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ICHNOFOSSILS FROM THE TYPE AREA OF THE GRUND FORMATION (MIOCENE, LOWER BADENIAN) IN NORTHERN LOWER AUSTRIA (MOLASSE BASIN)

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Abstract: The trace fossils *Arenicolites*, *Asterosoma*, *Diplocraterion*, *Zoophycos*, *Ophiomorpha*, *Saronichnus*, *Scolicia* and *Thalassinoides* have been recognized in the siliciclastics of the Grund Formation. Their occurrence and distribution is related to storm deposition. In proximal storm deposits, only monospecific *Asterosoma* occurs. It is typical of the transition between the *Skolithos* and the proximal *Cruziana* ichnofacies. A more diverse trace fossil association of the proximal and archetypical *Cruziana* ichnofacies occurs in more distal storm deposits. The vertical structures (*Arenicolites*, *Diplocraterion*, *Ophiomorpha*) are related to opportunistic colonization of the storm beds (post-event community). The horizontal forms (*Scolicia*, *Thalassinoides*) represent fair weather conditions. The chemosymbiotic structures (*Saronichnus*, *Zoophycos*) are a record of trophic competition that pressures trace makers to deeper and more complex feeding than simple deposit feeding. The horizontal and chemosymbiotic trace fossils represent the resident community. The development from the *Skolithos* via the proximal *Cruziana* ichnofacies to the proximal–archetypical *Cruziana* ichnofacies indicates a deepening from the middle shoreface to upper offshore environments.

Key words: Miocene, Austria, chemosymbiotic structures, molasse, storm deposits, trace fossils.

Introduction

Trace fossils from the North Alpine Molasse Basin are potentially a good source of information about benthic infaunal life, paleoenvironmental parameters, and sequence stratigraphy. Unfortunately, they are underrepresented in the literature (but see e.g. Ehrenberg 1938, 1944; Hohenegger & Pervesler 1985; Uchman & Krenmayr 1995, for the Austrian molasse). An interesting trace fossil assemblage has been discovered in the lower Middle Miocene (Lower Badenian) Grund Formation (Pervesler & Zuschin 2002; Pervesler & Roetzel 2002). It was studied during two excavation campaigns in 1998 and 1999 at the type locality of this formation (former "Grunder Schichten"). Several deep trenches were excavated in the farmland between the villages of Grund and Guntersdorf, north of Hollabrunn in Northern Lower Austria (compare Roetzel & Pervesler 2003). Trace fossils were found in the sections B2, C, D, E, F, G and H (Fig. 1). Their description and interpretation is the main aim of this paper.

