very small forms in background).
Atzbacher Sande, Ziegelwies.
Field photograph. Scale in cm.

Other models (e.g., Farrow, 1966; Schlirf, 2003) do not correspond to the examined trace fossil distribution.

The molasse trace fossil assemblages do not display significant similarities to Lebensspuren assemblages of modern tidal flat and coastal environments. The latter were studied at different geographical settings, for instance by Reineck et al. (1967, 1968), Hertweck (1972, 1973, 1994), Howard & Dörjes (1972), Frey et al. (1987, 1989a, b), and Cadée et al. (1994). The lack of *Rosselia* in these recent environments is striking.

7.4. Influence of Sedimentation Rates

The influence of sedimentation rates on trace fossil assemblages in our molasse deposits is a matter of speculation. A rough estimation of the sedimentation rate is only possible for the complete sediment pile of the Lower Ottnangian (Text-Fig. 2), and this gives a value of about 1 mm per year. This, of course, only provides an impression of the long-term depositional rate, which strongly differs from the short-term instantaneous sedimentation rate associated with certain facies, owing to the unestimateable influx of erosive events. But only the instantaneous sedimentation rate is relevant for the development of the ichnofauna. For example, in places of active sand wave migration it surely was high, but could drop to nearly zero when migration ceased. The only example of more or less continuous sedimentation is within facies type 1 (Text-Fig. 15) of the Robulus Schlier, where fluctuations of the sediment input rate might be responsible for the inter-bedding of thoroughly bioturbated, muddy beds with nearly undisturbed laminated beds of the same material.

7.5. Colonization and Response to Substrate

The ability of each tracemaker to colonize the substrate was different. The *Rosselia* tracemaker was successful in a wide range of facies. It is possible that its long, relatively thick, onion-skin-like muddy structure worked as an anchor in those environments where erosive events were common. The structure is also suited to protect the organism from burrowing of deposit feeders. The trophic strategy of *Rosselia* was seemingly independent of the substrate; it occurs within high- to low-energy facies, in nearly pure sandy as well as muddy substrates, and was able to penetrate through a few sedimentary cycles composed of sand and mud, in the same degree as *Ophiomorpha nodosa* (Text-Figs. 8–10). This substrate independence, we believe, suggests suspension-feeding activity. In the Upper Cretaceous shelf sediments of North America, *Rosselia* is almost independent of storm intensity, which strongly influences the occurrence of other trace fossils (MacEachern & Pemberton, 1992). *Cylindrichnus* makers reworked only heterolithic beds, whereas *Macaronichnus* makers reworked only sandy beds. *Bichordites* and *Scolicia* isp. colonized only sandy substrates. Generally, the sandy substrates were more attractive to burrowers, whereas mud drapes and flaser beds are generally less bioturbated having been avoided by most burrowers. Analogically, a decrease in the bioturbation of estuarine muds in comparison to sands was noted by Howard & Frey (1973).

Tiering (Text-Fig. 19) is not well developed. This may be due to rapid environment fluctuations, which caused an opportunistic r-selected style of colonization (e.g., *Cylindrichnus* and *Macaronichnus*). The r-selected style of colonization (Ekdale, 1985; Vossler & Pemberton, 1988) is probably caused by unstable substrate, changes of energy level, temperature, and salinity, all of which are connected with the tidal regime (cf. Ekdale et al., 1984). Also a relatively high and fluctuating sedimentation rate and the common change of substrate (from sand to mud) and probably food content might be responsible for the abundance of r-strategists.

8. Microfossil Assemblages

Foraminifera recovered from pelitic beds of facies 1–5 and investigated by Ch. Rupp (Geol. Survey of Austria) are of considerable interest. Unlike typical shallow marine foraminiferal assemblages these faunas are composed of high amounts of planktonic foraminifera (plankton associations of rather high diversity, juvenile and adult tests, up to more than 70 % of planktonic foraminifera within the fraction >125 m).

The Robulus Schlier (e.g. Hartberg – locality 21, Text-Fig. 1) yields high percentages of benthic genera from the deep shelf, e. g. *Lenticulina, Charltonina*, and in many samples considerable amounts of *Melonis pompilioides* (F. & M.), a constituent of deep neritic to middle bathyal foraminiferal assemblages.

