

## Ichnofabrics of the Upper Cretaceous fine-grained rocks from the Stołowe Mountains (Sudetes, SW Poland)

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Upper Cretaceous fine-grained rocks (the “Plänmergel”) from the Stołowe Mountains are in general strongly bioturbated. The sections studied (180 m thick), located in the southern part of the mountains, are dominated by mudstones, marlstones and siltstones; sandstones, partly unbioturbated, are subordinate. The entire sequence shows a succession of ichnofabrics, which reflects a transgressive-regressive cycle (Cenomanian) and a regressive cycle (lower to middle/upper? Turonian). The trace fossil assemblage contains nine ichnogenera: *Asterosoma*, *Cylindrichnus*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Taenidium*, *Teichichnus*, and *Thalassinoides*. Three basic types of ichnofabrics have been recognized: *Ophiomorpha*, *Thalassinoides* and *Phycosiphon*, all representing fully marine ichnofacies. The first two of these belong to the *Cruziana* ichnofacies, indicating the offshore zone, and the third one probably to the *Zoophycos* ichnofacies indicating a quiet shelfal setting below storm wave base.

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### INTRODUCTION

Fine-grained sediments are often partly or completely homogenized by the activity of benthic organisms. Thus, a primary sedimentary fabric is either preserved locally, in patches, or entirely destroyed and replaced by a secondary one termed an “ichnofabric” (Ekdale and Bromley, 1983). In such cases, the interpretation of the palaeoenvironment by standard sedimentological analysis provides little information and so there is a need to investigate the trace fossils. In contrast to body fossils, trace fossils are preserved *in situ* and their distribution in sediments is controlled by different environmental factors: not only water depth, as was originally assumed in the ichnofacies concept of Seilacher (1967), but also wave/current activity, substrate type, salinity, and oxygen and benthic food contents (Rhoads, 1974; Byers, 1982; Bromley and Ekdale, 1986). Therefore the description and study of trace fossils, their assemblages, density and especially the relationships between them, known generally as ichnofabric analysis (Bromley and

Ekdale, 1986; Ekdale and Bromley, 1991), have become widespread. Ichnofabric analysis may be used for all types of deposits, but is particularly valuable in the case of fine-grained, intensively bioturbated sediments; sometimes it is the only method to elucidate the sedimentation history in a given setting.

The Upper Cretaceous of the southern part of the Stołowe Mountains, in Poland, is represented by a succession up to 180 m thick consisting of fine-grained rocks and minor sandstones (Figs. 1 and 2). Most of them are strongly bioturbated, but until recently relatively little was known about the trace fossils assemblages of these deposits. Almost all previous studies have focused on their petrographic composition (e.g. Radwański, 1959, 1966a, b) and environmental interpretation was based on textural features, though it was noticed that the fine-grained rocks were burrowed. Only two papers identified ichnogenera. Radwański (1959) recognized *Ophiomorpha nodosa* and Jerzykiewicz and Wojewoda (1986) mentioned the presence of *Chondrites*, though my research indicates the latter identification is doubtful. This paper provides the first detailed ichnological study of these deposits.

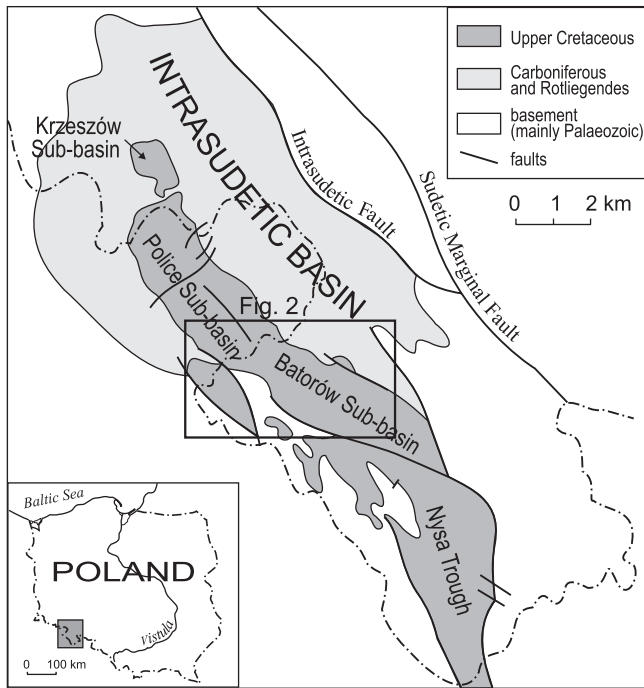


Fig. 1. Extent of Upper Cretaceous rocks in the Intrasudetic Basin

GEOLOGICAL SETTING

STRATIGRAPHY

The Upper Cretaceous rocks forming the Stołowe Mts. occur in the central part of the Intrasudetic Basin (Fig. 1): they transgressively overlie Lower Permian and Carboniferous deposits as well as Variscan crystalline rocks. The thickness of the Cretaceous deposits varies in each sub-basin, reaching ca. 400 m in the Batorów Sub-basin (Jerzykiewicz and Wojewoda, 1986) (Figs. 1–3). Two basic lithologies can be distinguished: (1) sandstones and subordinate conglomerates, and (2) various types of fine-grained rocks. The Germans who first investigated these rocks in the second half of the 19th century termed them Quadersandstein and Plänermergel respectively (e.g. Geinitz, 1843; Beyrich, 1849) and these names have been used in regional studies to date.

In the northern part of the Stołowe Mts. there are at least three units of Quadersandstein separated by Plänermergel (Figs. 2 and 3). The lower sandstone unit forms a continuous cover in the area, whereas the middle unit thins gradually towards the south-west. Therefore, in the southern part of the area there is only one interval of the Plänermergel rocks, which formed to-

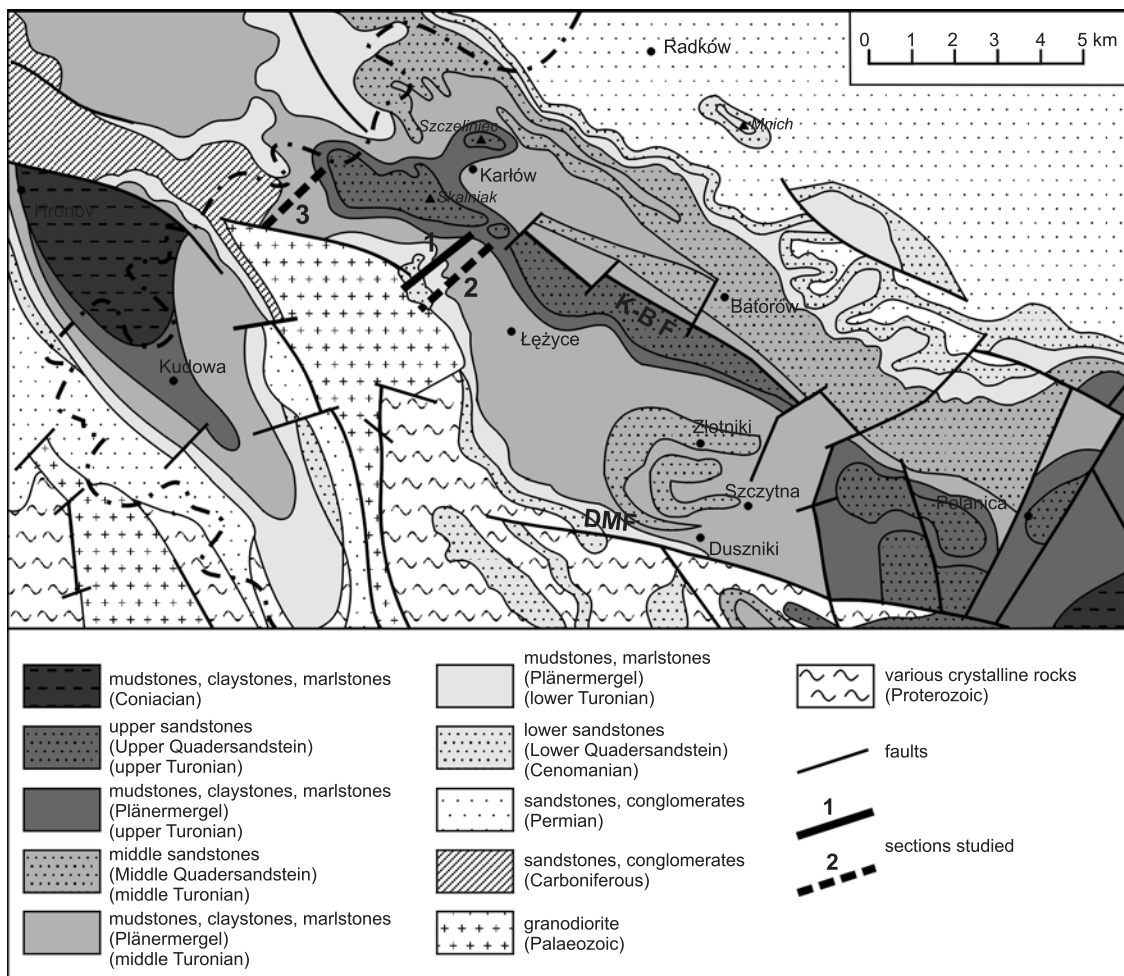


Fig. 2. Geological map of the Batorów Sub-basin and adjoining areas (after Sawicki, 1995, simplified) showing locations of the sections studied