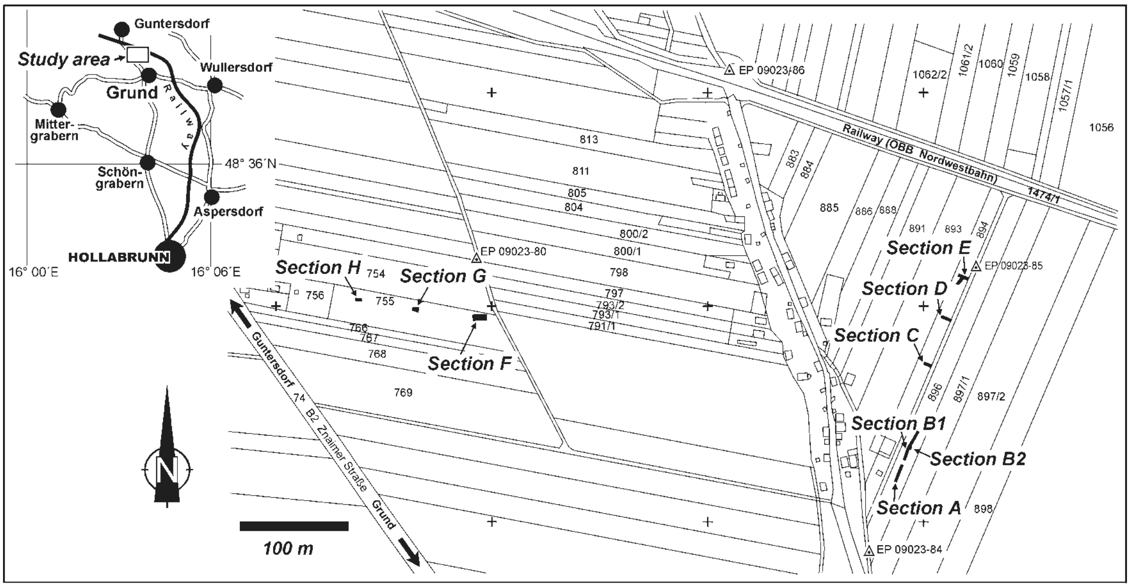

Fig. 1. Location map. Sections A, B1, B2, C, D, E were excavated in 1998, and sections F, G and H in 1999.

The sediment containing the trace fossils was carefully removed using a jet of compressed air (Fig. 2). A pistol-shaped valve helped to control the direction and volume of the airflow (Fig. 2). This method, mainly developed for uncemented sands, allowed even very delicate structures to be excavated and observed in three dimensions. For further studies in the laboratory, the trace fossils were collected together with the host sediment using boxes made of plastic or wood, whereby the samples were held in position fixed by polyurethane foam.

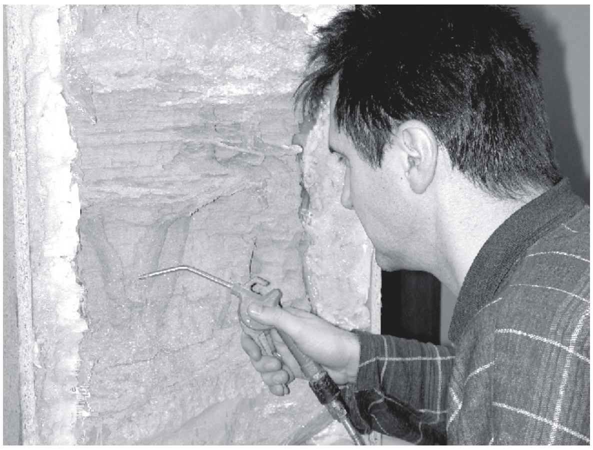

Fig. 2. Sediment was carefully removed with an air jet. The pistol-shaped valve helped to control the direction and volume of the airflow.

Systematic ichnology

Scolicia group

Scolicia De Quatrefages, 1849
Scolicia isp.
Fig. 3.1

Material: 2 field photographs.

Location: Grund, excavation 1999, section F, 247.6 m above sea level.

Host sediment: Silt.

Description: Subcylindrical, slightly winding horizontal structures with meniscate backfilling, 60–70 mm wide. Horizontal sections of this trace fossil visible on erosion surfaces, about 30 mm wide, resemble *Laminites* Ghent et Henderson, which was included in *Scolicia* (Uchman 1995; Uchman & Krenmayr 1995). *Scolicia* is a fossil burrow produced by irregular echinoids (e.g. Bromley & Asgaard 1975; Smith & Crimes 1983).

U-shaped forms

Arenicolites Salter, 1857
Arenicolites isp.
Fig. 3.2

Material: 8 field photographs.

Location: Grund, excavation 1999, section G, 248.1 m above sea level.

Host sediment: Fine- to medium-grained sand.

Description: Simple U-shaped cylindrical structures without spreiten. Diameters of the cylinders attain about 3.5 mm (Fig. 3.2), but decrease towards the upper terminations. Limbs of the U-structure are about 30 mm apart. Some limbs are inclined outward (Fig. 3.2) and give the impression of a J-shaped structure. Large specimens attain diameters of 14 mm with their limbs about 80 mm apart (Fig. 3.3). *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 (Crimes 1977). For discussion of this ichnogenus see Fillion & Pickerill (1990) and Ekdale & Lewis (1991).

Diplocraterion Torell, 1870
Diplocraterion isp.
Fig. 3.4–5

Material: 5 field photographs, 3 thin sections (microscope slides).

Locations: Grund, excavation 1998, section E, 245.3 m above sea level.

Host sediment: Fine- to medium-grained sand.

