GEOLOGICA CARPATHICA, 55, 2, BRATISLAVA, APRIL 2004
87–102

STORM-INDUCED EVENT DEPOSITS IN THE TYPE AREA OF THE GRUND FORMATION (MIDDLE MIOCENE, LOWER BADENIAN) IN THE MOLASSE ZONE OF LOWER AUSTRIA

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(Manuscript received June 5, 2003; accepted in revised form December 16, 2003)

Abstract: Excavations in the type area of the Grund Formation (Middle Miocene, Lower Badenian) in Lower Austria showed four different lithofacies. Sandy beds with typical vertically arranged sedimentological features like erosive base, basal concentrations of coarse shell debris, mud-clasts and clast-horizons, normal graded beds, horizontal lamination of the upper plane bed, concentrations of plant and wood debris, asymmetrical ripples at the top, and synsedimentary deformation structures point to storm-induced event deposits. The sands were mainly deposited as tabular to slightly wedge-shaped sand-sheets; only extreme events produced channel-shaped sediment bodies. Pelitic layers at the top of such event-strata represent fair-weather conditions. The basal shell debris mainly contains mixed, synchronous-allochthonous, highly fragmented but determinable marine faunas from shallow to moderately deep environments. Together with land snails and bones of terrestrial vertebrates bottom currents transported the shelly fauna from shallow-marine to offshore areas. Paleocurrent data from groove marks, gastropod orientation, asymmetrical ripples and small dunes point to a transport towards ESE–E–NE, from a coastal area at the margin of the Bohemian Massif. The various lithofacies clearly reflect a proximal–distal trend from the shoreface to the offshore area. The development from the *Skolithos* to the proximal *Cruziana* ichnofacies to the proximal–archetypical *Cruziana* ichnofacies indicates an upward deepening from middle shoreface to upper offshore environments. The role of the Early Badenian transgression versus extreme storm events responsible for the proximal–distal trend and the lithological and ichnological development is discussed.

Key words: Neogene, Miocene, Molasse Zone, Grund Formation, storm deposits, ichnofacies.

Introduction

Since the 19th century the Middle Miocene Grund Beds (“Grunder Schichten”: Rolle 1859), north of Hollabrunn, in the Molasse Zone of Lower Austria have been famous for their fossil content. Especially their diverse and well preserved molluscan faunas led to numerous taxonomic studies (e.g. M. Hörnes 1851, 1870; M. Hörnes & Partsch 1856; R. Hoernes & Auinger 1879–1891; Kautsky 1928, 1936, 1940; Sieber 1937a,b, 1947a,b, 1949, 1952, 1956, 1960; Schultz 2001). Although the Grund Beds had considerable and country-wide importance for Miocene stratigraphical correlations (history of investigation cf. Rögl et al. 2002; Ćorić et al. 2004) not much detailed geological work was done until the end of the 20th century. Geological mapping and investigations have been done by Prinzinger (1852), E. Suess (1866), Vetters (1914), Stiny (1928), Holy (1939), Grill (1947, 1958, 1960) and Weinhandl (1953, 1954, 1957a,b, 1959). However no detailed sedimentological and taphonomic studies have been carried out. New geological mapping of map-sheets Retz, Hollabrunn and Hadres since 1990 (cf. Roetzel 1998; Roetzel et al. 1999a) revealed in detail the occurrence of the Grund Formation (Roetzel et al. 1999b) and its varying lithology. The lack of outcrops inhibited detailed facies investigations and sedimentological studies so far.

Therefore in the summers of 1998 and 1999 two field campaigns were organized by the Department of Paleontology of the University of Vienna to study the sedimentology, paleontology and ichnology of the Grund Formation in its type area in artificial outcrops (e.g. Roetzel et al. 1999c). In 1998, about 900 m north of the village of Grund near the wine cellars, 5 trenches (section A, B, C, D, E) were excavated on the plots of land numbers 896 and 894. In the next year, about 400 m to the West and East of the wine cellars along the main road to Znojmo, another 3 trenches (section F, G, H) were opened on plot of land number 755 in a higher topographic position (Figs. 2, 3).

Altogether about 13 meters of predominantly sandy sediments of the Grund Formation could be studied. Contemporary investigations on micro- and nannofossils (Cicha 1999; Rögl et al. 2002; Ćorić & Švábenická 2004; Spezzaferri 2004), molluscs (Harzhauser et al. 1999; Pervesler & Zuschin 2002, 2004; Mandic 2004; Zuschin et al. 2001, 2002, 2004), ichnofossils (Pervesler et al. 1998, 1999; Pervesler & Roetzel 2002; Pervesler & Uchman 2004) and vertebrates (Daxner-Höck 2003; Daxner-Höck et al. 2004; Göhlich 2003; Miklas-Tempfer 2003; Nagel 2003; Schultz 2003; Ziegler 2003) have been carried out. This paper deals with sedimentological and ichnological investigations and environmental reconstructions in the type area of the Grund Formation.

Geological setting

In the Molasse Zone (Alpine-Carpathian Foredeep) of Lower Austria, which is a part of the Central Paratethys, the first marine transgression started during the Egerian (Late Oligocene to Early Miocene). North of the Danube shallow-water sediments associated with the Early Miocene marine transgression (Eggenburgian–Ottnangian) are confined, on the surface, to the eastern margin of the Bohemian Massif in the surroundings of Eggenburg. The following Karpatian transgression in the uppermost Early Miocene led to sedimentation of the Laa Formation, which has the largest regional surface distribution of Miocene sediments (Fig. 1).

Middle Miocene (Lower Badenian) marine sediments are mainly restricted to the surroundings of Hollabrunn and Krems. In the Hollabrunn area, they mostly overlie the Karpatian, wheras in the Krems area they rest on Egerian and Ottnangian sediments (Fig. 1).

The Grund Formation occurs in the Hollabrunn area; towards the West it passes laterally into the Gaindorf Formation.

Recent geological and paleontological investigations of the Grund Formation were carried out among others by Cicha (1999), Cicha & Rudolský (1991, 1993, 1995, 1996, 1997, 1998, 2000), Čtyroký (1996, 1997), Novák (2000), Roetzel (2003a), and Stráník (1992, 2000).

The largest interconnected distribution area of the Grund Formation is the flat to slightly hilly landscape northwest to northeast of Hollabrunn. There the type area of the Grund Formation is situated between the villages Grund and Guntersdorf, just east of the main road to Znojmo (Fig. 2), where a number of wine cellars were built within the Grund Formation. A smaller occurrence of the Grund Formation exists south of Znojmo, close to the Austrian-Czech border, in the vicinity of Unterretzbach and Hnanice (cf. Roetzel et al. 1999a).

South of the main area of the Grund Formation, Sarmatian marine to brackish sediments of the Ziersdorf Formation and fluvial sediments of the Pannonian Hollabrunn-Mistelbach Formation overlie the Grund Formation. To the East and West the contact with the underlying Karpatian Laa Formation is clearly concordant, whereas to the North a tectonic contact can be assumed (cf. Fig. 1).

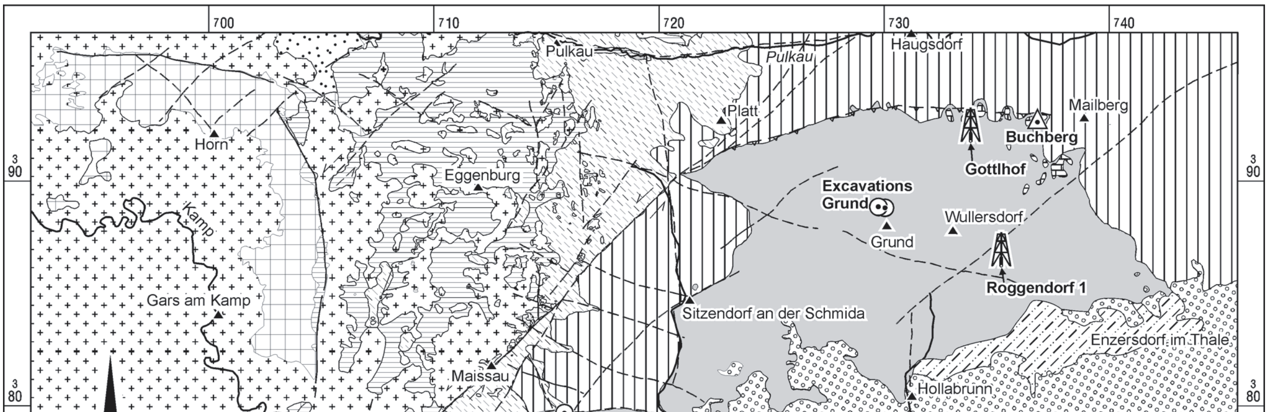

Fig. 1. Geological map of the Molasse Zone north of the Danube in Lower Austria (modified after Roetzel et al. 1999b).