K-B F — Karłów-Batorów Fault; DMF — Duszniki Marginal Fault

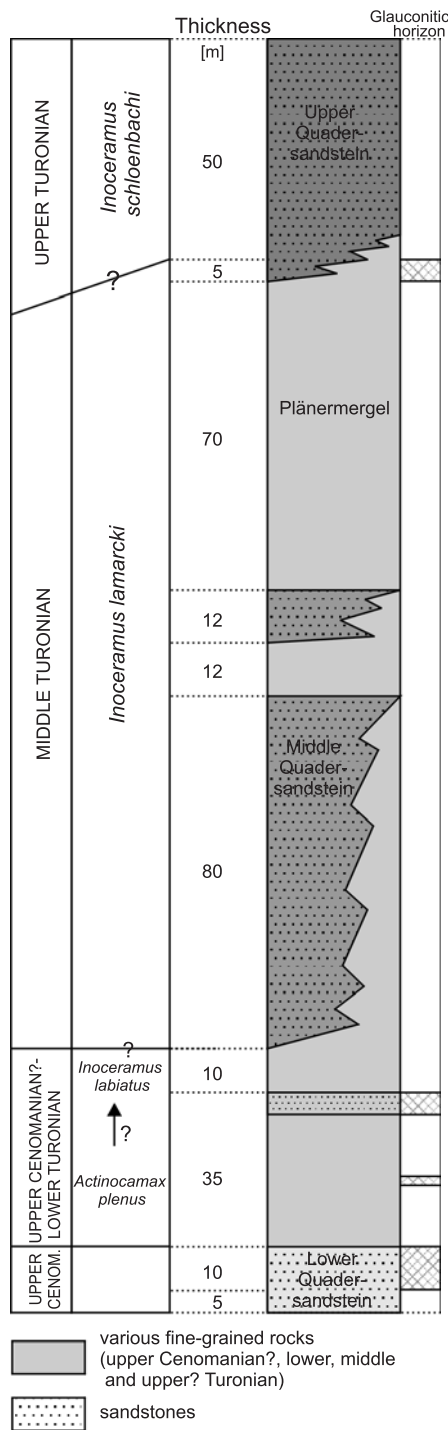


Fig. 3. Stratigraphy of the northeastern part of the Stołowe Mts. (after Jerzykiewicz and Wojewoda, 1986)

gether with underlying sandstones, the object of my research. By comparison with the middle sandstone unit, the upper one is less widespread and appears as remnant outliers (Fig. 2).

The stratigraphy was first studied by the Germans in the 19th century. The biostratigraphy used today for this region is based mostly on inoceramids. It was outlined initially by Radwański (1975) and was later modified by Jerzykiewicz and Wojewoda (1986). According to the latter authors, the entire succession represents the upper Cenomanian to upper Turonian interval (Fig. 3). However, according to Čech *et al.* (1980) the Upper

Quadersandstein may be partly Coniacian in age. Due to a few poorly preserved index fossils in the rocks studied the boundaries of Cenomanian and Turonian stages and substages are not well documented. Particularly, the boundaries between the lower, middle and upper Turonian within fine-grained rocks in the southern part of the Stołowe Mts., shown in Figure 2, should be treated as approximate.

#### DEPOSITIONAL SETTING

Sedimentation in the Intrasudetic Basin during the Late Cretaceous began during the worldwide Cenomanian transgression (e.g. Schlanger, 1986; Haq *et al.*, 1988). It continued until the late Turonian (Coniacian?) and was influenced by Laramide block tectonics (Jerzykiewicz, 1967, 1968a; Radwański, 1975; Vejlupek, 1986). Thus the Cretaceous deposits commence with typical basal conglomerates overlain by sandstones, which together form the Lower Quadersandstein that is commonly described as transgressive. By contrast, the middle and upper sandstone units show remarkable giant-scale cross-bedding occurring in sets up to 18 m thick with foresets normally dipping southwestwards (Jerzykiewicz, 1968b; Jerzykiewicz and Wojewoda, 1986; Wojewoda, 1989). Several hypotheses have been proposed to explain the depositional environment; a short review of these ideas was given by Uličny (2001). Two of the more recent ones are mentioned here. Jerzykiewicz and Wojewoda (1986) and Wojewoda (1989) interpreted these sandy units as being deposited in a shallow epicontinental sea, on the lee side of fault-controlled scarps (so-called "accumulation terraces") while Uličny (2001) considered that they represented coarse-grained, Gilbert-type deltas. The first interpretation was limited to the Polish part of the Stołowe Mts., i.e. to the Batorów Sub-basin, whereas the latter one was extended to other sandstone bodies of similar facies not only in the Intrasudetic Basin, but also through the entire Bohemian Cretaceous Basin (Uličny, 2001).

The Plänermergel rocks appear in exposures as structureless and homogeneous. They have always been regarded as the time equivalent of the sandstones, deposited in the deeper part of the basin where sedimentation was dominated by fallout from suspension (e.g. Radwański, 1975; Ziółkowska, 1996). Recently, in the southern part of the Stołowe Mts. some different facies have been distinguished, among them being various bioturbated fine-grained rocks (marlstones, mudstones, spongiolites) and sandstones as well as silty storm deposits. The succession of these facies is described below (for details see Rotnicka, 2000, 2001).

#### SECTIONS STUDIED

Ichnofabrics have been studied in three stream sections in the southern part of the Stołowe Mts. (Fig. 2). Sections 1 and 2 show a complete Upper Cretaceous section in this region, i.e. from the upper Cenomanian to the middle (upper?) Turonian, whereas section 3 shows only the Turonian succession. The thickness of deposits in sections 1–3 is 180, 150 and 160 m respectively. As all three sections show similar trace fossil as-

semblages and ichnofabric successions, only section 1 (Fig. 2) is shown herein. The data from other sections have been used to complete the data set.

The lowermost, Cenomanian, part of sections 1 and 2 represents a transgressive-regressive cycle (Wojewoda, 1989; Rotnicka, 2000). It begins with basal conglomerates and sandstones (Lower Quadersandstein) grading upwards into grey siliceous mudstones with pale grey spongiolite lenses and ending with a glauconitic, siliceous sandstone (for details see Fig. 10). One glauconitic horizon occurs within these siliceous mudstones and it probably marks the transgression maximum (Plint and Uličny, 1999; Rotnicka, 2000). From the lower Turonian onwards, all three sections are lithologically similar and generally show an overall coarsening-upwards trend, interpreted to be related to regression (Rotnicka, 2000). They consist of mostly fine-grained rocks dominated by massive dark grey calcareous spongiolites<sup>1</sup> passing into grey siliceous-calcareous mudstones and marlstones. Limestones appear sporadically (Rotnicka, 2000). In the uppermost portion of the sections some siltstone and sandstone interbeds are present.

In places, in the upper parts of all sections (middle Turonian) rhythmic bedding is present. It is expressed by “platy” calcareous mudstone layer 5–15 cm thick alternating massive, nodular marlstone or limestone layers 20–40 cm thick. These rhythms are accompanied by fluctuations in spicule and quartz contents (Rotnicka, 2001). Some marlstones and limestones are also rich in foraminifera.

## TRACE FOSSILS

### METHODS

Samples were collected systematically through sections 1–3 (Fig. 2). Altogether 240 samples were studied. The majority of observations on the ichnofabrics were conducted on slabs cut in different directions, with some observations on parting surfaces and weathered exposures. This procedure enabled a three-dimensional analysis of the trace fossils. To enhance the contrast between the structures observed and their background, which in case of the Plänmergel rocks is very low, slabs were polished and saturated with oil (Bromley, 1981).

### ICHNOSPECIES

***Asterosoma* isp.** (Figs. 4a, c and 7b, c). In vertical cross-sections cut at successive half-centimetre intervals this appears as slightly inclined cylindrical and flattened tunnels, 15–30 mm in horizontal diameter. Central tubes placed either centrally or eccentrically are filled with structureless material similar to that of the host rock and these are surrounded by a thick, dark, laminated lining. These trace fossils occur in clusters (Figs. 4c and 7c) or individually (Figs. 4a and 7b), both in calcareous mudstones and marlstones.

<sup>1</sup>Calcareous spongiolites are composed of calcified spicules (40–50%) of siliceous sponges in muddy-calcareous-siliceous host sediments (Rotnicka, 2000). This term is used to distinguish this type of rock from typical spongiolites, which are entirely siliceous.

Traces occurring in clusters may constitute a fragment of *Asterosoma radiceforme* (see Chamberlain, 1971), but as they were traced only in slabs and their entire morphology is unknown the taxonomic affinity to this ichnospecies is uncertain. On the other hand individual traces may represent the single burrows described by Spencer (1977 in Chamberlain, 1978) or the fragments of branched burrows shown by Dresser (1970 in Chamberlain, 1978).

The completely mottled background to these ichnofossils (Figs. 4c and 7b, c), and the cross-cutting by other trace fossils (Fig. 7b), suggest their near-surface formation with upward extension (Miller and Knox, 1985). According to Gregory (1985), *Asterosoma* expresses selective and progressive reworking of deposits from the central dwelling tube outwards and towards a surface layer rich in organic matter.

***Cylindrichnus* isp.** (Figs. 4b, c and 8a, b). These are single, isolated, unbranched, cylindrical, steeply inclined or vertical burrows, 2–10 mm in diameter. The lining is dark and only in some specimens is thick and gently, concentrically laminated (Fig. 8a, b). A central core, 1–3 mm in diameter, is filled with material similar to the host rock. The maximum length traced is 45 mm. *Cylindrichnus* is present in limestones, siliceous marlstones, and calcareous-siliceous mudstones.

Burrows of *Cylindrichnus* isp. are known as vertical and steeply inclined forms characteristic of high-energy environments (Howard and Frey, 1984; Frey and Howard, 1985; Frey, 1990), as well as forms which are horizontal and slightly oblique to the bedding plane which dominate in low-energy conditions (Fürsich, 1974; Frey, 1990). Frey and Howard (1985) have mentioned single structures that show connection with the surface layer, but it is uncertain whether one can attribute the same feature to horizontal structures occurring in groups. Therefore Uchman and Krenmayr (1995) consider that it is still unclear whether the vertical and horizontal forms should be assigned to the same ichnospecies.