Description: U-shaped retrusive spreiten-structures, 50–130 mm long, with diverging outwardly inclined limbs. The tops of the limbs are 70 to 100 mm apart. Up to 13 spreiten laminae per structure were counted. Some limbs display funnel-shaped entrances (Fig. 3.4). The shallowly inclined limbs are features of *Diplocraterion parallelum* var. *arcum* Ekdale et Lewis, 1991 (compare Fürsich 1974; Corner & Fjalstad 1993).

Diplocraterion is a typical component of the *Skolithos* ichnofacies, and occurs commonly in very shallow subtidal to intertidal facies (e.g. Fürsich 1974, 1981). In the Jurassic at least, this trace fossil also characterizes transgressive surfaces (e.g. Mason & Christie 1986; Dam 1990; Taylor & Gawthorpe 1993; Goldring et al. 1998). Horizons with abundant *D. parallelum* in the Upper Jurassic of Spain have been used by Olóriz & Rodríguez-Tovar (2000) to recognize more energetic and physically unstable environments (a transition from the *Cruziana* ichnofacies to the mixed *Cruziana–Skolithos* ichnofacies) in relation to sea level fall, and used to delineate sequence boundaries. *Diplocraterion* is also common in event beds, where it documents the opportunistic post-event colonization (Frey & Goldring 1992).

Ophiomorpha group

Ophiomorpha Lundgren, 1891
Ophiomorpha nodosa Lundgren, 1891
Fig. 3.8

Material: 16 field photographs, 12 tunnel-fragments.

Location: Grund, excavation 1999, section G, 248.1 m above sea level.

Host sediment: Medium-grained sand.

Description: Boxwork of long, slightly inclining tunnels and short, steeper shafts. Branching shows a 120° pattern.