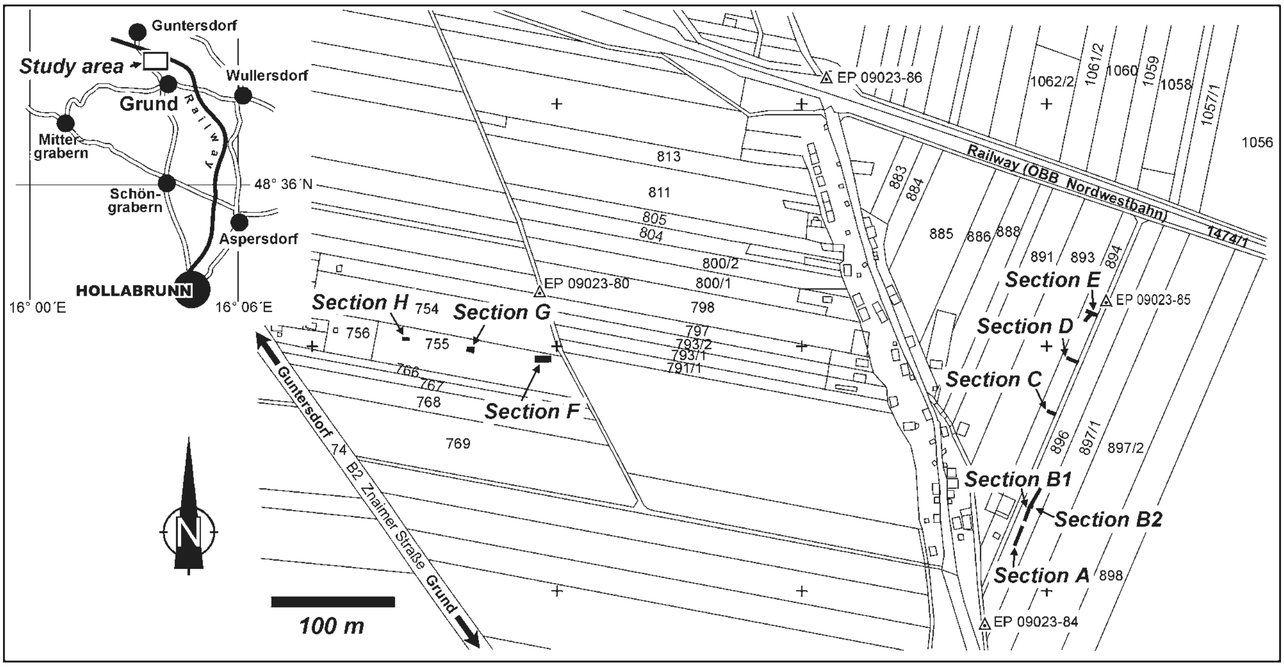

Fig. 2. Position of the sections from the excavations 1998 and 1999 in the type area at Grund.

The estimated total thickness of the Grund Formation is about 450 m, the main portion of which does not crop out.

The OMV-drilling Roggendorf-1, about 5.5 km southeast of Grund (Fig. 1; cf. Ćorić & Rögl 2004) revealed the thickest continuous section of Lower Badenian sediments of altogether 358 m. This section comprises the lower part of the Grund Formation. The depth interval 2–255 m reveals light brown to greenish grey, silty to sandy, micaceous marly shales intercalated with grey, micaceous, mostly fine, sometimes medium to coarse sands and gravels. Basal clastics with sandy gravels, sandstones and conglomerates occur at 255 to 360 m depth. The clast petrography comprises sandstone, limestone, dolomite, quartz, crystalline rocks and chert.

It can be assumed that much of the Grund Formation, cropping out at the surface, belongs to the upper part of the formation. Similarly to the drilling Roggendorf-1 they consist of 2 to 20 cm thick clayey to sandy and marly silt-beds, alternating with fine- to medium-, rarely coarse-grained sand-beds in the same range of thickness. Locally clayey silts with thin sandy layers occur. Between Grund and Wullersdorf and north of the villages of Guntersdorf, Kalladorf and Immendorf, at least two, several tens of meters thick sandy intercalations occur. They contain the famous, well-preserved molluscan fauna. One of these sandy intercalations also occurs in the type area of the Grund Formation.

In the northern- to northeasternmost part of the Grund Formation, west of Mailberg, upward thickening lenticular intercalations of biogenic limestones appear in the sandy and silty sediments. These limestones form the hilltops of the Buchberg, Galgenberg, Haidberg, Steinberg and Blickenberg and constitute a separate formation, called the Mailberg Formation (cf. Prinzinger 1852; Vetters 1914; Stiny 1928; Sieber 1952; Weinhandl 1953, 1957b; Čtyroký 1996, 1997; Novák 2000). This formation is up to 25 m thick. Main biogenic components are coralline algae, molluscs, balanids, foraminifers, bryozoans, serpulids and sea urchin spines. Mainly thick-walled molluscs are often concentrated in coquinas (Sieber 1952). Thin pelitic layers within the limestones contain a rich and well-preserved micro- and nannofauna, typical of the Lower Badenian (Achuthan 1967).

To the west and southwest the Grund Formation passes into a sandier to gravelly facies, called the Gaindorf Formation (cf. Roetzel et al. 1999b). It is possible, that the Gaindorf Formation is connected to the south and southwest below younger formations with Lower Badenian sediments in the Krems area. The district south to southeast of Krems contains Lower Badenian submarine delta conglomerates with pelitic intercalations belonging to the Hollenburg-Karlstetten Formation (Grill 1957). In the distal part to the north and west, in the Krems bight and the Wachau Valley, they interfinger with pelitic sediments.

The Gaindorf Formation occurs in this area between Gaindorf and Mühlbach am Manhartsberg and in the Schmida Valley between Ziersdorf and Sitzendorf an der Schmida. An artificial outcrop in the Gaindorf Formation at Mühlbach (cf. Roetzel 2003b) allowed the correlation of terrestrial and marine biostratigraphy in the Middle Miocene Molasse Basin by a fairly rich fossil assemblage (Harzhauser et al. 2003).

According to Daxner-Höck (2003) the rodent fauna of Mühlbach is representative for the late mammal Zone MN5 and is definitely older than the Ries event, which is dated roughly at about 14.9 Ma. This observation points to an absolute age of the Gaindorf Formation of about 15.1 Ma, corresponding to the top of the planktonic foraminiferal Zone M5b/Mt5b (Rögl & Spezzaferri 2003).

A direct correlation of the Gaindorf Formation with the Grund Formation is based upon foraminifers (Rögl et al. 2002; Rögl & Spezzaferri 2003; Spezzaferri 2004), ostracods

Fig. 3. Excavations at Grund-type area. Left side: excavation 1998, section B1-B2. Right side: excavation 1999, section F.

(Zorn 1999, 2003, 2004) and micro-mammals (Daxner-Höck 2003; Daxner-Höck et al. 2004) (cf. also Roetzel et al. 1999b; Harzhauser et al. 2003).

According to these results and in correspondence with Papp et al. (1978) the Grund Formation and the Gaindorf Formation biostratigraphically belong to the Lower Lagenidae Zone of the regional ecostratigraphical foraminiferal zonation. This points to an Early Badenian age of the studied sediments, thus correlatable to the Langhian of the international timescale (cf. Rögl et al. 2002; Rögl & Spezzaferri 2003; Spezzaferri 2004; Ćorić & Rögl 2004).

Lithofacies

About 13 m of predominantly sandy sediments of the Grund Formation were studied in eight excavated sections (Figs. 3, 4b–d).

Quaternary sediments covered the Neogene sediments in all sections. Because of a morphological depression, in sections A to D this Quaternary cover was up to 3 m thick. Sections E to H, situated at a higher elevation, mostly showed a thinner Quaternary cover. The basal portions of these Quaternary sediments mostly consist of fine to medium sands, sometimes laminated or cryoturbated and with reworked Neogene molluscs. The sandy material is reworked from the Neogene and probably fluvial and eolian in origin. On top of these sands, Quaternary loess and loam was deposited, which is capped by the Holocene soil.

Four different lithofacies have been recognized in the Miocene sediments of the Grund Formation (Table 1). They will be described in detail.

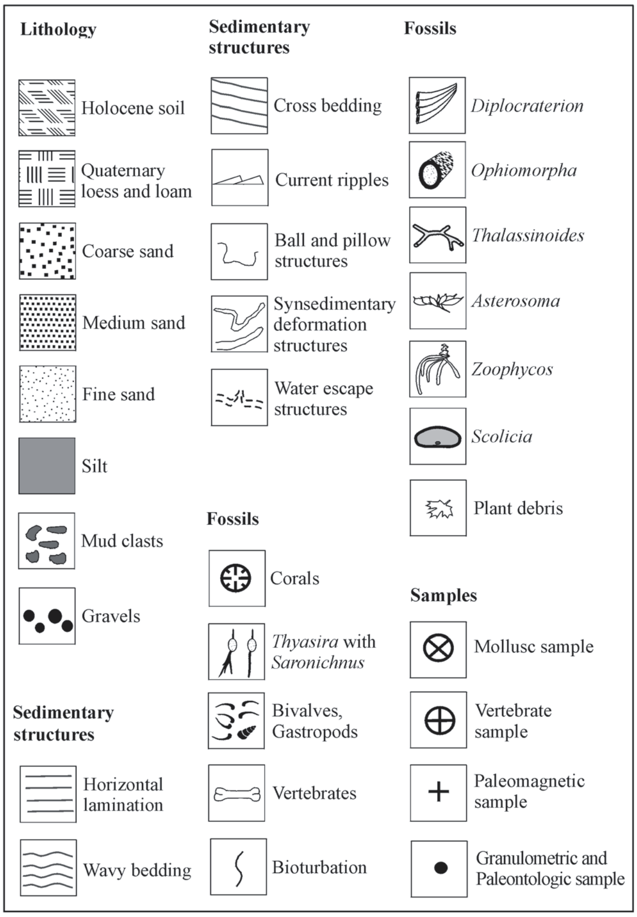

Fig. 4a. Legend to sections A to H (Fig. 4b–4d).