Larger specimens of horizontal *Cylindrichnus* are similar to single burrows of *Asterosoma* and vertical ones are difficult to distinguish from the lower parts of *Rosselia* isp. (Frey and Howard, 1985). Since the broadening upward cone characteristic of *Rosselia* isp. has not been observed, the structures described are attributed to *Cylindrichnus* isp. with both vertical and steeply inclined burrows being included here in this ichnogenus.

***Ophiomorpha* isp.** (Figs. 4d and 7a, c, d). Most of the observed specimens are horizontal, Y-shaped branched cylindrical burrows, 7–15 mm in diameter. Walls are very distinct and consist of regularly, closely spaced muddy pellets (1–2 mm in diameter) (Figs. 4d and 7d); the lining is thin (max. 1 mm thick). Rarely-occurring vertical structures show thin walls with irregularly spaced, individual, elliptical pellets. The fill of tunnels is structureless and similar to the host rock. The shape of the pellets and their arrangement suggest that most of the specimens observed can be assigned to *Ophiomorpha nodosa* (Figs. 4d and 7d), and some vertical forms to *O. irregulare* (Frey *et al.*, 1978). Most of the specimens have been found in sandstones, and some in calcareous mudstones and siltstones.

*Ophiomorpha* isp. is a good environmental indicator. Horizontal burrows predominate in low-energy environments and vertical ones in high-energy environments (Frey *et al.*, 1978;



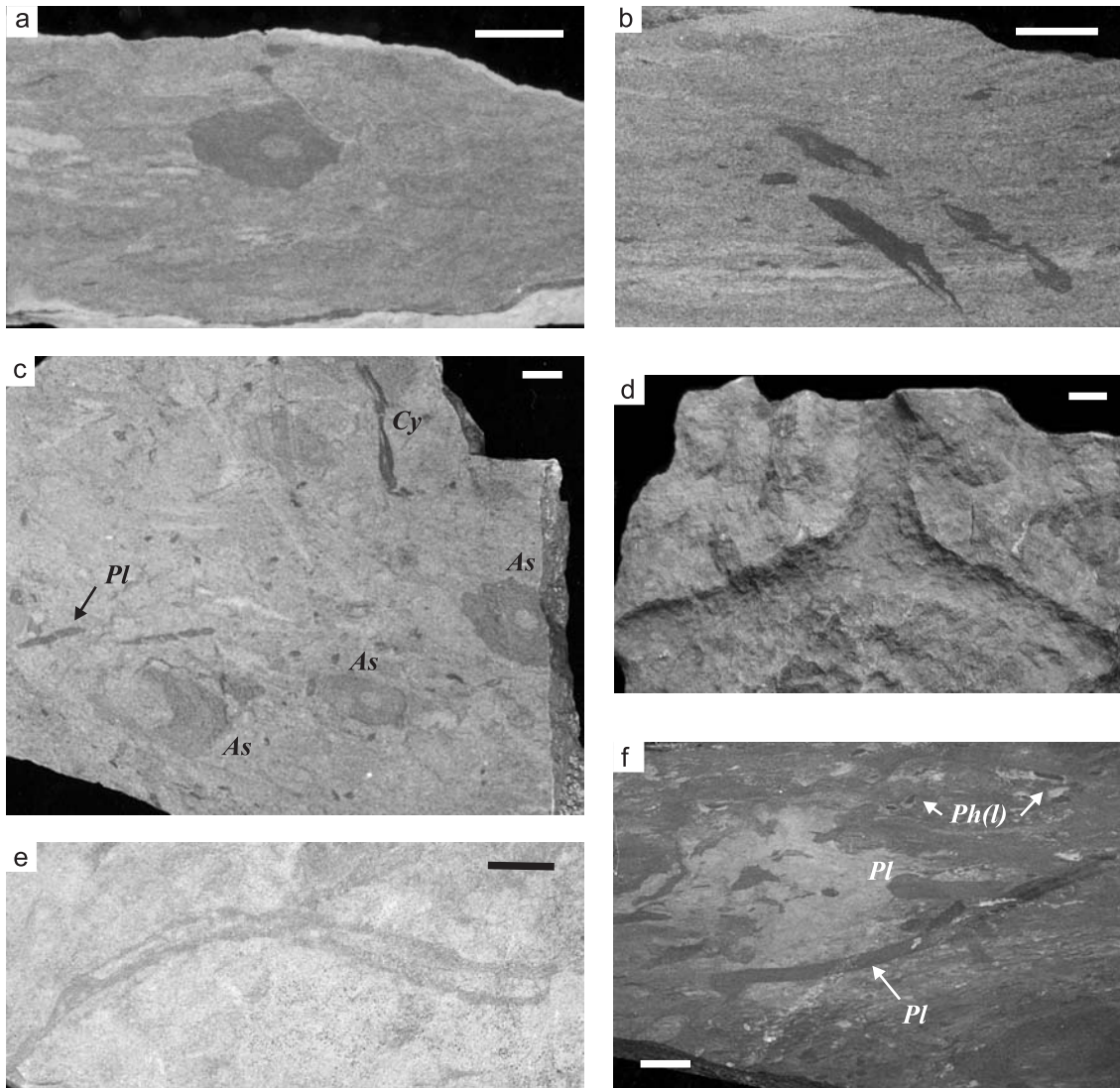


Fig. 4. Trace fossil assemblages

**a** — individual *Asterosoma* in totally bioturbated siliceous-calcareous mudstone, vcs, S1; **b** — *Cylindrichnus*, laminated calcareous mudstone, vcs, S2; **c** — *Asterosoma* (*As*) occurring in clusters, *Cylindrichnus* (*Cy*) and *Planolites* (*Pl*), mottled background, silty limestone, vcs, S3; **d** — *Ophiomorpha nodosa*, glauconitic siliceous sandstone, horizontal parting surface, S1; **e** — *Palaeophycus*, totally bioturbated calcareous sandstone, hcs, S1; **f** — *Planolites* (*Pl*) and large forms of *Phycosiphon incertum* (*Ph(l)*), totally bioturbated calcareous spongiolite, vcs, S2; **a–c** — *Thalassinoides* ichnofabric, **d, e** — *Ophiomorpha* ichnofabric, **f** — *Phycosiphon* ichnofabric; scale bar — 1 cm; vcs, hcs — vertical and horizontal cross-sections, respectively; S1, S2, S3 — section numbers

Howard and Frey, 1984; Pollard *et al.*, 1993). Distinct, knobby walls provide evidence that the burrows have been made in loose sand (Frey *et al.*, 1978).

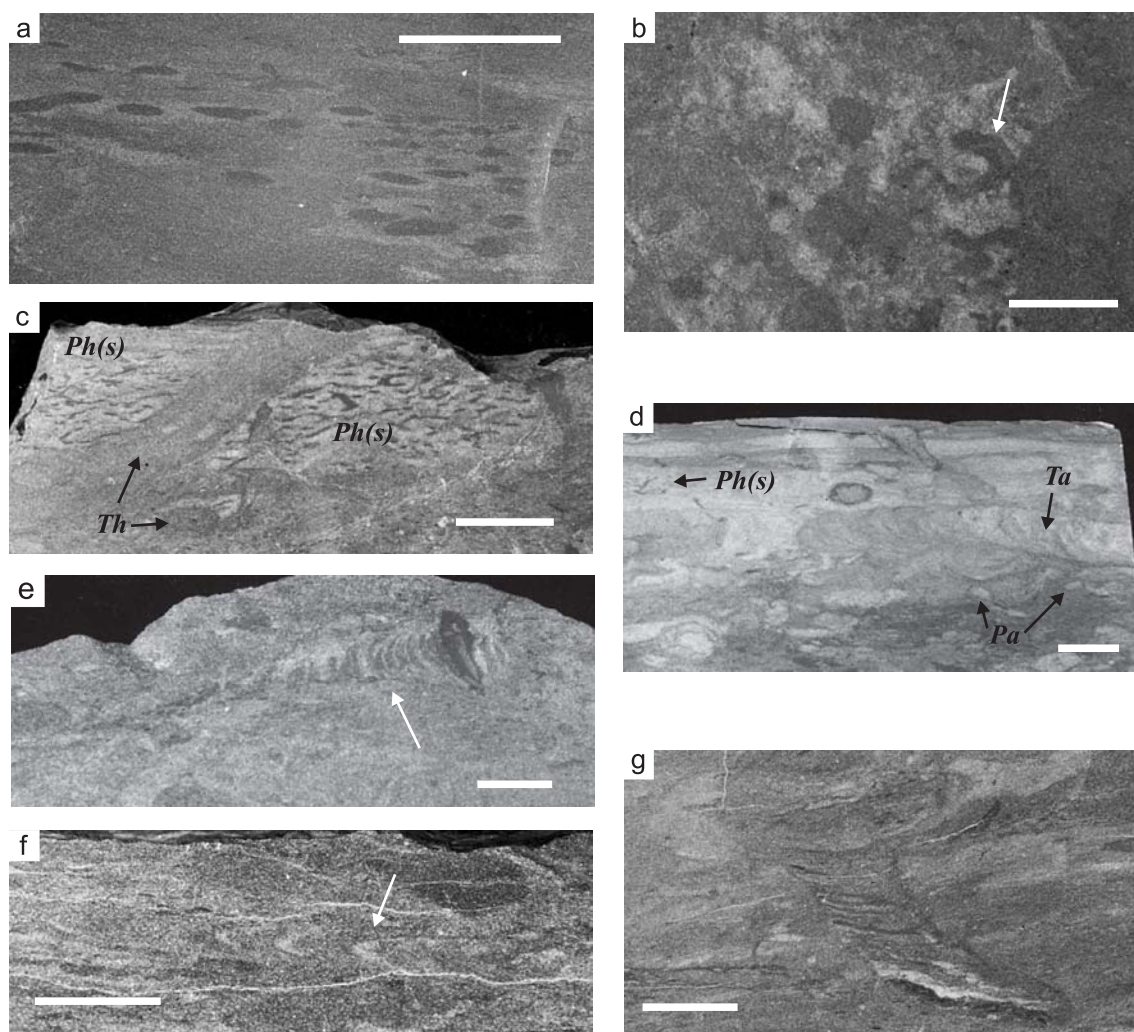
***Palaeophycus* isp.** (Figs. 4e, 6b, 7a, b, e and 8c). This appears as subhorizontal, gently winding, lined tubes. In cross-section they are elliptical with a horizontal axis 3–10 mm and a vertical axis 2–5 mm long. The lining is commonly thick and dark grey or green in colour, contrasting with the structureless fill and host rock (pale grey siltstones, grey mudstones and cream-coloured or glauconitic sandstones).