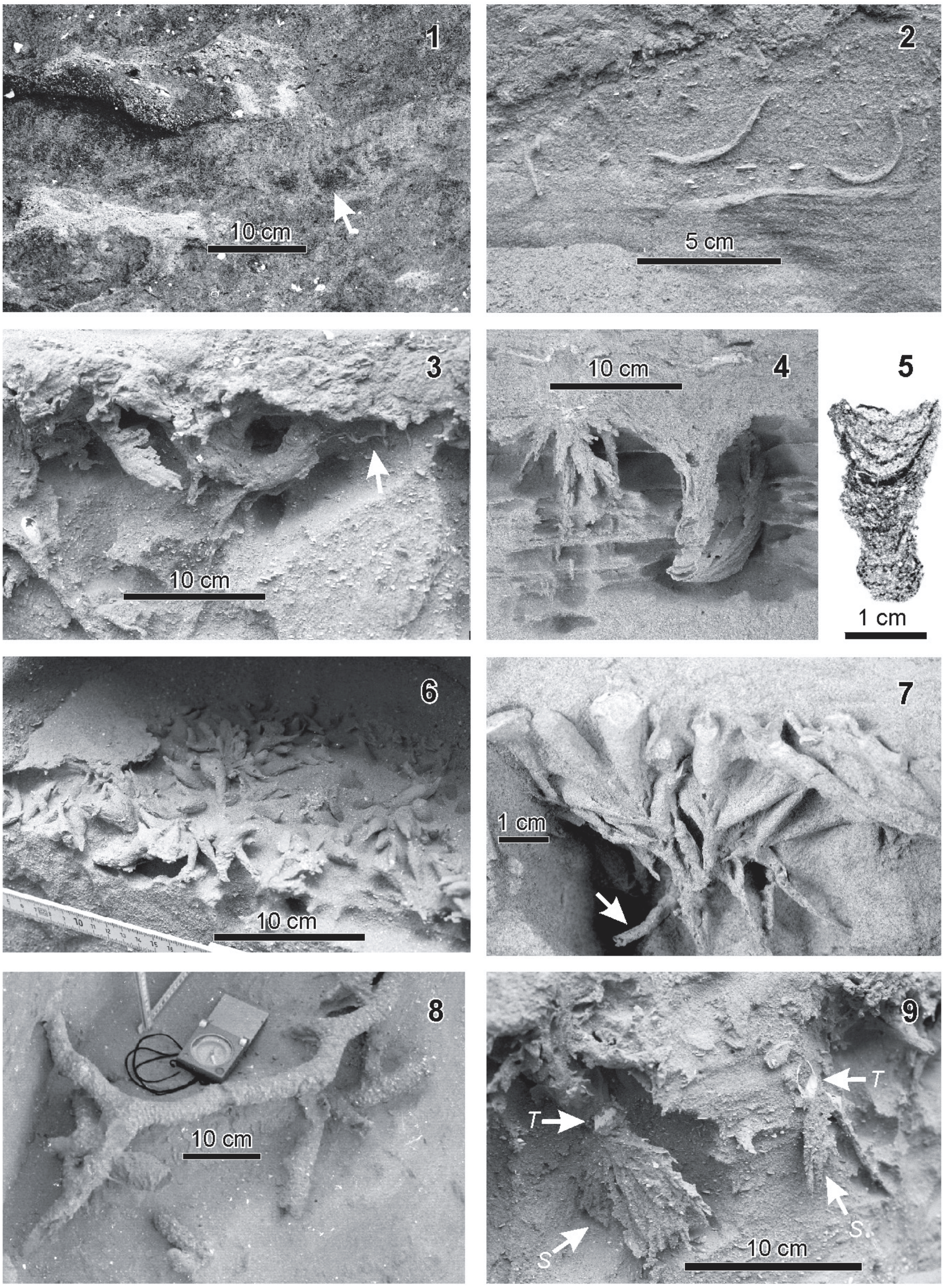

Fig. 3. Trace fossils from the type area of the Grund Formation. **1** — Oblique view of *Scolicia* isp. at the top of a pelitic layer. Excavation 1999, section F, 247.6 m above sea level. **2** — *Arenicolites* isp. in fine- to medium-grained sands. Excavation 1999, section G. **3** — *Arenicolites* isp. and irregularly winding tubes (arrow) that enter the coarser layers below. Excavation 1999, section G, 248.1 m above sea level. **4** — *Saronichnus abeli* (left side) and *Diplocraterion* isp. (right side; only a half of the trace fossil is visible). *Diplocraterion* isp. shows funnel-shaped burrow openings with a horizontal shift of the limbs. Excavation 1998, section E. **5** — Thin section (small magnitude picture) of *Diplocraterion* isp. from the deepest part of the U-shaped burrow. Excavation 1998, section E. **6** — Oblique view of *Asterosoma radiciforme*. Excavation 1998, section C, 239.8 m above sea level. The bulb-shaped trace fossils show tiny shaft-like connections to the pelitic layer representing the former sea floor. **7** — Lateral view of *Asterosoma radiciforme* in a fining upward sequence, from a fine-grained sand at the base to a silt at the top. Intervening tunnels (arrow) connect different generations of *Asterosoma.* Excavation 1999, section G, 247.5 m above sea level. **8** — Boxwork of the *Ophiomorpha nodosa* in medium-grained sand with shell fragments. Excavation 1999, section G, 248.1 m above sea level. **9** — Two specimens of *Saronichnus abeli* (S) associated with their producer, the chemosymbiotic bivalve *Thyasira michelottii* (T).

Slight swellings occur at the branching points. The exterior of the tunnel walls is generally lined with sandy granules. The interior is smooth; the bottom surface of some horizontal and inclined tunnels is unlined. The wall is 3 to 9.4 mm thick. Cross-sections of the compressed horizontal tunnels are up to 37 mm wide and up to 31 mm high. The vertical extension of this trace fossil measures up to 40 cm.

Ophiomorpha nodosa is one of the most common shallow-marine trace fossils and is produced mostly by callianassid 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).

Thalassinoides Ehrenberg, 1944
Thalassinoides suevicus (Rieth, 1932)
Fig. 4

Material: 7 field photographs.

Location: Grund, excavation 1999, section F, 247.6 m above sea level.

Host sediment: Silt.

Description: System of shallowly inclined tunnels and steep shafts, which are about 20 mm in diameter. There are chamber-like swellings around the branching points, up to 35 mm wide, resembling turning chambers of recent crustaceans (see Bromley 1996 for review). This trace fossil was constructed in a semi-consolidated mud and later truncated by erosion. The burrow wall is smooth. The vertical extension measures 15 cm. *Thalassinoides* was produced by crustaceans, mostly decapods (Frey et al. 1984). For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992) and Schlirf (2000).