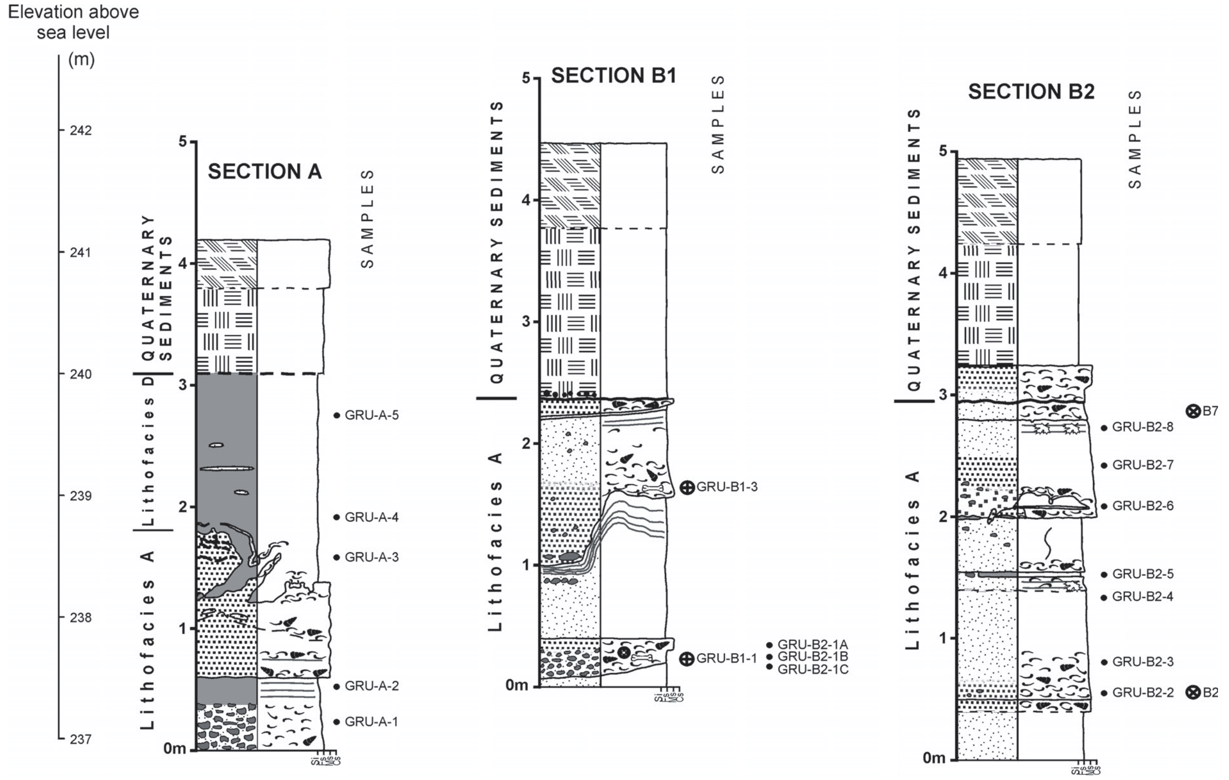

Fig. 4b. Sections A, B1, and B2 from the type area of the Grund Formation at Grund (position cf. Fig. 2).

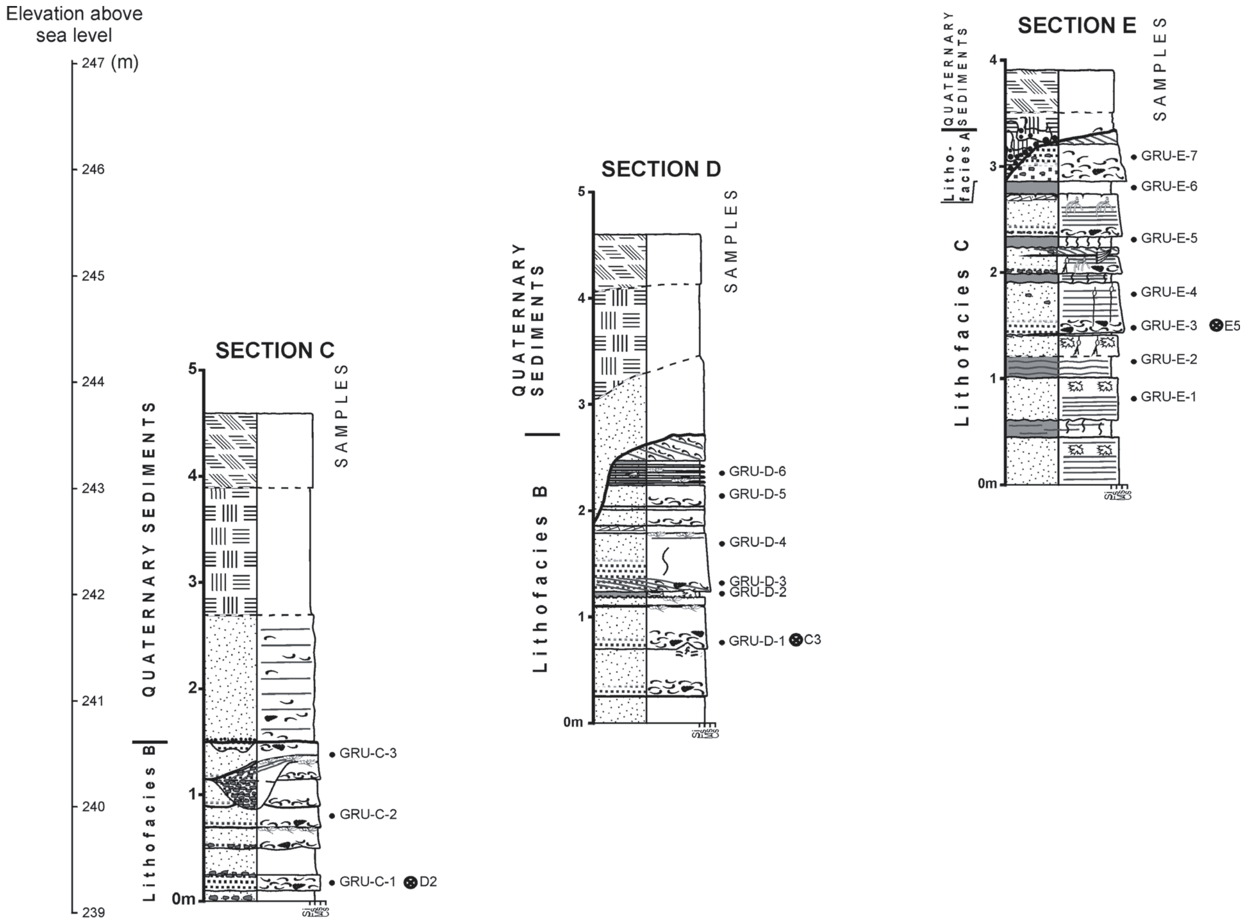

Fig. 4c. Sections C, D, and E from the type area of the Grund Formation at Grund (position cf. Fig. 2).

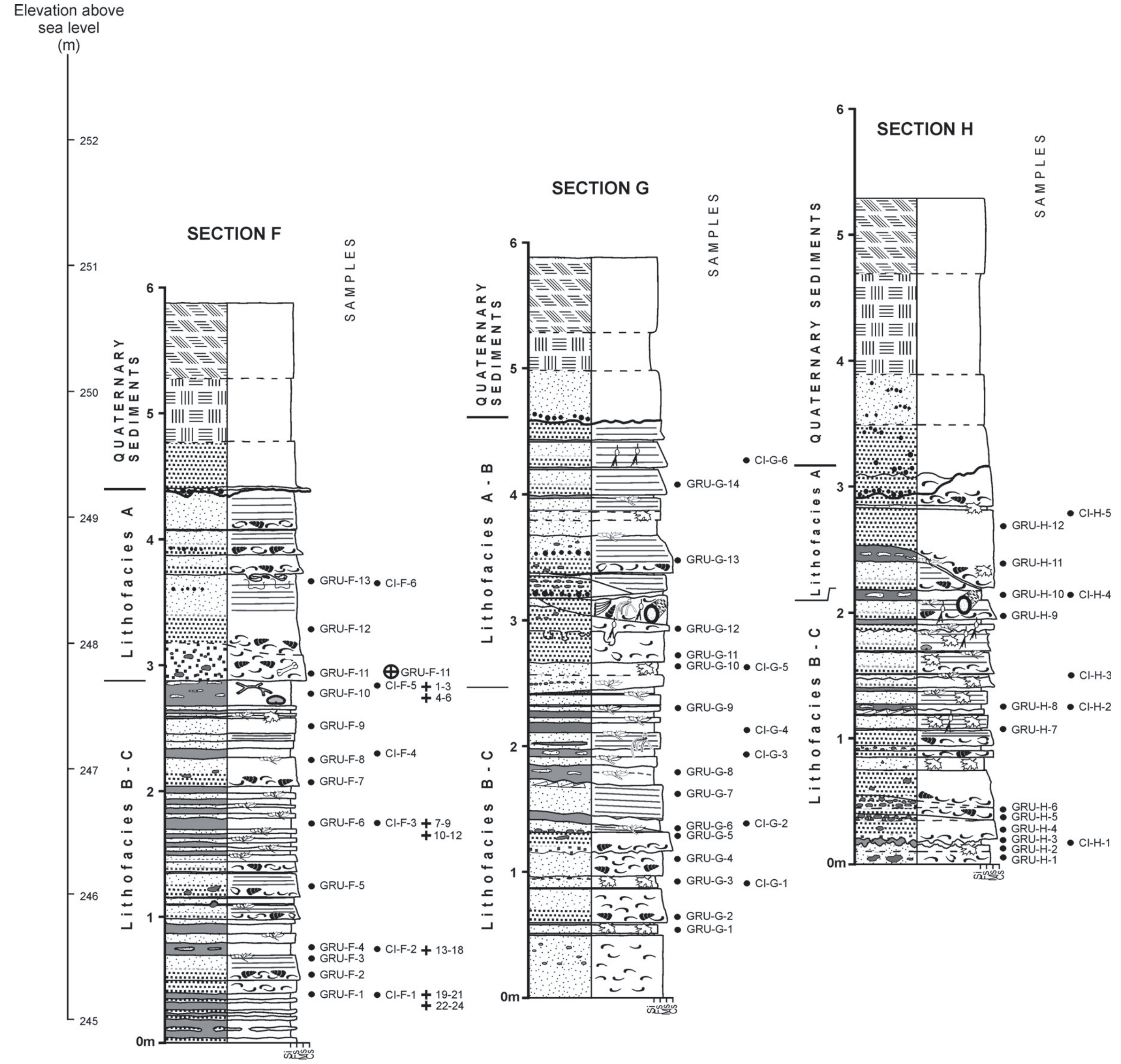

Fig. 4d. Sections F, G and H from the type area of the Grund Formation at Grund (position cf. Fig. 2).