Pemberton and Frey (1982) revised and reduced *Palaeophycus* to five component ichnospecies. They also gave unequivocal ichnotaxbases: the character of the fill and the external surface of the lining. Since the trace fossils have been observed mainly on slabs it is impossible to determine the wall surface and thus assign given specimens to any ichnospecies.

Features of the burrow-fill show that the animal neither sorted nor reworked deposits, but formed originally open tubes, which later were filled passively with sediment.

***Phycosiphon* isp.** (Figs. 4f, 5a–c, 6c and 8). In vertical cross-sections this appears as strongly elliptical, small spots with dark (nearly black) cores surrounded by a pale grey mantle. Two size classes of this trace fossil can be determined:

— large forms (Figs. 4f, 5a, b, 6c and 8d, e) occur mostly in horizontal planes. The cores range between 1.7 and 4.2 mm in diameter (average 2.6 mm); in vertical sections a strong flattening is visible. Due to intensive bioturbation only fragments of U- and J-shaped lobes can be traced (Fig. 5b). There is no perceptible trace of spreiten between arms. This trace fossil occurs only in calcareous spongiolite and here, when compared with the host rock, the core is depleted, and the mantle is enriched, in sponge spicules;



**Fig. 5.** Trace fossil assemblages

**a, b** — large forms of *Phycosiphon incertum* in homogeneous calcareous spongiolite: **a** — easily visible pale mantle, vcs, S1; **b** — fragment of U-shaped lobes, hcs, S1; **c** — small forms of *Phycosiphon incertum* (*Ph(s)*) cross-cut by *Thalassinoides* (*Th*), totally bioturbated marlstone, vcs, S1; **d** — *Taenidium* (*Ta*), *Palaeophycus* (*Pa*), small *Phycosiphon incertum* (*Ph(s)*), moderately bioturbated marlstone (relicts of horizontal lamination visible), vcs, S2; **e, f** — *Taenidium*, siliceous-calcareous mudstones, vcs, S1; **g** — *Teichichnus*, calcareous-siliceous mudstone, vcs, S1; **a, b** — *Phycosiphon* ichnofabric, **c–g** — *Thalassinoides* ichnofabric; other explanations as on [Figure 4](#)

— small forms ([Figs. 5c](#) and [8](#)) occurring without any spatial pattern in all Plänermergel rocks. Cores are less than 0.8 mm in diameter. Both in horizontal, vertical and oblique cross-sections these appear as dark hooks in a paler patchy background. The background is also paler than the host rock, which is probably due to merging of the mantles of closely packed burrows. Probably because of the manner of cementation, spreiten are not seen.

This trace fossil has recently been classified as *Phycosiphon incertum* (Wetzel and Bromley, 1994), the only ichnospecies among this ichnogenus. It has been previously described as *Anconichnus horizontalis*, *Helminthopsis* and *Chondrites* (for lists of synonyms see Fu, 1991 and Wetzel and Bromley, 1994). Kern (1978), who first recognized *A. horizontalis*, described it as structures 0.2–2.0 mm across; Goldring *et al.* (1991) distinguished two size classes: small (cores 0.25–0.75 mm in diameter) and large (cores 1–2 mm in diameter) forms. The class of small forms recognized here con-

forms to that of Kern (1978) and Goldring *et al.* (1991), but the maximum size of the larger structures is twice that of Goldring *et al.* (1991). In general, such large forms occur seldom — the only similar example cited was figured by Bromley (1996).

***Planolites* isp.** ([Figs. 4f, 7e](#) and [8a–c, e](#)). This is a horizontal burrow, randomly oblique to layering, slightly winding, unlined and 1–4 mm in diameter. The fill is structureless, often much darker than and contrasting with the host rock. It is present throughout the Plänermergel rocks.

According to Pemberton and Frey (1982), ichnospecies are distinguished on the basis of the burrow size, amount winding, and the character of the burrow boundary. Again, because the observations have been carried out on slabs, the last two criteria could not be applied in this study. Using the first criterion, the specimen described may be assigned to *Planolites montanus*.

***Taenidium* isp.** ([Fig. 5d–f](#)). This appears as horizontal, cylindrical, unbranched, and unlined, actively filled burrows. It occurs in all types of Plänermergel rocks, excluding calcareous



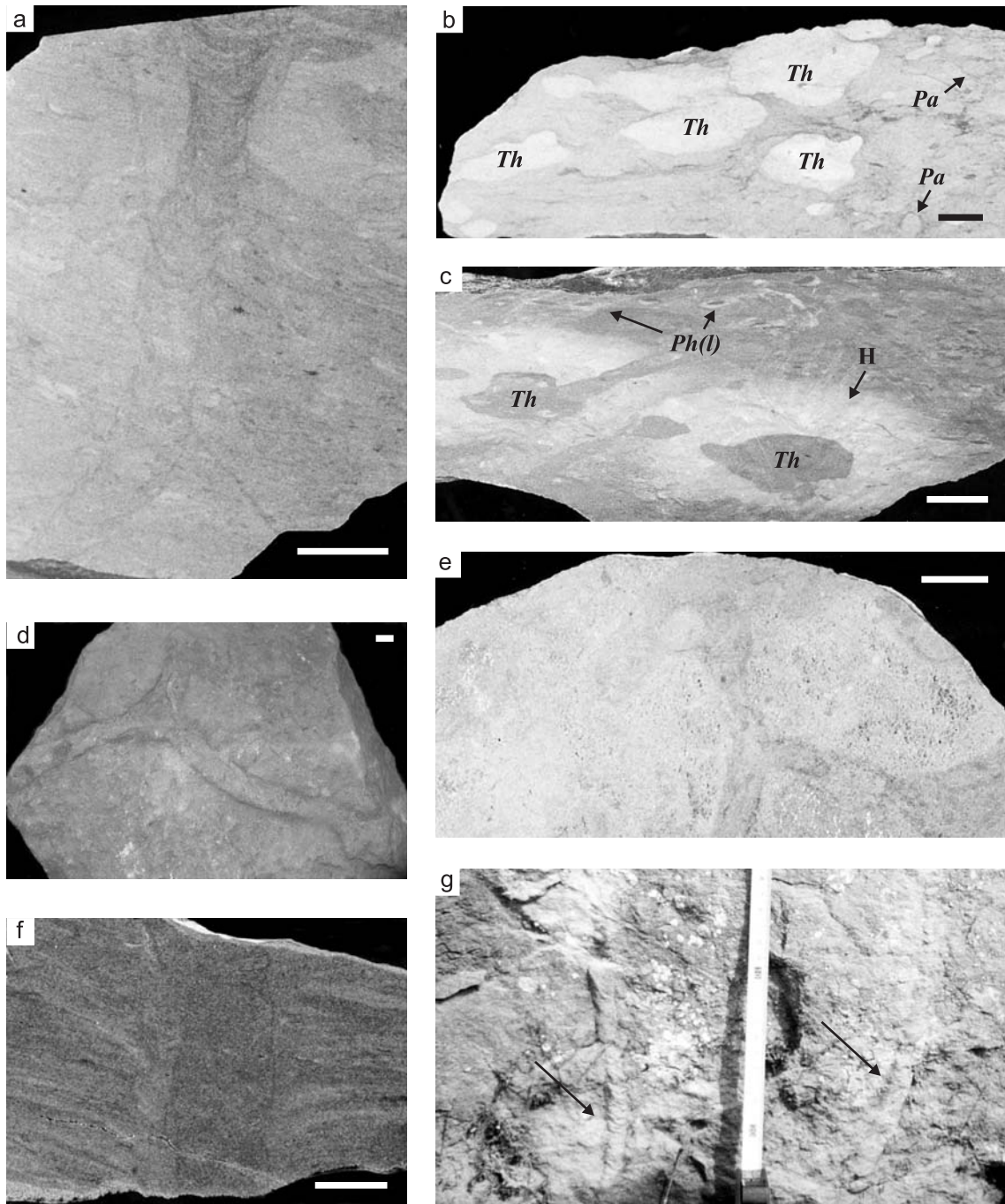


Fig. 6. Trace fossil assemblages

**a** — *Teichichnus rectus*, siliceous marlstone, vcs, S3; **b** — *Thalassinoides* (*Th*) and *Palaeophycus* (*Pa*), siliceous mudstone, vcs, S1; **c** — *Thalassinoides* (*Th*) surrounded by halo (*H*) and *Phycosiphon incertum* (*Ph(l)*), mottled background, calcareous spongiolite, vcs, S1; **d** — *Thalassinoides*, calcareous-siliceous mudstone, horizontal parting surface, S2; **e** — branching *Thalassinoides*, siliceous-calcareous mudstone, hcs, S1; **f** — shaft in laminated calcareous sandy mudstone, vcs, S3; **g** — shafts in totally bioturbated calcareous sandstone, weathered exposure wall, S2; **a, b, d, e** — *Thalassinoides* ichnofabric, **c** — *Phycosiphon* ichnofabric, **f, g** — *Ophiomorpha* ichnofabric; other explanations as on Figure 4

spongiolites. Based on the fill structure and burrow size, two types of this trace fossil can be described:

— burrows 5–8 mm in diameter having a meniscate fill (Fig. 5d, e) with arcuate to deeply arcuate lamellae. Distance between neighbouring menisci is less than the burrow diameter. In the case of semicircular menisci that merge at the tube margin, an impression of the wall results;

— burrows 2–3 mm in diameter filled with chevron-shaped alternating thin (0.5–1.5 mm), pale and thick (4.5–5.5 mm), dark packets of sediment (Fig. 5f).