Fig. 4. Erosion surface truncates a *Thalassinoides* burrow system formed in a silty mud. Grund, excavation 1999, section F, 247.6 m above sea level.

Asterosoma group

Asterosoma von Otto, 1854
Asterosoma radiciforme von Otto, 1854
Fig. 3.6–7

Material: One box sample, 36×26 cm wide and 25 cm high, with numerous specimens in four horizons, 11 field photographs.

Location: Grund, excavation 1998, sections C, D; excavation 1999, sections F, G, H, 239.8–249.2 m above sea level.

Host sediment: Fine- to medium-grained sand capped by pelites.

Description: Vertical to inclined elongated bulbs, up to 14 mm wide and up to 25 mm long, tapering at both ends, with concentric internal lamination. Clusters of such bulbs form tree-like structures, up to 10 cm wide, spreading out from a common vertical or inclined shaft that is 3–4 mm in diameter. The main portions of the clusters are located in the sands directly below the overlying pelitic layers. Steep shafts connect the clusters from subsequent sedimentary sand-pelite cycles. *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 group

Saronichnus Pervesler et Zuschin, 2004
Saronichnus abeli Pervesler et Zuschin, 2004
Fig. 3.4, 9

Material: 14 field photographs, type specimens: Holotype IPUW No. 2004-0001-0001, paratype IPUW No. 2004-0001-0002.

Location: Grund, excavation 1999, section E, G, H, 244–249.5 m above sea level.

Host sediment: Medium- to fine-grained sand covered with pelites.

Description: Bundles of vertical to steeply inclined, simple, blade- or club-shaped probes, up to 100 mm long and about 3 mm wide. They spread downwards below the life position of the chemosymbiotic bivalve *Thyasira michelottii* (R. Hörnes, 1875) (compare Pervesler & Zuschin 2004). The bundles resemble a downward-oriented fan or a broom.

The probes, produced by the bivalve foot, are thought to be wells for sulphides for the use of chemosymbiotic bacteria (Zuschin et al. 2001; Pervesler & Zuschin 2004).

The trace fossil is similar to *Pragichnus fascis* Chlupáč (1987) known from the Ordovician of Bohemia, which however, displays rather only club-shaped probes, which are actively back-filled and branched, especially in distal (lower) part where dichotomous branches occur. This trace fossil was also interpreted as sulphide wells produced by an animal using chemosymbiotic bacteria (Mikuláš 1997).

Zoophycos group

Zoophycos Massalongo, 1856
Zoophycos isp.
Fig. 5.1–7

Material: 19 field and 8 laboratory photographs, one box sample, 40×50 centimeters wide and 70 centimeters high, with two specimens (section E), fragments from a further specimen (section G).