Table 1: Main characteristics of the lithofacies in the type area of the Grund Formation.

LITHOFACIES	LITHOLOGY	ICHNOLOGY
A	60 to 120 cm thick, medium to fine sandy beds, normal graded, basal coquinas, mud-clasts. At the top horizontal lamination (upper plane bed) and plant debris. Sometimes highly erosive lower bedding planes and multiple intersecting of sandy beds, basal groove marks. Water escape structures, load-structures and ball and pillow structures. Rarely pelitic layers, mostly as relics, laterally passing over into layers of mud-clasts.	Trace fossils absent
B	20 to 45 cm thick, medium to fine sandy beds, normal graded. Shell-debris and mud-clasts finer-grained than in A. Horizontal lamination (upper plane bed) and plant debris in the top portion of beds, sometimes with asymmetrical ripples at the very top. Tabular to slightly wedge-shaped sand bodies. Erosive structures rare. Thin pelitic layers frequent.	Monospecific bioturbation in sandy layers close below pelitic layers (*Asterosoma*). Steep shafts connect the *Asterosoma* clusters from subsequent sendimentary sand-pelite successions
C	Frequent alternation of sands and silts. 20 to 50 cm thick, medium to fine sandy beds with horizontal lamination. Normal grading, basal shell debris and mud-clasts less frequent than in A and B. Small dunes or asymmetrical ripples at the top. Intercalated thick (5 to 20 cm) pelitic layers and beds with horizontal lamination or undulatory bedding, sometimes thin sandy layers or asymmetrical ripples inside. Bedding often destroyed by bioturbation.	Diverse trace fossil assemblage (*Arenicolites, Diplocraterion, Ophiomorpha*, *Zoophycos, Saronichnus*) starting from pelitic beds downwards into sandy sediments or spreading within the pelitic layers (*Thalassinoides, Scolicia*)
D	Thick, massive clayey silt beds, few sandy layers and lenses.	No distinct structures visible but possibly thoroughly bioturbated

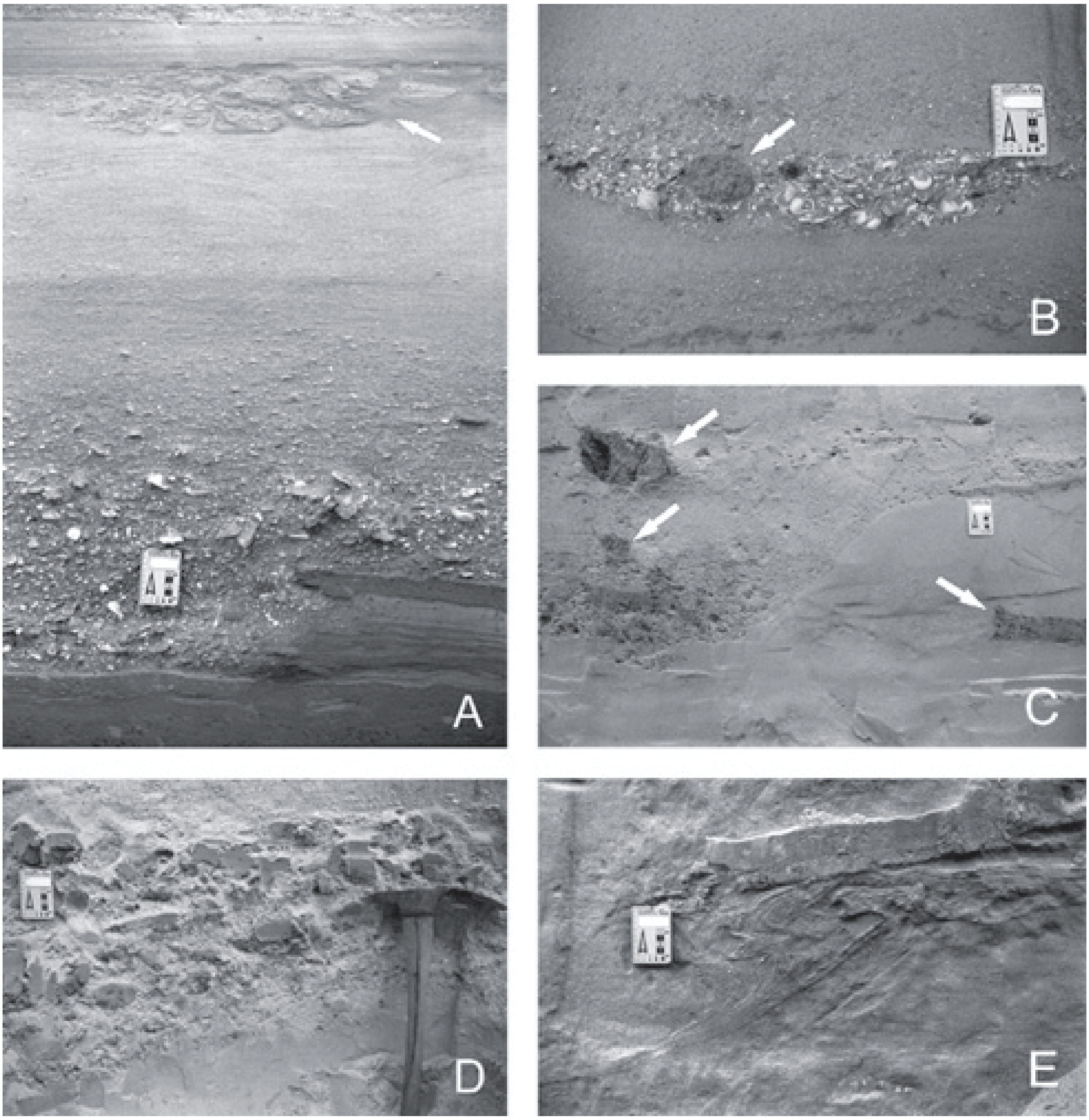

Fig. 5. Lithofacies A. **(A)** Fining-upward sandy bed with basal shell debris and erosive base. Note ball and pillow structures at the top (arrow). **(B)** Small channel-shaped sediment-body with shell debris of marine and terrestrial molluscs and mud-clasts (arrow). **(C)** Composite sand body consisting of multiple erosive channelized sand-beds. Note partly eroded pelitic layer at right side (arrow) and mud-clasts at left side (arrows). **(D)** Densely packed, matrix-supported clast-horizon with shell debris in the matrix. **(E)** Synsedimentary deformation structure below a pelitic layer close to an erosive margin.

Lithofacies A

Lithofacies A mostly consists of 60 to 120 cm thick sandy beds with distinct normal grading of coarse-grained to medium- or fine-grained sands and sharp, sometimes erosive bases (Fig. 5A). Occasionally such sandy beds are multiply intersecting each other, only preserving the basal portion of the normal graded beds and forming up to 50 cm thick composite sediment bodies (Fig. 5C). Frequently coquinas occur at the base of the normal graded beds, forming beds or lenses containing a mixed allochthonous fauna, mainly of marine bivalves and gastropods and subordinately scaphopods (tusc shells), chitons (polyplacophores), corals, crabs, serpulids, balanids, bryozoans, echinids and different vertebrates (Fig. 5A,B). In some shell beds additionally land snails and bones of terrestrial vertebrates like rhinos, small carnivores and micro mammals point to a terrestrial supply. According to the terminology of Kidwell et al. (1986) the molluscan shells are mostly orientated concordant to oblique and show a densely packed, bioclastic-supported biofabric.

Flat-shaped, angular to well-rounded mud-clasts also are common in these beds (Fig. 5B,C,D). The clasts measure up to 20 cm in diameter, may show internal lamination and bioturbation and are armed by shell debris. Outcrops in neighbouring wine cellars occasionally show clasts up to 1.2 meter in size, with internal bedding preserved. In some cases, these clasts can form up to 40 cm thick, densely packed, but usually still matrix-supported clast-horizons with a high amount of shell debris in the matrix (Fig. 5D). The top and base of these horizons are generally irregular and wavy and show snout-like lateral boundaries.