The taxonomy of meniscate filled trace fossils (*Muensteria*, *Taenidium*, *Beaconites*, *Ancorichnus*) was discussed by D'Alessandro and Bromley (1987) and Keighley and Pickerill (1994); all authors agreed that the only unequivocal criterion of

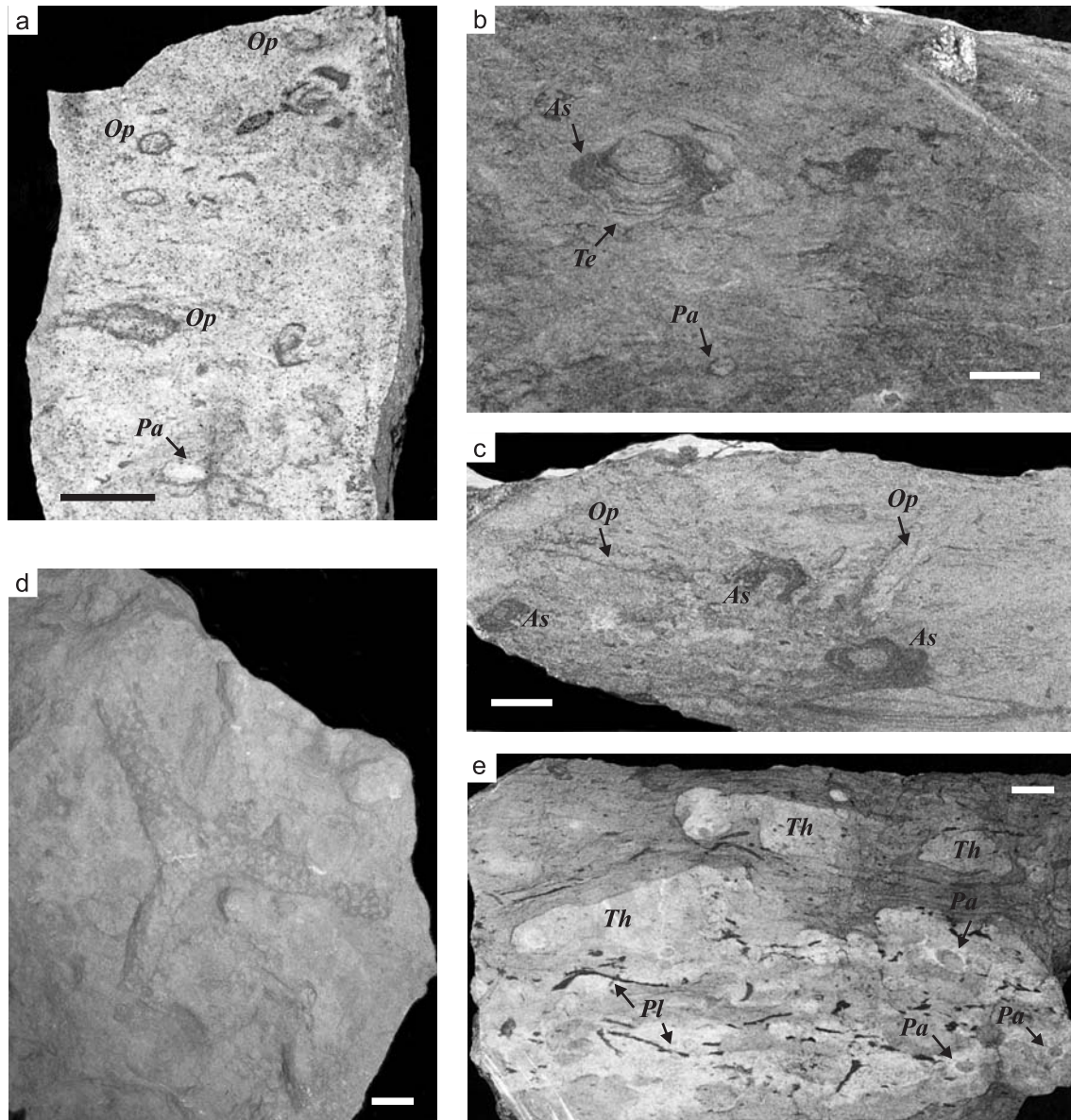


Fig. 7. Ichnofabrics

**a–d** — *Ophiomorpha* ichnofabric: **a** — type Oa (*Op* — *Ophiomorpha*, *Pa* — *Palaeophycus*), siliceous glauconitic sandstone, vcs, S2; **b**, **c** — type Ob (*As* — *Asterosoma*, *Te* — *Teichichnus*, *Pa* — *Palaeophycus*, *Op* — *Ophiomorpha*), calcareous sandstones, vcs, S2; **d** — type Oa, easily visible Y-branched *Ophiomorpha nodosa*, siliceous glauconitic sandstone, horizontal parting surface, S2; **e** — *Thalassinoides* ichnofabric, type Ta, *Thalassinoides* (*Th*) reworked partly by *Planolites* (*Pl*) and *Palaeophycus* (*Pa*), siliceous mudstone with spongiolites, vcs, S1; other explanations as on [Figure 4](#)

ichnospecies determination is the structure of the fill. The first of the trace fossils described above resembles *Taenidium serpentinum*. The other one is seemingly possesses features of two ichnogenera: *Taenidium* and *Beaconites*. The lack of any lining suggests affinity to *Taenidium*. On the other hand, none of the *Taenidium* isp. have a chevron filling, which is typical of *Beaconites capronus* (= *Ancorichnus horizontalis*, Howard and Frey, 1984). The lining of *B. capronus* is very thin and weathers quickly (Howard and Frey, 1984). The samples investigated were fresh and, therefore, the lack of a lining suggests inclusion of this specimen in *Taenidium* isp.

***Teichichnus* isp.** (Figs. 5g, 6a and 7b). This has the form of vertically or obliquely stacked spreite. In cross-section, the width of this trace fossil ranges from 5 to 15 mm and the length

from 20 to 70 mm. It is present in very fine and fine-grained calcareous sandstones, siltstones and mudstones.

Long structures with retrusive spreite (Fig. 5g) may be classified as *Teichichnus rectus* (Frey and Bromley, 1985). This is generally interpreted as dwelling/feeding burrows of a deposit feeder; furthermore, the retrusive spreite probably represents an equilibrium response to a slowly aggrading substrate (Pemberton *et al.*, 1992a).

***Thalassinoides* isp.** (Figs. 6b–e and 7e). Most of the observed specimens are horizontal. Burrows are cylindrical, 7–35 mm in diameter, and they often display an elliptical cross-section. The lining is extremely thin, but the burrow boundary is quite distinct. The fill is structureless and differs from or is similar to the host rock. Y-shaped branching with