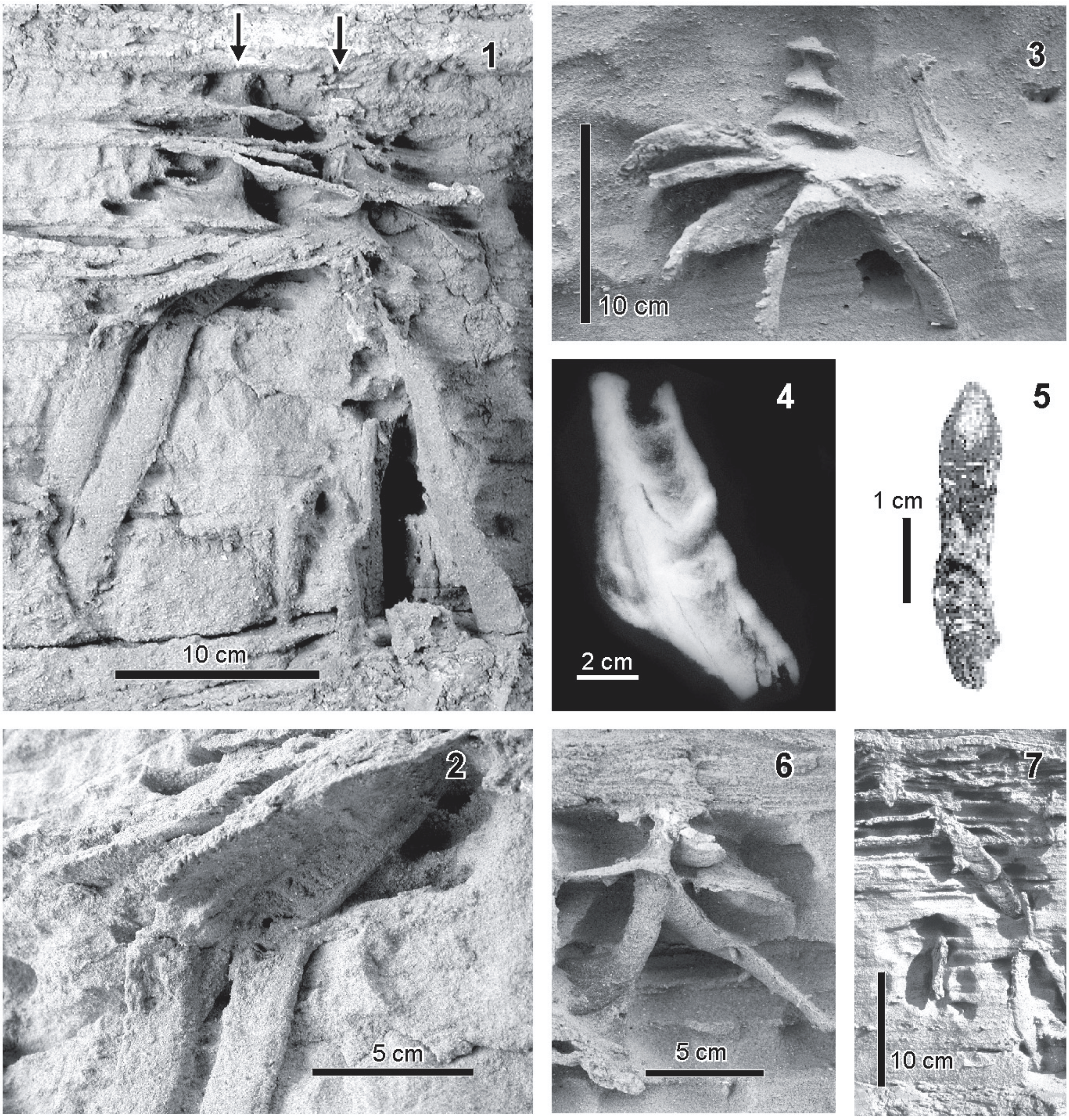

Fig. 5. *Zoophycos* isp. from the type area of the Grund Formation. Photographs 1, 2, 5, 6 and 7 from excavation 1998, section E. Photographs 3 and 4 from excavation 1999, section G. **1** — Two interfingering specimens of *Zoophycos* isp. Arrows indicate their upper terminations. **2** — Transitional area between the planar structure and the *Rhizocorallium*-like steep lobes. Detail of 1. **3** — Single *Zoophycos* isp. consisting of the helical part with 3 whorls passing into the planar spreite structures and lobes. Most of the structures were destroyed during excavation. **4** — Fragment of a single lobe illustrated in 3. X-ray image. **5** — Cross-section of a single lobe showing the passively filled marginal tube (at the top) and actively backfilled tube (at the bottom). **6** — A specimen with shallowly inclined lobes. **7** — Steep, twisted lobes in the lower part of *Zoophycos* isp.

Location: Grund, excavation 1998, section E, 245.5 m above sea level (Fig. 5.1,2,5–7); excavation 1999, section G, 247.4 m above sea level (Fig. 5.3–4).

Host sediment: Fine- to medium-grained sand.

Description: Planar helical spreite structures transitioning in the lower part into numerous *Rhizocorallium*-like long lobes (Fig. 5.1,3). The whole trace fossil is up to 350 mm high. The upper helical part forms three to five whorls, which are subcircular in outline (Fig. 5.3), showing clockwise or anti-clockwise development; they are inclined downward at the angle of 10 to 30° and penetrate 60 to 100 mm into the sediment. The diameter of the whorls increases downward.