Most biogenic particles of the coquinas are highly fragmented and show signs of abrasion and bio-erosion. Nevertheless, they can be readily determined. Most of the fauna is synchronous-allochthonous. Only a small portion, predominantly herbivorous gastropods from the eulittoral, show obviously strong abrasion and striking limonitic staining, being most probably heterochronous-allochthonous and reworked from Karpatian deposits below (Harzhauser et al. in Roetzel et al. 1999c; Zuschin et al. 2001, 2004). Analogous to the grain-size trend, the shell-debris shows declining particle-size as well as particle-density from base to top within the sandy beds (Fig. 5A).

The beds are often massive at the base and show horizontal lamination towards the top. Concentrations of plant and wood debris are frequently present in the top portion, which is sometimes covered by thin, nearly non-bioturbated pelitic layers. In most cases, however, these layers are preserved only as relics (Fig. 5C) or completely eroded. Occasionally they pass laterally into a horizon of mud-clasts. In one case, small groove marks, probably caused by dragged off fragments of molluscs, were visible at the upper bedding plane of a pelitic bed (Fig. 10). In rare cases a mud drape was deposited on an erosive surface, before the next sandy bed was laid down.

In some cases, when pelitic layers overlie the sandy beds, deformational structures like convolute bedding, ball and pillow structures, and water-escape structures (Fig. 5A) have been observed. Below a thick pelitic sequence of lithofacies D in section A (cf. Fig. 4b) the sands of lithofacies A show intensive synsedimentary deformational structures, which most likely can be interpreted as a combination of load- and water-escape structures. Another case of synsedimentary deformation in sandy sediments below a pelitic layer, close to an erosive margin, can be interpreted as folding and sliding due to undercutting (Fig. 5E).

Due to the limited extent of the excavation trenches it is difficult to estimate the dimension of erosive depressions. However, in neighbouring wine cellars channel-shaped sand bodies with singular normal grading, at least 7–8 m wide and 0.5–1 m thick,

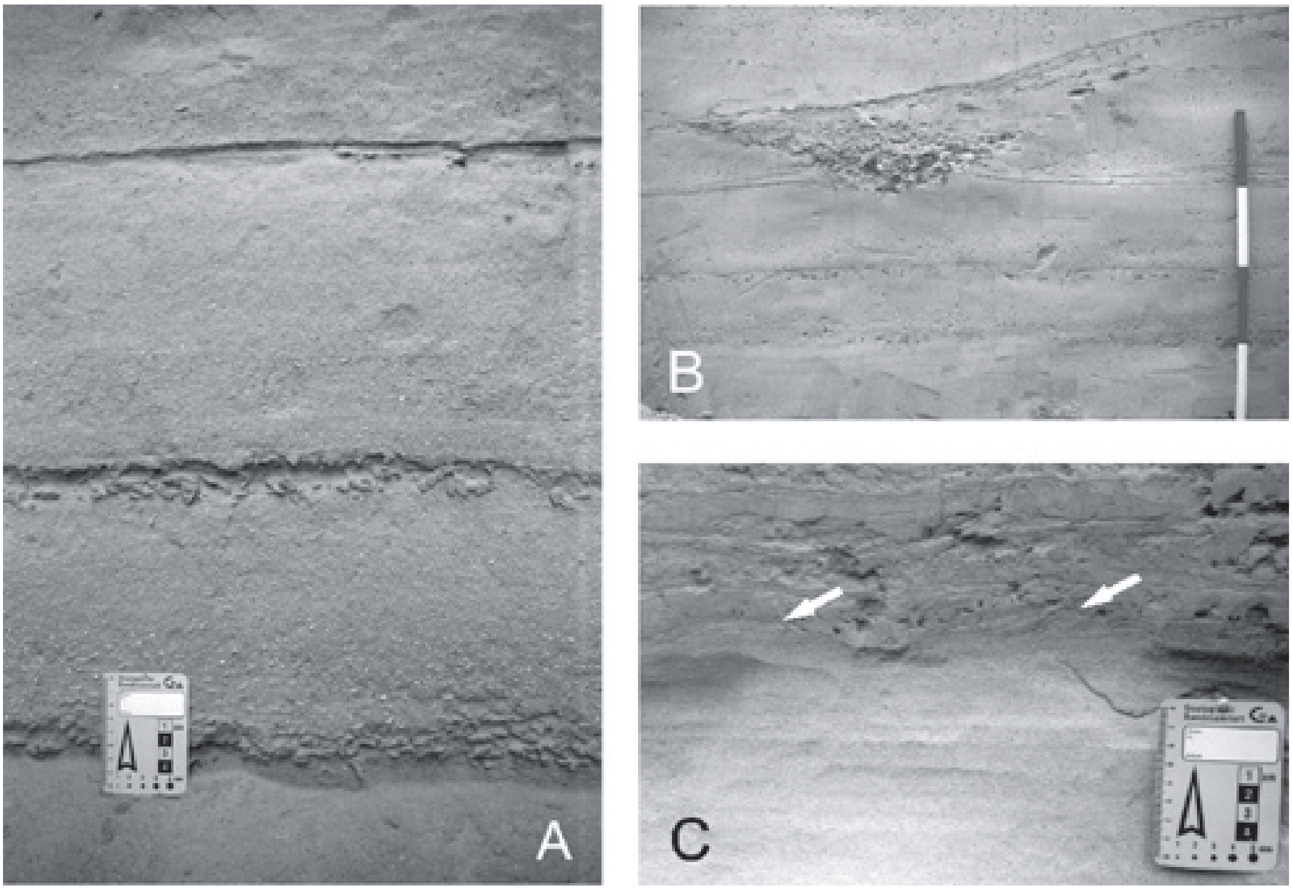

Fig. 6. Lithofacies B. **(A)** Fining-upward sandy beds with basal fine-grained shell debris and pelitic layers at the top. From the pelitic layers monospecific bioturbation of *Asterosoma* reaches downwards into sandy beds. **(B)** Small runnel filled with mud-clasts, cutting into a series of fining-upward sandy beds. Subdivisions of the scale: 20 cm. **(C)** Form sets (arrows) of asymmetrical ripples at the top of horizontally laminated sands.

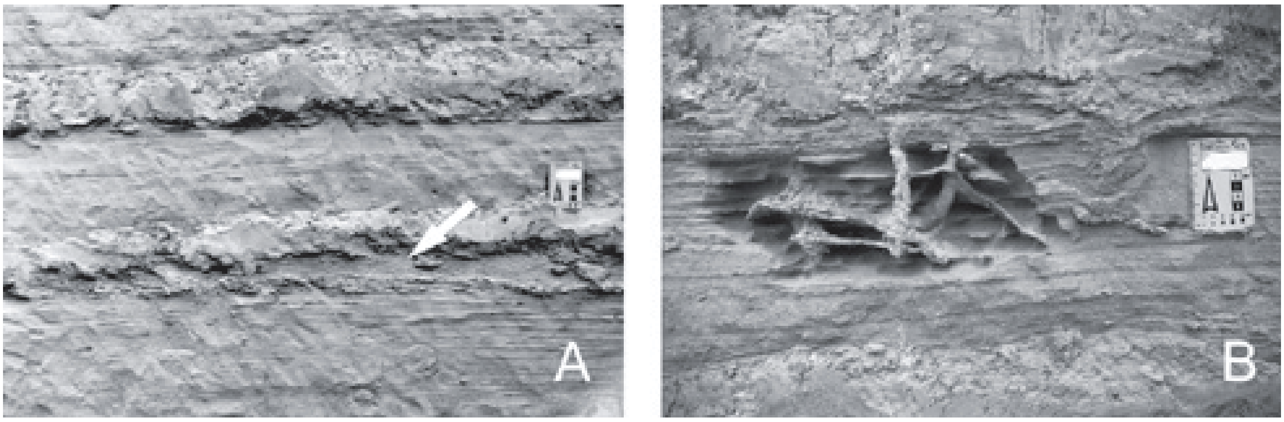

Fig. 7. Lithofacies C. **(A)** Alternation of horizontally laminated sandy beds and pelitic layers. Small cross-bedded dune (arrow) on top of the lower sandy bed. **(B)** *Zoophycos* starting from thick pelitic bed and reaching downwards into horizontal laminated sand.

were observed. In an outcrop west of Nexenhof, a composite channel-shaped sediment body was traceable for at least 100 m.

Lithofacies B

In lithofacies B the 20 to 45 cm thick sandy beds are much thinner than in lithofacies A, but also show distinct normal grading from coarse to medium or fine sands (Fig. 6A). Shell-debris and mud-clasts at the base of the beds are finer-grained than in lithofacies A and decline rapidly towards the top in grain-size and density. The sandy beds usually show upper plane bed horizontal lamination, but can also be massive in their lower portion. Sometimes asymmetrical ripples at the top of the beds, which may occasionally be developed as form sets, indicate a reduction of current velocity at the end of the depositional event (Fig. 6C). The sandy beds are covered by thin (1–3 cm) pelitic layers in nearly all cases (Fig. 6A). A dense, but monospecific bioturbation (*Asterosoma*) reaches 3 cm downwards from these pelitic layers into the sandy beds (Fig. 6A, Fig. 12). In neighbouring wine cellars the thickness of these sandy beds and pelitic layers is laterally very stable. The sand bodies are mostly tabular, sometimes slightly wedge-shaped. In rare cases, small and narrow runnels, 60 to 80 cm wide and 10 to 25 cm deep, with erosive base and filled with mud-clasts, cut into the sandy beds (Fig. 6B). In a three-dimensional outcrop, the long axis of such a runnel had a NW–SE orientation. Lithofacies B is the predominate type in the wine cellars in the type area.