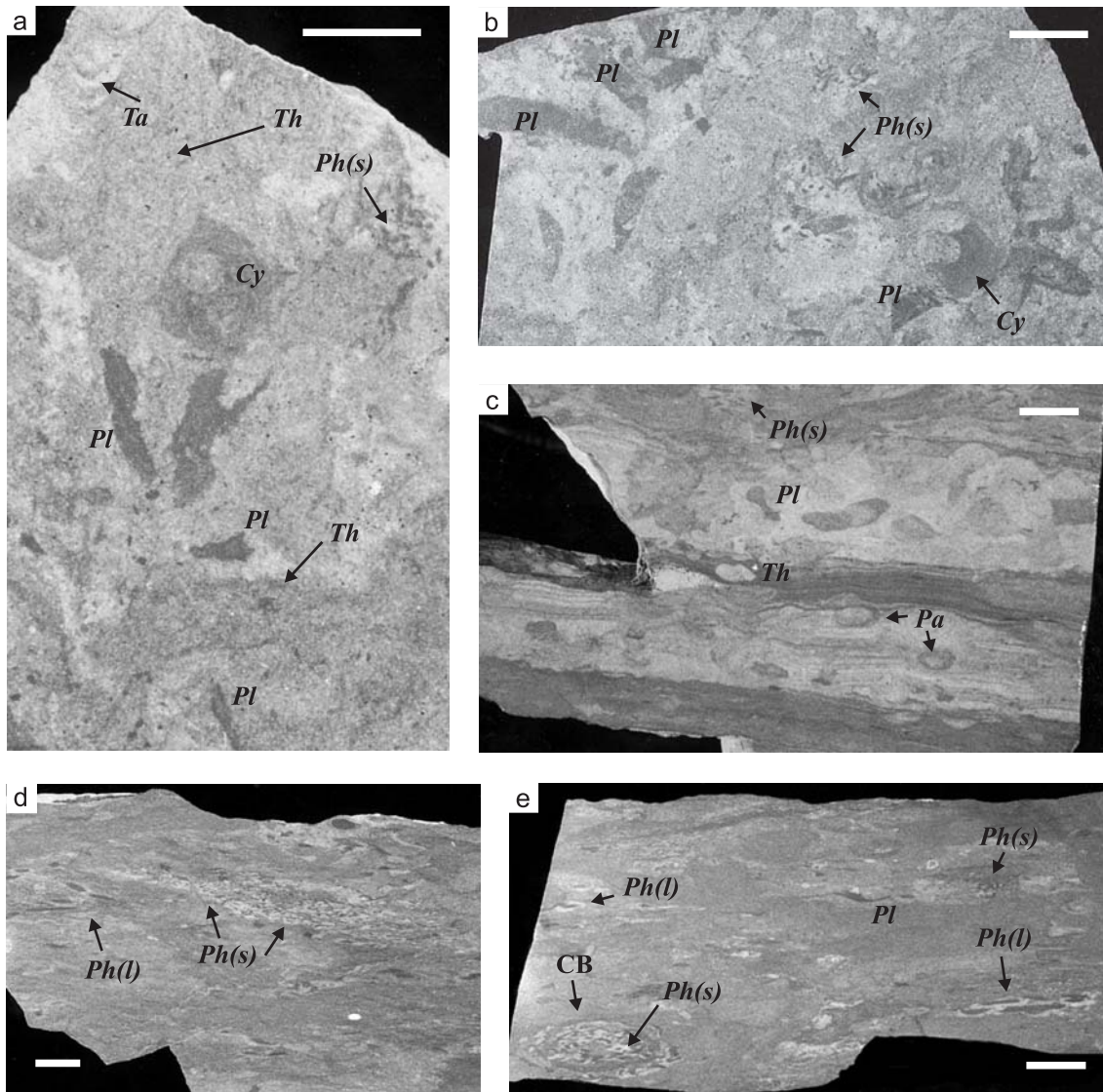


Fig. 8. Ichnofabrics

**a–c** — *Thalassinoides* ichnofabric: **a, b** — type Ta, vertical *Cylindrichnus* (Cy) with thick, concentric lining, small forms of *Phycosiphon incertum* (Ph(s)), *Planolites* (Pl), *Thalassinoides* (Th) and *Taenidium* (Ta), mottled background, siliceous mudstone with spongiolites, hcs, S1, **c** — type Tb within storm beds (small forms of *Phycosiphon incertum* (Ph(s)), *Planolites* (Pl), *Thalassinoides* (Th), *Palaeophycus* (Pa)), calcareous-siliceous mudstone with silty interbeds, vcs, S3; **d, e** — *Phycosiphon* ichnofabric (Ph(s), Ph(l)) — small and large forms of *Phycosiphon incertum*, respectively, Pl — *Planolites*, CB — composite burrow: probably *Thalassinoides* reworked by *Phycosiphon*, calcareous spongiolite, vcs, S1; other explanations as on [Figure 4](#)

thickening in places of bifurcations has been observed. The trace fossils described occur in all types of mudstones, siltstones and fine-grained sandstones.

The lack of, or a very thin lining are characteristic of fine-grained, coherent ground, in which burrows do not need additional strengthening of their walls (Howard and Frey, 1984). Structureless fill often represents passive way of sedimentation constrained by gravitation (Pemberton *et al.*, 1992a). Since in most cases the fill differs clearly from the surrounding material ([Figs. 6b](#) and [7e](#)), it probably originated from lithologically different layers, which, however, have not been traced in the sections. These layers, if thin enough, may have been reworked by animals and mixed with the underlying sediments.

**Other trace fossils.** Shafts ([Fig. 6f, g](#)) which take the form of vertical, cylindrical, thinly lined burrows, 8–15 mm in diam-

eter and up to 50 cm long. The fill is often meniscate. The taxonomic affinity of these specimens is unclear; however, according to Frey *et al.* (1978), some of these may represent shafts of *Ophiomorpha* and so the meniscae indicate an abandoned burrow component that was actively backfilled by the animal. These burrows are found in horizontally laminated fine-grained sandstones and siltstones.

Composite burrows (Chamberlain, 1975) ([Fig. 8e](#)) are predominately horizontal, unlined, elliptical in cross-sections burrows, 20–25 mm in diameter, filled with material paler than the host rock, and cut by small forms of *Phycosiphon incertum*. Larger burrows are probably of *Thalassinoides* type, which is regarded as one of the shallowest trace fossils and thus is often cut by other deeper penetrating burrowers. Composite burrows are particularly characteristic of calcareous spongiolites.

Halo burrows (Chamberlain, 1975) (Fig. 6c) are horizontal, cylindrical, branched burrows filled with material similar to that of the host rock and surrounded by a paler zone, the external margin of which is gradational (the so-called “halo”). Its size exceeds the burrow diameter. Halo burrows are typical of calcareous spongiolites.

Other bioturbation structures include mottles (Chamberlain, 1975) (Fig. 7b, c, e), which are faint, variably shaped spots composing the background for more distinct, recognizable trace fossils. The character, distinctiveness and intensity of mottles depend on the rock type, but in general they are present in almost all samples. They indicate intensive and repeated reworking of sediment in the topmost, “mixed” layer, that partly may have represented a soupy substrate.

#### ICHTNOFABRICS

Three main ichnofabrics (*Ophiomorpha*, *Thalassinoides* and *Phycosiphon*) have been distinguished among the Upper Cretaceous rocks from the southern part of the Stołowe Mts.

The *Ophiomorpha* ichnofabric (Figs. 4d, e, 7a–d and 9A) is dominated by horizontal burrows of *Ophiomorpha* isp. and *Ophiomorpha nodosa* that very rarely cross-cut *Palaeophycus*. This type of ichnofabric occurs in fine- to medium-grained siliceous glauconitic sandstones of Cenomanian age as well as in fine-grained calcareous sandstones of middle Turonian age (Fig. 10). The ichnofabric varies slightly depending on lithology. In Cenomanian glauconitic sandstones, trace fossils are easily visible due to the greenish colour of the trace fossil walls (Fig. 7a). *Ophiomorpha* and *Palaeophycus* are the only ichnofossils recognized and they occur within the homogenized sediments (ichnofabric type Oa, Fig. 7a, d). In thick and very thick calcareous sandstone interbeds of the middle Turonian the ichnofabric additionally contains single shafts. The background is generally mottled, only sometimes with relicts of primary lamination, and furthermore, in some cases, it contains coalified plant detritus. As the thickness of these sandstone interbeds increases, the diversity of trace fossil assemblage also increases, *Planolites* and single *Teichichnus* cross-cutting *Asterosoma* appear (ichnofabric type Ob, Fig. 7b, c).

The *Thalassinoides* ichnofabric (Figs. 4a–c, 5c–g, 6a, b, d, e, 7e, 8a–c and 9B) may be described in terms of complete (type Ta) and incomplete (type Tb) categories. Even though both contain the same trace fossil assemblages, they have different appearances.

The first type (Ta) is composed of abundant horizontal *Thalassinoides* cross-cut by black *Planolites* and *Palaeophycus* (Fig. 7e) accompanied by individual *Cylindrichnus*, *Taenidium*, and small *Phycosiphon*. The background is totally bioturbated and characterized by dense mottles; there is no evidence of primary sedimentary structures. *Palaeophycus* and *Cylindrichnus* cut *Planolites* (Fig. 8a, b). *Cylindrichnus* may be partly reworked by *Thalassinoides* or any undetermined trace fossils (Figs. 8a, b and 9B). *Taenidium* and *Phycosiphon* are the best-preserved traces. The colour contrast between trace fossils and their background is here rather strong. This type of ichnofabric dominates in siliceous mudstones with spongiolite

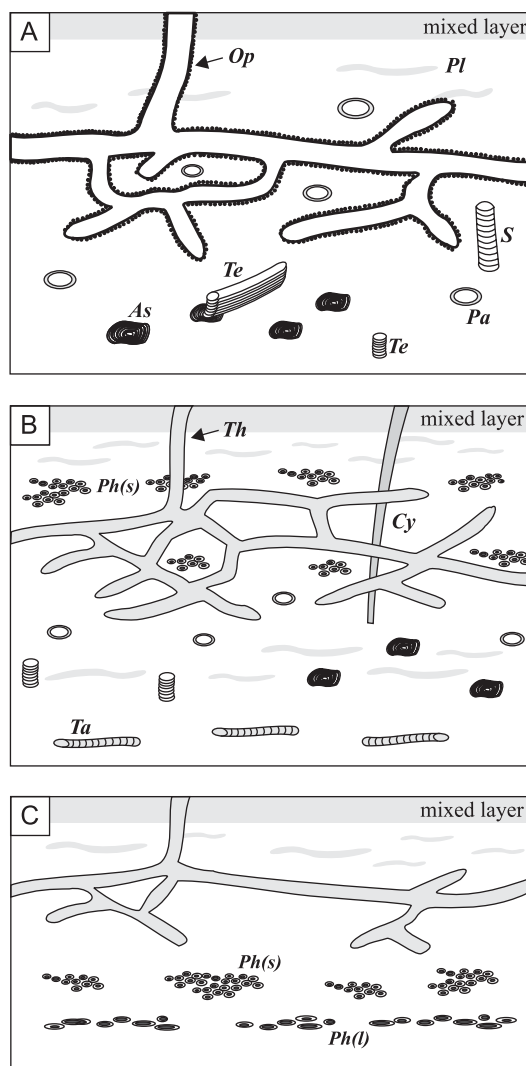


Fig. 9. Tiering patterns reconstructed on the basis of particular ichnofabrics

A — *Ophiomorpha* ichnofabric, B — *Thalassinoides* ichnofabric, C — *Phycosiphon* ichnofabric; included are all trace fossils occurring in a given ichnofabric; presence of “mixed layer” is valid for samples showing a mottled background; in the opposite case, i.e. when primary lamination is still preserved, such a layer did not exist; S — shaft; other explanations as on Figures 5–8

lenses, which are present only in the upper section of the Cenomanian part of section 1 (Fig. 10).