The uppermost whorls are about 20 mm, and the deepest at least 100 mm in diameter. The helical part develops into larger, planar, one- or two- spreite structures, which are at least 250 mm wide and are inclined up to 30°. In the distal part they can be horizontal or even slightly ascending. Locally, the *Rhizocorallium*-like lobes (Fig. 5.4), surrounded partly by a marginal tube, start from the margin of the deepest planar structures. Exceptionally, lobes can develop directly from the axial part of the helical portion. They show more or less equal inclination within the same lobe, or slight steepening from about 30° in the proximal part to about 40° in the distal part. The lobes developing from the planar structures overlap in their proximally. The marginal tubes of the older lobes give the impression of "rays with pinnulae on one side only" as described by Girotti (1970). Proximally, the lobes are inclined about 30°. Distally, they steepen rapidly steepening to a vertical *Diplocraterion*-like position (Fig. 5.1–3). The lobes are twisted according to the general development of the burrow system. They are up to 250 mm long and about 20 mm wide. The steep part is up to 200 mm long. Their marginal tube always displays a passive filling from one side and active backfilling from the other side of the lobe (Fig. 5.5). This indicates a J-shaped causative burrow, whose shifting resulted in formation of the lobe structures. Interestingly some of the passively filled marginal tubes display sandy or carbonate linings, in which the sand is brownish and darker than the surrounding sediment (Fig. 5), similar to oxygenated shafts of recent burrows. Occasionally, the lobes interpenetrate (Fig. 5.2). In one case, the vertical lobes terminate at a silty layer (Fig. 5.1). Their lowest part deviates from the vertical position and develops along the layer over a distance of several millimeters.

The U-shaped lobes can be considered to be a product of J-shaped causative burrows. They correspond to the U-burrow model proposed for *Zoophycos sensu lato* by Ekdale et Lewis (1991) and discussed later by Uchman et Demírcan (1999). The described trace fossil displays general similarity to *Zoophycos rhodensis* described by Bromley et Hanken (2003), but the latter is much larger and shows phobotaxis of the lobes. The upper, helical part of *Z. rhodensis* Bromley et Hanken (2003) ("skirt-like zone") was interpreted as a deposit-feeding structure, and the lobes as sulphide wells for chemosymbiotic bacteria. This interpretation can be generally accepted for *Zoophycos* isp. from the Grund Formation. The steep and deep lobes were probably produced in anoxic sediment. The spreite laminae in the lobes can be produced when the trace maker exploited the sediment to obtain the bacteria.

The *Zoophycos* trace maker is thought to have migrated to deeper environments during the Jurassic (Bottjer et al. 1988; Olivero 2003). In Upper Quaternary sediments, *Zoophycos* occurs at depths below 1000 m (Löwemark & Schäfer 2003). Thus, the described *Zoophycos* is one of the shallowest (upper offshore–lower shoreface; see discussion) occurrences of this ichnogenus after the Jurassic. Pemberton et al. (2001) mentioned the occurrence of this ichnogenus at similar depths in the Cretaceous. These depths probably delineate the upper bathymetric range of this trace fossil. The small size of the described *Zoophycos* may be related to stress close to the border of its environmental range.

Discussion

The sections at the type locality of the Grund Formation show sediments from a shallow marine, highly erosive environment with small channels (compare Roetzel & Pervesler 2004). The channels, maximally 7–8 m wide and 0.5–1 m deep, always have a sharp erosive base. Their fill with densely packed bioclast-supported shell layers at the base, fining upward cycles of coarse- to fine-grained sands, and thin pelitic layers on the top, indicate periodically high-energy events with rapidly decreasing energy level.

In the lower part of the sequence (sections A, B), sandy beds, 60 to 120 cm thick, contain up to 40 cm thick layers of pelitic clasts, showing strong physical reworking. Moreover, they contain a mixed allochthonous fauna of marine molluscs, terrestrial gastropods and bones of different vertebrates (turtles, whales, rhinoceroses, small carnivores and micro-mammals). These deposits are distinguished as lithofacies A (Roetzel & Pervesler 2004).