Lithofacies C

Significant for lithofacies C is a frequent alternation of sandy and pelitic beds and strong bioturbation originating from the latter. Like lithofacies B, it contains horizontally laminated, 20 to 50 cm thick, coarse to fine sandy beds (Fig. 7A), but fining-upward, small mud-clasts, and plant debris at the top are less frequent than in lithofacies A and B. Beds without basal shell debris can also occur. Rarely asymmetrical ripples and small dunes with low-angle, sigmoidal foresets were recognized at the top of sandy beds (Fig. 7A). In contrast to lithofacies A and B, the pelitic layers and beds are much thicker and more frequent. Besides that they show frequent alternation with sandy beds. Sometimes the 5 to 20 cm thick pelitic beds show horizontal lamination or undulatory bedding, rarely with thin sandy layers or lenses of asymmetrical ripples. In most cases the bedding is nearly completely destroyed by intense bioturbation. Starting from these pelitic layers a diverse trace fossil community reaches down into the sandy beds (Fig. 7B). *Diplocraterion*, *Ophiomorpha*, *Arenicolites* and *Zoophycos* are very frequent structures. *Scolicia* and *Thalassinoides* can be observed in thicker pelitic layers. As an exclusively autochthonous inhabitant of these beds the chemosymbiotic burrowing bivalve *Thyasira michelottii* occurs (Harzhauser et al. 1999; Zuschin et al. 2001; Pervesler & Zuschin 2002, 2004). The *Thyasira*-shells are sometimes connected with deep shafts, but in most cases with ventral probes from the *Saronichnus abeli* type.

Lithofacies D

Lithofacies D was recognized only once in section A (cf. Fig. 4b). It consists of at least 1.5 m, mostly massive, possibly thoroughly bioturbated clayey silts with only a few sandy layers and lenses. At its base this pelitic package and the sandy sediment below were strongly affected by synsedimentary deformational structures, which most likely can be interpreted as a combination of load- and water-escape structures. No distinct bioturbation was visible in these pelites.

Interrelation of lithofacies

In the excavated sections of 1998 and 1999 (Fig. 4b–d) the recognized lithofacies show distinct successions in a vertical direction (Fig. 8). In the lower sections A to E (Fig. 4b–c) the lithofacies A to C consequently follow one another from base to top. Only in section A exceptionally lithofacies D follows above lithofacies A. Section B proves that lithofacies A is also present in a lateral position to lithofacies D. Another lateral change of lithofacies A to B can be recognized between sections B2 and C. A lateral change from lithofacies B to C occurs between sections D and E. In sections F to H the basal portions of the profiles belong to lithofacies B–C, whereby

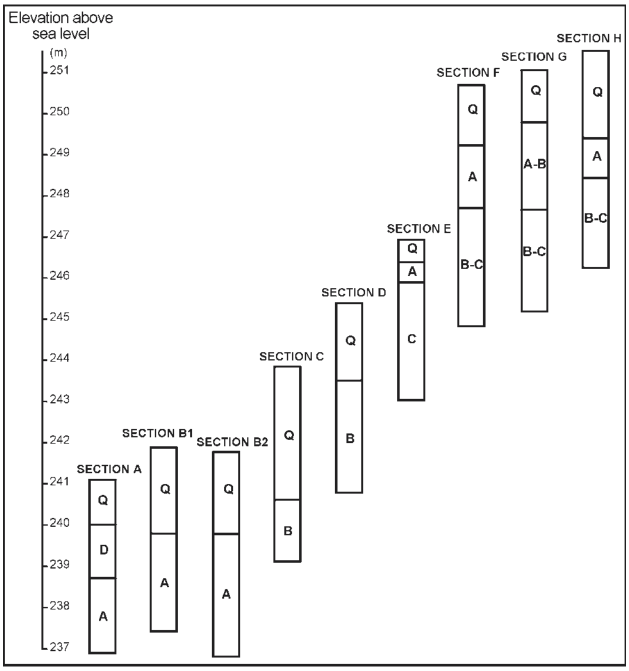

Fig. 8. Interrelation of lithofacies in sections A to H (**A** to **D** — lithofacies of the Grund Formation; **Q** — Quaternary sediments).

the lower parts of sections G and H lithologically resemble lithofacies B and the upper parts show more characteristics of lithofacies C. Section E reveals lithofacies A on top of lithofacies C, the first of which taking a position laterally to lithofacies B–C in section F. In sections F and H, as in section E, lithofacies B–C is overlain by lithofacies A, whereas in section G a transitional lithofacies A–B is present on the top (cf. Fig. 4b–d).

Summarizing these observations it can be stated that there is a threefold, vertical succession of lithofacies A to C, but lateral shifts and transitional types of lithofacies are also evident (Fig. 8).

Granulometric data

From the excavation at Grund the grain size of 70 samples was analysed by sieving and sedigraph-analysis.

The sandy sediments of lithofacies A to C have nearly similar grain size distribution. Generally they can be classified as medium to fine sands with a mean between 2.14 and 3.90 Phi (Fig. 9). Rarely silty fine sands or gravelly and coarse sands occur and particles of coarse sand- or fine gravel-size are exclusively biogenic in origin.

The pelitic sediments show larger differences from clayey-silty sand, clayey silt-sand and sand-silt-clay to sandy clay-silt, sandy silt-clay and silt-clay (Fig. 9). The content of silt and clay is quite the same, but the content of sand strongly varies. The mean varies between 5.00 and 10.23 Phi.

Most of the pelitic layers of lithofacies A have a lower content of sand-sized particles than the pelites of lithofacies B and C. The sorting of the pelites is generally very bad to extremely bad. The high portion of sand in pelites of lithofacies B and C is most probably due to the admixture of sand by bioturbation.

The pelitic samples of lithofacies D show similar grain-size distributions as the other pelites, but they contain the highest amounts of silt among all samples (Fig. 9).

Paleocurrent data

Meaningful data for paleocurrent analysis are rare in the outcrops at Grund. In one case in section F, the upper bedding plane of a pelitic bed displayed small, parallel-arranged groove marks (Fig. 10). Most probably these were caused by fragments of molluscan shells being dragged over the mud-surface by strong currents. The orientation of these groove marks in a WNW–ESE-direction (Fig. 11) roughly corresponds to the dip-direction of the foresets of a single asymmetrical current ripple (080/10) in a sandy bed directly above.

The long-axis of the gastropod *Turritella* in the lower portion of a bipartite coquina of the same section (Fig. 4d, at

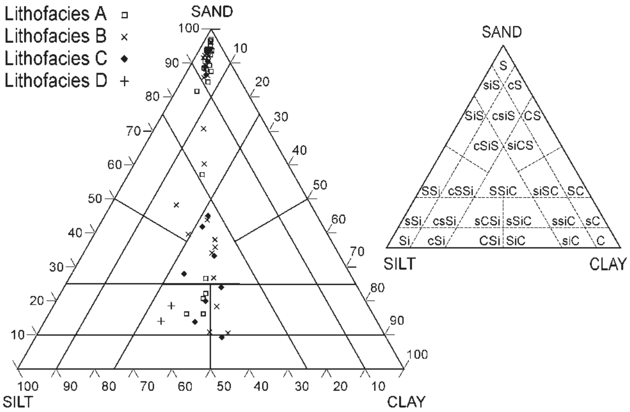

Fig. 9. Results of grain-size analysis of samples from the excavation Grund plotted in a ternary sand (2 mm–63 μm) — silt (63 μm–2 μm) — clay (< 2 μm) diagram (after Füchtbauer 1959 and Müller 1961).

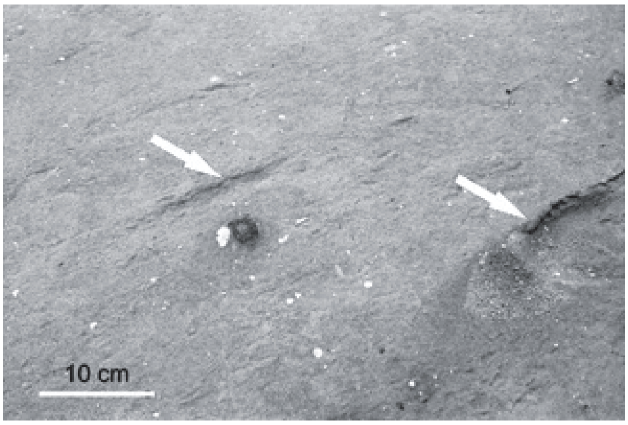

Fig. 10. Pelitic surface with groove marks (arrows) reflecting the paleocurrent direction from West (lower left) to East (upper right).

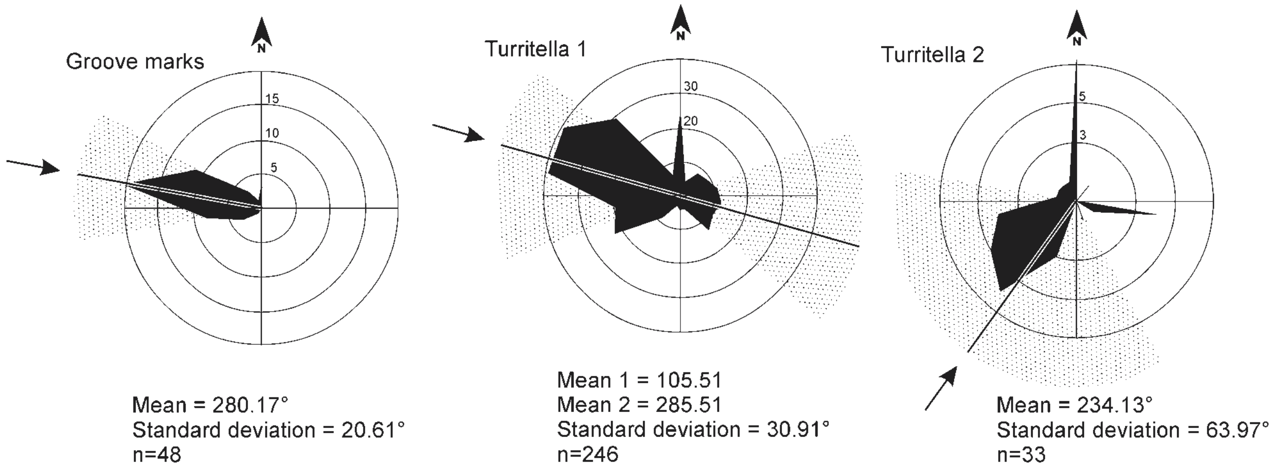

Fig. 11. Paleocurrent data from groove marks and long axis from *Turritella* in section F. Arrows show current direction, dotted area: standard deviation.