Within the Vöckla Schichten (e.g. Timelkam – locality 6, Fig. 1) and the Atzbacher Sande (e.g. Puchkirchen-Berg – locality 4, Humplberg – locality 18, Fig. 1) these benthic genera decrease in numbers, but are still present in low percentages (<1 % to >7 % each genus) within the fraction >125 m. Counts based on this fraction show associations dominated by *Cibicidoides* and shallow water elements like *Ammonia, Elphidium* or *Nonion*. Size ranges and preservation of many of these shallow water elements suggest transport. Counts of the same samples, based on the fraction >250 m, which excludes most of the tests transported in suspension (Murray, 1991), are dominated by deeper water elements like *Melonis* or *Lenticulina* (>10%) and yield considerable smaller numbers of shallow water foraminifera. These data indicate transport of small, shallow water benthonic foraminifera into deeper marine (?deep neritic) depositional environments. A micropalaeontological investigation concerning Lower Miocene foraminiferal faunas from the geological units discussed here also gives evidence, that these sediments were deposited in a cool, deep neritic environment (Rupp & Haunold-Jenke, 2003).

However, palaeontological data are too scarce yet, to draw precise conclusions. The discrepancy between the micropalaeontological data and the sedimentological-ichnological approach cannot be successfully explained at this stage of the research.

9. Conclusions

1) The examined trace fossil assemblage from the Ottnangian molasse deposits is most similar to the Cruziana ichnofacies, with forms produced by both suspension and deposit feeders. *Cylindrichnus, Macaronichnus,* and *Rosselia* are the most characteristic trace fossils of the assemblage.
2) The representation of the Skolithos ichnofacies, expected towards the high-energy facies, does not occur, except one locality with sediments of the moderate-energy facies. This may reflect trophic group amensalism or poor preservation.
3) There are few similarities of the molasse ichnofacies to other fossil examples, and there are no similarities with Lebensspuren assemblages of modern tidal flats.
4) The distribution of trace fossils depends on the substrate and changes of the energy-level within the environment. *Cylindrichnus* and *Macaronichnus* depend on the substrate; the first form is restricted to sandy muds, the latter form to sands. *Rosselia* is largely independent of the substrate and environmental energy level. *Teichichnus* and *Thalassinoides* are connected with the lower energy facies.
5) Recovered microfossil assemblages (foraminifera) do not correlate with the shallow-subtidal facies concept of the middle- and higher-energy facies as interpreted from the sedimentological-ichnological point of view.

Appendix

Coordinate-pairs of outcrops mentioned in the text using the system of the Austrian "Bundesmeldenetz" on map-sheets no. 47 Ried, no. 48 Vöcklabruck, and no. 49 Wels of the "Österreichische Karte 1:50.000", Bundesamt für Eich- und Vermessungswesen, Krotenthallergasse 3, A 1080 Wien.

1	Gries	47	462750 / 320000
2	Dachschwendau	47	465500 / 321150
3	Oberthumberg	47	467225 / 320900
4	Puchkirchen-Berg	47	467500 / 322750
5	Bruck	47	468500 / 326100
6	Timelkam	48	470730 / 318600
7	Eiding	48	471260 / 319100
8	Ziegelwies	48	475500 / 320510
9	Vöcklabruck-Ager	48	475860 / 318100
10	Attnang	48	478815 / 320210
11	Winkl	48	481000 / 323880
12	Ottnang-Fischer	48	474740 / 328500
13	Oberepfenhofen	48	477580 / 331970
14	Kasberg	48	480680 / 327810
15	Hinterschützing	48	483750 / 327500
16	Offenhausen	49	487420 / 334820
17	Burgstall	49	489200 / 336500
18	Humpelberg	49	489925 / 334300
19	Holzing	49	491440 / 333550
20	Silbersberg	49	491390 / 340300
21	Hartberg	49	499140 / 344170

Acknowledgements

We thank three anonymous referees for improvements of the manuscript. P. Radzicki carried out part of the photographic work. J. Ruthner and M. Brüggemann-Ledolter prepared the profil-images and the geological map. Ch. Rupp did the micropalaeontologic research.

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Manuskript bei der Schriftleitung eingelangt am 8. März 2004

Zeitschrift/Journal: Jahrbuch der Geologischen Bundesanstalt

Jahr/Year: 2004

Band/Volume: 144

Autor(en)/Author(s): Uchman Alfred, Krenmayr Hans Georg

Artikel/Article: Trace Fossils, Ichnofabrics and Sedimentary Facies in the Shallow Marine Lower Miocene Molasse of Upper Austria 233-251