Towards the top of the sequence, the thickness and grain size of these beds decrease. In the middle part of the sequence, in the sections C and D, 20 to 45 cm thick medium- to fine-grained sand beds show even lamination. Current ripples and plant debris at the top of some beds, together with the fining of grain size, indicate reduced current velocity. Pelitic layers several centimeters thick commonly cover the laminated sands. Intense but monospecific bioturbation (*Asterosoma*) starts from these layers but only reaches down maximally 3 cm into the sandy layers. The sand bodies display mostly tabular, locally slightly wedge-shaped geometry. They are cut by sparse, small and narrow runnels, 60 to 80 cm wide and 10 to 25 cm deep, with erosive base and filled with pelitic clasts. These deposits are distinguished as lithofacies B (Roetzel & Pervesler 2004).

The uppermost part of the studied section (sections E, F, G, H) also contains evenly laminated, medium- to fine-grained sands with graded bedding, but the thickness of the pelitic layers increases towards the top of the sequence. These pelitic layers 10 to 20 cm thick contain a diverse trace fossil assemblage starting from the pelitic horizons and penetrating down into the coarser fine- to medium-grained sands. The erosive deposition of coarse material stopped the work of the burrowers. *Arenicolites, Diplocraterion, Zoophycos* and *Ophiomorpha* are common in these sediments. Thicker pelitic layers contain rare *Scolicia* and *Thalassinoides*. The chemosymbiotic bivalve *Thyasira michelottii* (R. Hörnes, 1875) occurs as an exclusively autochthonous inhabitant of these layers. Some of the *Thyasira*-shells are associated with *Saronichnus*. These deposits are distinguished as lithofacies C (Roetzel & Pervesler 2004).

The trace fossil assemblage and its distribution can be interpreted by means of the model related to the hydrodynamic level that was elaborated on the basis of long-term studies of the North American Cretaceous Seaway and summarized by Pemberton et al. (2001).

The basal sections of the sequence (lithofacies B) show the highest but mostly monospecific biological disturbance. Only opportunistic organisms that are able to colonize mobile sediment (trace makers of *Asterosoma*) can settle during short periods of quiet conditions. This is a typical situation for the middle shoreface settings in the transitional zone between the *Skolithos* and the proximal *Cruziana* ichnofacies (Pemberton et al. 2001: p. 121).

During deposition of the lithofacies C, longer periods of benthic recovery after physical disturbances lead to greater burrowing depth and higher trace fossil diversity. Deposit feeding and chemosymbiotic strategies are characteristic features of the uppermost parts of the excavated sections of the Grund Formation. The lateral and vertical change of the hydrodynamic energy level is the main factor governing the development and distribution of different trace fossil assemblages. There are vertical trace fossils typical of higher energy (*Ophiomorpha, Diplocraterion, Arenicolites*); these are characteristic for the *Skolithos* ichnofacies. There are also typical, mostly horizontal components of the *Cruziana* ichnofacies (*Scolicia, Thalassinoides*), and trace fossils typical of the *Zoophycos* ichnofacies (*Zoophycos, Saronichnus* as an equivalent of *Chondrites*). Ichnofacies clearly cannot be interpreted on the basis of single ichnotaxa, but rather on the whole ichnoassemblage (e.g. Frey & Seilacher 1980). Such a mixture of trace fossils of different ethology is characteristic of the upper offshore–lower shoreface settings, where the proximal and archetypical *Cruziana* ichnofacies typically occurs (Pemberton et al. 2001). The vertical structures are related to opportunistic colonization of the storm beds (post-event community). Storm currents can transport the trace makers to the deeper environments (Frey & Goldring 1992). The horizontal structures are related to fair weather conditions. The chemosymbiotic structures (*Saronichnus* and probably *Zoophycos*) are a record of trophic competition which forces trace makers to shift to deeper and more complex feeding than simple deposit feeding. The horizontal and chemosymbiotic trace fossils represent the resident community.

The studied trace fossil assemblage shows a transition from the *Skolithos* to the proximal *Cruziana* ichnofacies to the proximal–archetypical *Cruziana* ichnofacies up the section. This indicates a deepening from the middle shoreface to upper offshore environments dominated by storms.

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