2.9 m in section F) were orientated roughly parallel to the groove marks (Fig. 11 — Turritella 1). The orientation of *Turritella* in the upper part of the coquina (Fig. 4d, at 3.2 m in section F) pointed to a current direction from SW (Fig. 11 — Turritella 2).

The orientation of the groove marks and Turritella 1 roughly matches the foreset direction of a few small asymmetrical current ripples (R_H: 2–2.5 cm, R_L: 15–16 cm) in section G, dipping towards SSE (140/15, 145/20, 150/18). The long axis of a small runnel in section C (Fig. 6B) also displayed a NW–SE orientation.

Data from the foreset direction of small asymmetrical current ripples (R_H: 1.5–1.8 cm, R_L: 11–12 cm) and dunes in sections D and E (015/20, 040/20, 060/10) point to a transport from SW to NE, analogous to that deduced for Turritella 2.

Considering all these data a transport from approximately WNW–W–SW towards ESE–E–NE can be assumed.

Ichnofacies

Trace fossils from the *Skolithos* and the *Cruziana* ichnofacies dominate the Grund Formation in the investigated sections, but traces typical of the *Zoophycos* ichnofacies were also identified.

Skolithos *ichnofacies*

The *Skolithos* ichnofacies in Grund was found in sections G and H. Both occurrences are intercalations within lithofacies A or A–B and related to high-energy events. The *Skolithos* ichnofacies contains the trace fossils *Ophiomorpha, Diplocraterion* and *Arenicolites* all of them being typical of higher energy environments. These vertical structures represent a post-event community and are related to opportunistic colonization of the storm beds. *Arenicolites* occurs in different environments, but is typical of shallow-marine settings (Crimes 1977). *Diplocraterion* is common in event beds, where it documents the opportunistic post-event colonization (Frey & Goldring 1992). *Ophiomorpha nodosa* produced mostly by callianassid shrimps is one of the most common shallow-marine trace fossils. It typically occurs in the *Skolithos* ichnofacies, but also in deeper shelf tempestites (Frey 1990; Frey & Goldring 1992).

Skolithos *to proximal* Cruziana *ichnofacies*

In the sections C and D *Asterosoma* was documented in the lithofacies B, in section F, G and H in a transitional type of lithofacies B–C. The trace makers of *Asterosoma* settled the transitional zone between the *Skolithos* and the proximal *Cruziana* ichnofacies during short periods of quiet conditions. *Asterosoma* is interpreted as a selective-feeding burrow of a worm (Pemberton et al. 2001). 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 successions and are interpreted as equilibrium-structures (Fig. 12). *Asterosoma* occurs in the upper lower shoreface in soft substrates.

Cruziana *ichnofacies*

The archetypical *Cruziana* ichnofacies in the Grund Formation was recognized in the sections E, F and H and corresponds mostly to the lithofacies C, or to a transitional type of lithofacies B–C. The archetypical *Cruziana* ichnofacies occurs in more distal storm deposits and contains trace fossils from the *Cruziana* ichnofacies as well as additional elements from the *Zoophycos* ichnofacies.

Mostly horizontal components of the *Cruziana* ichnofacies are the trace fossils *Scolicia* and *Thalassinoides* representing fair-weather conditions. These structures were constructed in thick semi-consolidated mud layers and mostly truncated by later erosion. The chemosymbiotic structures *Saronichnus* (produced by the chemosymbiotic bivalve *Thyasira michelottii*) and *Zoophycos* are a record of trophic competition that pressures trace makers to deeper and more complex feeding than simple deposit feeding (Pervesler & Uchman 2004). The horizontal and chemosymbiotic trace fossils represent the resident community.

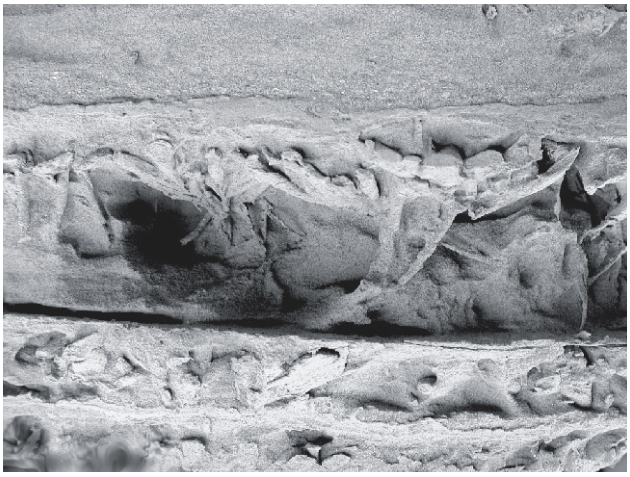

Fig. 12. Several subsequent generations of *Asterosoma* connected by steep shafts interpreted as equilibrium-structures. Lithofacies B in section C.

Interpretation and conclusions

The lithology and sedimentary structures of **lithofacies A** document a rapid alternation of deposition and erosion and a high amount of reworking. Especially the well-developed normal grading in thick sandy beds points to short-term, high-energy current events followed by rapid deceleration of current velocity. The basal concentration, fining-upward, and declining density of coarse shell debris in single beds support this interpretation. Rapid alternation of erosion and deposition is also demonstrated by the frequent occurrence of highly erosive, channel-shaped lower bedding planes of sandy beds, displaying a relief of up to half a meter deep. Continuous outcrops in wine cellars show channel-shaped sediment bodies up to 7–8 m wide and 0.5–1 m thick. However, a still larger outcrop near the type area exhibited a composite, channel-shaped sediment body with a length of at least 100 m. This sediment body can be interpreted as a multi-storey filling of a shallow submarine channel.

Synsedimentary deformation structures caused by dewatering, such as water-escape structures, convolute bedding and ball and pillow structures, also indicate quick deposition of the sands above beds with such structures and generally high sediment input. Also the groove marks on the surface of a pelitic bed, most probably caused by fragments of molluscan shells, which were dragged over the mud-surface by strong currents, reflect the high transport energy.

Horizontal lamination mostly in the upper part of sandy beds is due to sediment transport under conditions of the upper-flow regime, causing lamination of the upper plane bed. Concentrations of plant and wood debris at the top of such beds, sometimes overlain by small asymmetrical ripples, indicate a rapid decrease of current velocity after high-energy events.

Rare, thin pelitic layers between the thick sandy beds reflect deposition during low energy conditions (fair-weather pauses). The nearly complete absence of bioturbation in pelitic layers points to only short-time intervals of mud deposition. However, these layers are mostly preserved as relics, which is demonstrated by the frequent lateral passing into horizons of mud-clast.

Clast-horizons with densely packed but usually still matrix-supported mud-clasts, irregular wavy top and base and snout-like lateral boundaries indicate transport as debris flows. Observed clast-sizes up to more than 1 meter reflect high matrix strength of these debris flows. Investigations of the foraminiferal fauna of such mud-clasts prove their origin and reworking from synchronous Badenian sediments (pers. comm. F. Rögl).

The mixed allochthonous fauna of the basal shell debris horizons is indicative of a marine, shallow to moderately deep, sub-littoral, soft bottom environment (Harzhauser et al. in Roetzel et al. 1999c; Zuschin et al. 2001, 2004).

In **lithofacies B** the fining-upward sandy beds are still a clear reference to episodic, short-term, high-energy depositional events. But decreasing thickness of the beds, smaller size of the biogenic components and only rare occurrence of beds with an erosive base clearly reflect a decline of transport-energy compared to lithofacies A. Horizontal lamination of the sandy beds indicates sediment transport under conditions of the upper-flow regime, analogous to lithofacies A. The reduction of the current velocity towards the top of the sandy beds again is signified by the concentration of plant debris, but also by asymmetrical ripples at the top of the beds. The sandy beds are predominantly tabular to slightly wedge-shaped, sheet-like bodies, which could be traced in wine cellars for several tens of meters. Frequently occurring, several cm-thick pelitic layers at the top of sandy beds contain a monospecific bioturbation of *Asterosoma* trace makers, which point to relatively longer calm periods of pelitic sedimentation between numerous subsequent events providing the coarser sediments. Equilibrium structures connect several subsequent *Asterosoma* clusters indicating that the *Asterosoma* producers could survive the events and settle close below the new seabottom-surface. Periods of at least several weeks or months between the events can be assumed for a new generation of trace makers to bioturbate the sediments in the observed intensity.