The second type (Tb) (Figs. 4a–c and 5c–g) is characterized by completely bioturbated, or partly bioturbated and partly homogeneous, or partly bioturbated and partly laminated background sediments, in which individual trace fossils were observed. The colour contrast between traces and the background is usually very weak. The most frequent trace fossils are: *Phycosiphon* (small), *Palaeophycus*, *Teichichnus* and *Asterosoma*; *Planolites*, *Taenidium* and *Thalassinoides* appear rarely. All these trace fossils may coexist; however, in most cases only 2–3 trace fossils co-occur in anyone sample and they do not cross-cut each other. In consequence, it is very difficult to determine tiering. The only relationship observed is *Thalassinoides* cross-cutting patches of small *Phycosiphon* (Fig. 5c).

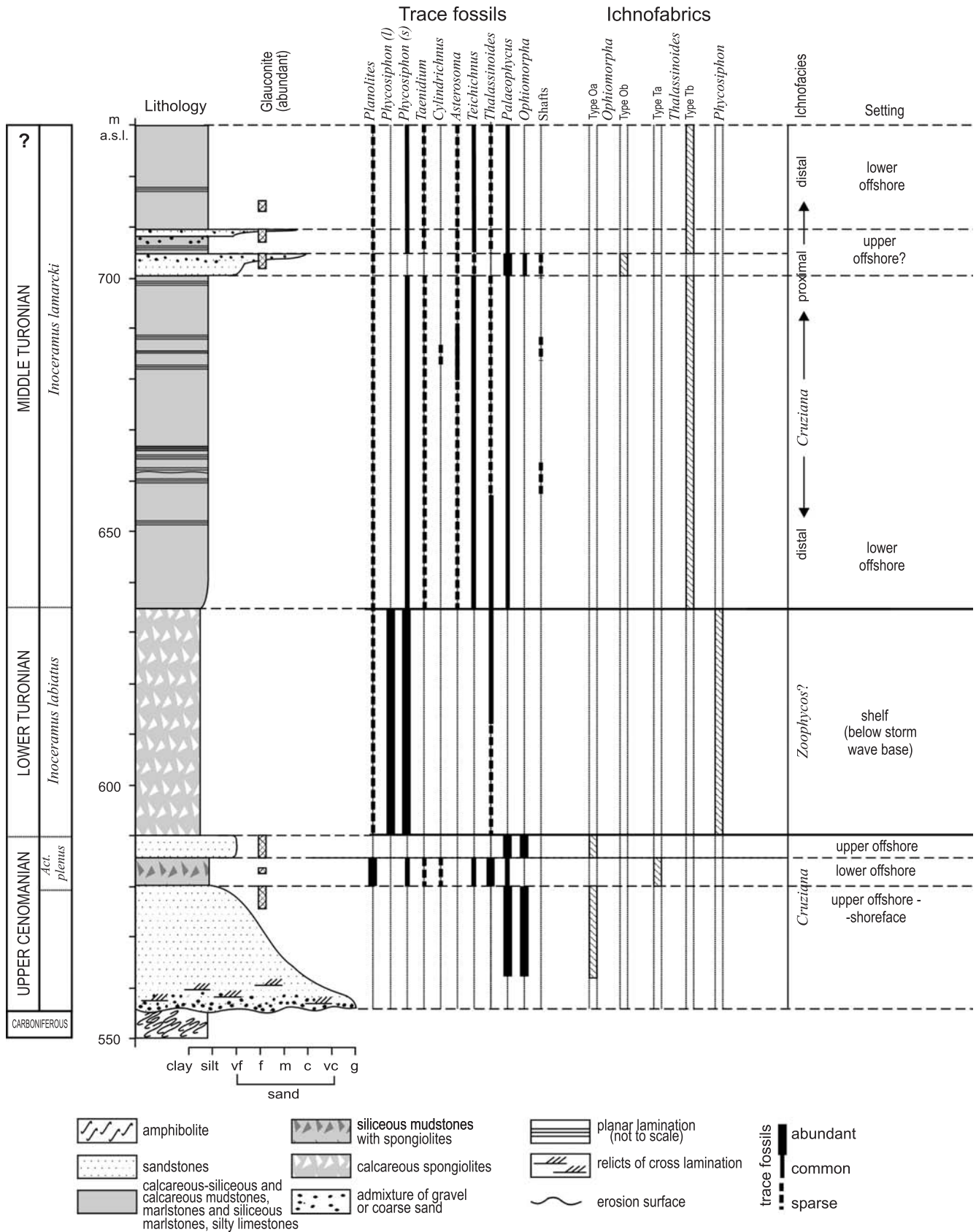


Fig. 10. Generalized lithological column of the southern part of the Stołowe Mts. (section 1, compare Fig. 2) compiled with distribution of trace fossils, ichnofabrics and ichnofacies



Individual thin laminated siltstone interbeds, interpreted to be of storm origin (Rotnicka, 2000), contain a similar assemblage of trace fossils (Fig. 8c). In such layers small *Phycosiphon*, *Palaeophycus*, *Planolites* and probably escape structures are present. Pre- and post-storm deposits comprise the same traces, the only exception is *Taenidium*, which is quite common in deposits underlying storm layers (Fig. 5d). This type of *Thalassinoides* ichnofabric is typical of the entire succession of the middle Turonian Plänermergel rocks (i.e. calcareous-siliceous mudstones and siltstones; Fig. 10).

The ***Phycosiphon* ichnofabric** (Figs. 5a, b, 8d, e and 9C) comprises abundant *Phycosiphon* in both size classes, rare *Planolites* and individual *Thalassinoides*. These trace fossils occur in either totally bioturbated, densely mottled (Fig. 8e) or structureless, homogeneous background sediments (Fig. 5a). In vertical cross-sections, large *Phycosiphon* appears in certain horizons (Fig. 5a), whereas small *Phycosiphon* occurs in patches (Fig. 8d, e). Some small *Phycosiphon* seem to rework larger burrows, whose ichnotaxonomical status is doubtful (see: composed burrows). *Planolites* is commonly cross-cut by *Phycosiphon*. Among *Phycosiphon*, large forms usually cross-cut the small forms. All trace fossils display only slight colour contrasts to the host rock, excluding “halo” burrows (Fig. 6c). This ichnofabric is characteristic only of calcareous spongiolites in the lower Turonian part of section 1 (Fig. 10).

## DISCUSSION

### ICHOFACIES

The trace fossil assemblages belonging to both *Ophiomorpha* and *Thalassinoides* ichnofabrics suggest a fully marine *Cruziana* ichnofacies (Frey and Seilacher, 1980). The presence of two trophic groups (deposit feeders, i.e. *Planolites*, *Taenidium*, *Phycosiphon* and suspension feeders, i.e. *Ophiomorpha*) as well as *Thalassinoides* and *Ophiomorpha*, which appear mostly as horizontal or slightly inclined tunnels (two-dimensional irregular mazes according to Frey *et al.*, 1978), support this. In general this ichnofacies is characteristic of “...low-to medium energetic environment, below daily wave base but not storm wave base to somewhat quieter offshore conditions” (Frey and Seilacher, 1980). Such conditions prevail in a broad variety of environments, such as estuaries, bays, lagoons as well as open continental shelves or epeiric seas (e.g. Frey and Pemberton, 1985).

*Ophiomorpha* ichnofabrics represent conditions that are probably slightly more energetic than those of the *Thalassinoides* ichnofabric, but both may be placed in the offshore zone, which is regarded “... to lie below minimum (fair-weather) wave base and maximum (storm) wave base” (MacEachern and Pemberton, 1992) and may extend down to the storm wave base (Raychaudhuri *et al.*, 1992). The lack of hummocky cross-stratified sets, a paucity of erosion surfaces, sparse sharp-based, thin, horizontally laminated and slightly bioturbated silty layers (distal tempestites within the *Thalassinoides* ichnofabric), and rare

thicker sandy layers, strongly bioturbated, but with relicts of lamination (of doubtful origin within the *Ophiomorpha* ichnofabric), all point to such a setting.

The typical *Ophiomorpha* ichnofabric (type Oa) occurs in clean fine-grained sandstones and represents a trace fossil assemblage of low diversity and high individual densities, dominated by dwelling burrows (*Ophiomorpha*, *Palaeophycus*) generated by suspension feeders and carnivores (Frey *et al.*, 1978; Pemberton and Frey, 1982; Pemberton *et al.*, 1992a) in loose ground. However, as the grain size of the sand diminishes and the thickness of the sand beds decreases, the diversity of the trace fossils suite increases. A deposit-feeding strategy, manifested by individual *Asterosoma*, *Teichichnus* and *Planolites*, starts to appear (type Ob). All observations suggest that type Oa of the *Ophiomorpha* ichnofabric prevails in settings of higher physical stress expressed by episodic, but not very frequent, sand supplies. There is no evidence of storm deposition (as for example hummocky or swale cross-stratification) implying that sand has been deposited in relatively thin layers at a frequency allowing strong or total biogenic reworking. According to Wheatcroft (1990) the maximum thickness of rapidly-deposited sand beds, that may be completely reworked by burrowing organisms in an upper offshore to lower shoreface setting, does not exceed 15 cm. The presence of vertical shafts and equilibrium traces (i.e. some specimens of *Teichichnus*) that are typical rather of slow and continuous deposition (Bromley, 1996) partly supports such an interpretation. Thus, the type Ob marks the conditions that may be defined as transitional between a typical *Ophiomorpha* ichnofabric (Oa) and a typical *Thalassinoides* ichnofabric (Ta).