A further decrease of the hydrodynamic energy level is reflected by the lithology and ichnofacies of **lithofacies C**. This is primarily expressed by an increasing thickness of the pelitic beds. Quick, short-term deposition of sandy beds is less frequent than in lithofacies A and B. Fining-upward successions are mostly lacking within the sandy beds, but horizontal lamination of the upper plane bed is still frequent. Asymmetrical ripples and small dunes at the top of sandy beds are more frequent, indicating rapid decline of current velocity during deposition.

Long periods of benthic recovery after events of physical disturbances led to an increase of bioturbation rate, burrowing depth and trace fossil diversity. The variegated trace fossil community is rich in individuals and is characterized by deposit feeders (*Scolicia*) and chemosymbiotic strategies (*Saronichnus, Zoophycos*).

The most complex *Zoophycos* trace fossil systems are composed of planar helical spreite structures, which in their lower part change into numerous *Rhizocorallium*-like long lobes. The upper, helical part is interpreted as a deposit-feeding structure, the lobes as sulphide wells for chemosymbiotic bacteria. The steep and deep lobes were probably produced in anoxic sediment. The spreite laminae in the lobes were produced when the trace maker exploited the sediment to obtain the bacteria.

Compared with lithofacies A to C the massive pelitic **lithofacies D** shows a clearly different lithology. With the exception of a few thin sandy layers and lenses the pelites are very uniform, showing no bedding or distinct bioturbation structures. However, it can be speculated, that the massive structure of this pelite is not of primary origin, but that it is due to thorough bioturbation. Synsedimentary deformation structures at the base, mostly load-structures and water-escape structures, affect both the pelites and the underlying sands and are due to the sediment load of the pelites.

Lithofacies A and B are closely related, reflecting sedimentation during short-term intervals of high-energy events with a rapidly declining current velocity in a shallow-marine, sub-littoral environment. Most probably the observed event strata can be attributed to storms.

Typical features of storm-generated sandy beds, given, for example, by Aigner & Reineck (1982), Johnson & Baldwin (1996: p. 248) and Wanless et al. (1988) are 1. sharp erosive base; 2. basal lag of mud-clasts, shells, plant debris and/or rock fragments; 3. normal graded beds (reflecting deposition from suspension); 4. horizontal or low-angle lamination, which, in three dimensional outcrops, can turn out to be a hummocky-type cross-stratification (deposition from suspension pulse); 5. wave-ripple cross-lamination (abating or post-storm bedload movement); 6. a mud blanket at the top; 7. post-event burrowed interval. Most of these characteristics, part of which are similarly developed in Bouma-sequences of turbidite beds (Aigner & Reineck 1982; Nelson 1982), are present in lithofacies A and B. During such storm events strong erosion and reworking by offshore directed bottom currents takes place in nearshore areas (Allen 1982, p. 471 ff.) and sand is transported offshore (Gadow & Reineck 1969). As the current velocity increases, the sea floor is eroded, but as the current wanes, the sediment is deposited as a graded bed (cf. Niedoroda et al. 1989; Swift & Thorne 1991). Fining-upward and erosively bounded beds with horizontal lamination of the upper plane bed and ripples at the top are typical features of storm (cf. Nelson 1982; Johnson & Baldwin 1996: p. 249; Rice 1984). The parallel to low angle lamination of the sandy beds reflects the shooting flow conditions of the upper-flow regime during storms. The overlying asymmetrical ripples or small dunes reflect rapid decrease of transport capacity during waning storms and display a good tool for the reconstruction of the transport direction of the wind induced bottom current (Allen 1982).

The paleocurrent data at Grund point to current directions from WNW–W–SW towards ESE–E–NE. As shown by the molluscan assemblage of the shell-debris horizons, the sediments were transported from nearshore to offshore areas, occasionally with biogenic material from terrestrial sources being involved. These observations correspond to the paleogeographical model, which assumes a coastal area of the Molasse-sea along the margin of the Bohemian Massif, west of Grund.

The highly erosive bases of sandy beds in lithofacies A indicate a high amount of sediment cannibalism. The surviving beds are the truncated basal portions of extreme-event deposits. Pelitic low-energy deposits of fair-weather conditions are thin or even reworked as mud-clasts. These features point to a proximal environment on the upper shoreface (Swift et al. 1991: p. 100).

In lithofacies B the graded sandy beds rarely show an erosive base and they are regularly separated from each other by mud intercalations. Therefore they are interpreted as single-event beds. According to Swift et al. (1991: p. 101) the preservation of such pelitic layers is indicative of a distal environment on the lower shoreface and inner shelf, where the mud caps, deposited during the last stage of waning storm flow, survive through the accumulation process. In the offshore areas the storm layers were normally deposited as tabular to slightly wedge-shaped sand-sheets, only extreme event beds show a channel-like geometry.

Abrasion and fragmentation of molluscan shells in the basal coquinas indicate wave influence in a shallow-marine environment, however their graded appearance suggests that the final transport and deposition of the skeletal elements is due to short-term, high-energy events such as storm flows (cf. Fürsich & Oschmann 1993). The characteristics of the shell concentrations of lithofacies A, like signs of transport, a sharp erosive base and grading are comparable with those described by Fürsich (1995) for proximal tempestites. In lithofacies B the smaller size of shell-debris components points to distal tempestites (cf. Fürsich 1995).

The nearly complete absence of bioturbation within the surviving mud-layers of lithofacies A implies a short recurrence time of storm events, whereas the monospecific bioturbation of *Asterosoma* in lithofacies B can be interpreted as an indication for relatively long-lasting fair-weather periods and/or a more distal environment.

Lithofacies C is still influenced by storms, however, the lesser thickness of sandy storm beds and much thicker, highly bioturbated pelitic beds point to a deeper and hydrodynamically quieter environment. The larger colonization windows allowed the construction of complex trace fossils like *Zoophycos*. In Upper Pleistocene and recent sediments, *Zoophycos* occurs at depths below 1000 m (Löwemark & Schäfer 2003). The *Zoophycos* from the Grund Formation is one of the shallowest (upper offshore–lower shoreface) occurrences of this ichnogenus after the Jurassic (Olivero 2003).

The predominance of horizontal lamination but without grading of the sandy beds is also an indication of a more distal environment, where the energy of storm flows is less effective.

Lithofacies C is connected with the regionally predominant lithofacies of the Grund Formation, which generally consists of clayey to sandy and marly, frequently intensively bioturbated silts, alternating with fine to medium sands in intervals of 2 to 20 cm. Such a distal lithofacies type, quite similar to lithofacies D in section A, appears, for example, west of Grund at the Windmühlberg, in a slightly higher position than in the type area. The mud-dominated lithofacies D in section A can probably be interpreted as a local relic of this muddy facies, which is still widespread in the neighbourhood of the sandy facies at Grund.

At first sight the lithological succession from lithofacies A to B and C to D would imply a development from a proximal to a distal marine environment (cf. Aigner & Reineck 1982) typical for a transgressive system. However, a threefold repetition of these lithofacies was met in the excavated sections and also a lateral change and transitional types of lithofacies are evident. Therefore it can be assumed that not only the transgression of the Early Badenian sea towards the West, onto the Bohemian Massif is responsible for that proximal–distal trend and the lithological and ichnological development. Autocyclic driving forces, like extreme storm events, also additionally influenced the lithological development in the Grund Formation. The distribution of the trace fossil assemblages seem to support this interpretation. Lateral and vertical changes of hydrodynamic energy seems to be the main factor influencing the development and distribution of the different trace fossil assemblages in the Grund Formation (Pervesler & Uchmann 2004). The frequency of sedimentary events and the period of recovery between subsequent events, providing colonization windows of different size, controlled the diversity and intensity of the trace fossil distribution.

From mapping in the distribution-area of the Grund Formation a belt-like distribution of a sandy facies in a direction from WSW to ENE can be recognized clearly on the surface. This observation is also confirmed by a number of drillings (cf. drilling Roggendorf-1: Ćorić & Rögl 2004; but also the drillings at Immendorf and Gottlhof: cf. Fig. 1). That sandy facies within the Grund Formation (including the type area at Grund) can be regarded as an exceptionally thick, sand-rich intercalation of extreme-event deposits, among a number of analogous intercalations within a generally mud-dominated succession.

Acknowledgments: Project 13743-BIO (Temporal and spatial changes of microfossil associations and ichnofacies in the Austrian marine Miocene) and Project P 13745-BIO (Evolution Versus Migration: Changes in Austrian marine Miocene Molluscan Paleocommunities) of the Austrian Science Fund and the Department of Palaeontology at the University of Vienna supported this study. For their help during the excavations we thank Barbara Becker, Hans Behawetz †, Harald Bichler, Gudrun Daxner-Höck, Hubert Domanski, Anton Englert, Manfred Fritz, Sigrid Gmoser, Alexander Hodac, Nadja Kavcik, Markus Lebmann, Martina Marinelli, Tom Masselter, Franz Mayer, Gerhard Reiner, Fred Rögl, Manfred Schmitzberger, Johann Stutz, Thomas Suttner, Petra Tempfer and Franz Topka. For help with the evaluation of paleocurrent data we thank Manfred Schmitzberger and Johann Hohenegger (University Vienna, Department of Palaeontology). For discussion and critical remarks we thank Hans Georg Krenmayr (Geological Survey Vienna), Martin Zuschin (University Vienna, Department of Paleontology) and Fred Rögl (Museum of Natural History, Vienna). For the review of the manuscript we thank Nicolaas Molenaar (Lyngby, Denmark), Tadeusz Peryt (Warszawa, Poland) and Szczepan Porębski (Krakow, Poland). Thomas Suttner (University of Vienna, Department of Paleontology) and Jacek Ruthner (Geological Survey Vienna) did parts of the graphical work.

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