The trace fossils constituting the *Thalassinoides* ichnofabrics are dominated by structures produced in soft ground by deposit feeders (*Thalassinoides*, *Taenidium*, *Phycosiphon*, *Cylindrichnus*), some showing active backfill strategies. The overall ichnotaxonomic diversity is much higher compared to the *Ophiomorpha* ichnofabric, but individual densities are rather low, particularly within the *Thalassinoides* ichnofabric type Tb. The paucity of dwelling structures, the abundance of mottling (which originated in a soupy substrate) as well as the predominance of horizontal *Thalassinoides* characterises low energy, quiet water conditions that do not favour suspension feeding organisms, i.e. a lower offshore setting (MacEachern and Pemberton, 1992). The complete bioturbation within ichnofabric type Ta additionally indicates a setting where the rate of bioturbation equals or exceeds that of deposition, i.e. where sedimentation is slow and continuous (Byers, 1982; Ekdale *et al.*, 1984; Bromley, 1996).

The ichnofabric type Tb differs from Ta by the intensity of bioturbation, which varies between slight and complete. The many samples studied do not even show relicts of any lamination. The background is totally mottled, implying that the strongest bioturbation took place just after deposition, in a soupy substrate (Goldring, 1995; Bromley, 1996), and thus it is the record of the shallowest tiering. As dewatering of the deposit increased with burial, deeper tiering traces occurred and active backfill strategies became more pronounced (*Taenidium*, *Planolites*). Individual bioturbation structures are characteristic

of silty and sandy, horizontally laminated interbeds that bear features of distal tempestites described by Dott and Bourgeois (1982) and Rotnicka (2000). According to Miall (1990), Myrow (1992) and Myrow and Southard (1996), the sediments might have been deposited from storm-generated hemipelagic suspension in settings close to storm wave base or even below it. In storm beds, *Palaeophycus* and *Phycosiphon* are the best-preserved trace fossils. *Palaeophycus* is considered to reflect the first stage of opportunistic colonisation of storm beds, whereas *Phycosiphon* feeds of organic material left by original opportunistic ichnofossil suites and, therefore, represent the second stage of colonisation (Frey, 1990; Raychaudhuri and Pemberton, 1992). Even though the ichnodiversity and bioturbation indices of storm beds are lower, storms must have induced only short-lasting and weak physiological stresses, which were probably expressed by higher sedimentation rates. However, the amount of the sediments delivered and the rate of their supply was not high enough to cause significant changes in the benthic community as the pre- and post-storm trace fossils suites are the same.

To sum up, both ichnofabrics included in the *Cruziana* ichnofacies represent fully marine, well oxygenated, and low energy settings within an offshore zone. The *Ophiomorpha* ichnofabric may indicate a more proximal *Cruziana* ichnofacies within the upper offshore zone, where sand supply was more common and abundant, indicating slightly more energetic conditions. The *Thalassinoides* ichnofabric indicates a distal *Cruziana* ichnofacies within the lower offshore zone with transition to a slightly deeper (shelfal) environment characterized by infrequent and weak storm influence (Raychaudhuri *et al.*, 1992).

The assignation of the *Phycosiphon* ichnofabric to any ichnofacies is open to question. It is present in dark calcareous spongiolites, moderately to intensively bioturbated, but with no remnants of any laminae, and no evidence of input of coarser material; these features indicate low energy conditions probably in a setting with restricted circulation, below storm wave base, and continuous, slow deposition. Furthermore, the general characteristic of this ichnofabric: low ichnogeners diversity, high density of deposit-feeding traces (*Phycosiphon*), and sparse other feeding traces, linked with the lack of primary sedimentary structures indicate conditions that are very similar to those described for the *Zoophycos* ichnofacies (Frey and Pemberton, 1985; Pemberton *et al.*, 1992b). Although the trace fossil assemblage does not contain the name-giving component *Zoophycos*, the ichnofabrics studied may represent a case in which this has been replaced by *Phycosiphon*. Frey and Pemberton (1985) note that under certain conditions (e.g. in pelitic sediments) such an exchange may take place. In the case studied, the pelite is nearly entirely composed of siliceous sponge spicules.

The *Zoophycos* ichnofacies is attributed to areas free of turbidity and bottom currents, below storm wave base, where bottom sediments are rich in organic matter and somewhat deficient in oxygen (Frey and Seilacher, 1980; Frey and Pemberton, 1985). The reason for attributing this ichnofacies to

settings depleted in oxygen is due to the common occurrence of *Chondrites* (which is related to substrate anoxia — Bromley and Ekdale, 1984) within the *Zoophycos* ichnofacies. The typical ichnofacies is reported thus from continental slopes (Seilacher, 1967) but it is also known from shallower-water settings with restricted circulation such as near-shore or epeiric seas, and silled basins (Osgood and Szmuc, 1972; Seilacher, 1978).

It seems that the *Phycosiphon* ichnofabric represents the deepest and least energetic setting of those described here. It probably marks an environment located basinward of the *Cruziana* ichnofacies and corresponding to shelfal areas below storm wave base. However, in contrast to conditions typical of the *Zoophycos* ichnofacies, this setting must have been well oxygenated. This conclusion is supported by the lack of *Chondrites* and the presence of siliceous sponges. The abundance of spicules, the lack of terrigenous quartz, and lack of sediment redistribution suggest that the spongiolites are composed of material produced *in situ* by sponges.

#### PALAEOENVIRONMENTAL EVOLUTION

All the ichnofabrics described and the reconstructed ichnofacies suggest a fully marine, rather low energy and well-oxygenated environment. Studying the given section in terms of ichnofabric the following succession is observed (Fig. 10): at the base, unbioturbated cross-bedded sandstones followed by a *Thalassinoides* ichnofabric (type Ta) in siliceous mudstones, an *Ophiomorpha* ichnofabric (type Oa) in glauconitic sandstones, a *Phycosiphon* ichnofabric in calcareous spongiolites, and eventually a *Thalassinoides* ichnofabric (type Tb) in marlstones and mudstones with a locally occurring (in sandstone interbeds) *Ophiomorpha* ichnofabric (type Ob). The following palaeoenvironmental succession may be envisaged:

The lowermost, Cenomanian part of section 1 (Fig. 10) records the succession from a probably high energy shoreface (cross-bedded sandstones) to lower offshore and later to upper offshore conditions. Such a succession is coincident with the transgressive-regressive cycle reconstructed by Wojewoda (1989). The abrupt appearance of the *Phycosiphon* ichnofabric (*Zoophycos* ichnofacies) indicates a rapid rise of relative sea level during the early Turonian and places the area studied in a shelfal setting. The succeeding *Thalassinoides* ichnofabrics (type Tb), which appear in the middle Turonian part of section 1, show a generally continuous influx of coarser material interrupted by episodic storms, indicating a lower offshore setting close to the storm wave base. Sparse sandstone interbeds in the upper part of section 1, displaying an *Ophiomorpha* ichnofabric (type Ob) indicates more energetic conditions and increasing sand supply, though it is doubtful whether these sandstone interbeds are of storm origin. Anyway the entire section from the beginning of the middle Turonian onwards may be included in the *Cruziana* ichnofacies, distal and more proximal respectively, i.e. in the offshore zone.

In contrast to section 1, coeval Turonian sections from the northern part of the Intrasudetic Basin are composed of two main regressive cycles, each terminated by sandstones (Middle and Upper Quadersandstein, Fig. 3). According to Jerzykiewicz and Wojewoda (1986), these cycles were caused by block tectonics that affected the sea floor and sediment source areas during early middle and late Turonian time, respectively. Large amounts of terrigenous material produced in the source area were deposited in rapidly subsiding areas on the lee sides of prograding accumulation terraces filling the basin. Therefore, the appearance of the *Cruziana* ichnofacies in early middle Turonian time coincided with the formation of the first accumulation terrace. Also, the *Ophiomorpha* ichnofabric, occurring randomly in the Turonian part of section 1 of the southern part of the basin, may be connected with distal tongues of prograding terraces rather than with storm deposits. However, due to the low stratigraphic resolution of this section, it is questionable whether they are connected with the Middle or Upper Quadersandstein lithosomes.

### CONCLUSIONS

The Upper Cretaceous rocks from the southern part of the Stołowe Mts. have been studied as regards their bioturbation for the first time. Altogether nine ichnogenera have been described: *Asterosoma*, *Cylindrichnus*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon* (both small and large forms), *Planolites*, *Taenidium*, *Teichichnus* and *Thalassinoides*. Excluding *Ophiomorpha*, which is present only in sandstones, all trace fossils are related mainly to fine-grained rocks.

Three basic types of ichnofabrics have been recognized: *Ophiomorpha*, *Thalassinoides* and *Phycosiphon*, all representing fully marine ichnofacies. The first two of these belong to

the *Cruziana* ichnofacies, indicating a well-oxygenated and low energy setting within an offshore zone. The *Ophiomorpha* ichnofabric probably indicates a more proximal *Cruziana* ichnofacies within the upper offshore zone, where sand supply was more common and abundant. The *Thalassinoides* ichnofabric marks the distal *Cruziana* ichnofacies within the lower offshore zone with transition to a slightly deeper (shelfal) environment characterized by infrequent and weak storm influence. The *Phycosiphon* ichnofabric reflects the deepest and least energetic setting located basinward of the *Cruziana* ichnofacies and corresponding to shelfal areas below storm wave base; the nature of this ichnofabric is thus suggestive of the *Zoophycos* ichnofacies.

The ichnofabrics and the ichnofacies succession suggest that the lower part of the section studied (Cenomanian) represents a transgressive-regressive cycle. The sediments above record a progressive change of environment from a shelfal setting to lower offshore conditions with episodes of upper offshore conditions. Such a succession shows a generally regressive trend, which is probably coeval with the lower-middle Turonian regressive cycle well-documented in the northern part of the Stołowe Mts. (Jerzykiewicz and Wojewoda, 1986).

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