First discovery of Mississippian trace fossils in the Świebodzice Unit from the Witoszów region (SW Poland)

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Abundant and moderately diverse trace fossil assemblage have been discovered for the first time in mudstones of the Pogorzała Formation from the Witoszów region, SW Poland. Fifteen ichnospecies including fourteen ichnogenera are described. The ichnofauna is dominated by Dictyodora liebeana and contains numerous Palaeophycus tubularis, rare Archaeonassa fossulata, Archaeonassa isp., Chondrites cf. intricatus, Curvitholithus simplex, Diplopodichnus biforis, Lockeia isp., ?Lophochnenium isp., Nereites isp., Phycosiphon isp., Protovirgularia isp., ?Psammichnites isp., Taenidium isp. and one ichnospecies of fish swimming trails, Undichna cf. britannica. Some other structures (wave ripples influenced by microbial mats and zigzag structures) also occur. The trace fossil assemblages differ in various exposures, but three of them are similar and display the Dictyodora liebeana ichnoassemblage. It is represented mostly by the ethological categories fodiinichnia and repichnia, with fewer paschichnia, domichnia and cubichnia. This new data from the Świebodzice Unit sheds light on the palaeontology, age and palaeoenvironment of the Pogorzała Formation. The occurrence of D. liebeana and U. cf. britannica indicates the Mississippian age of most mudstones studied, formerly considered Upper Devonian. The trace fossil assemblage belongs to the non-standard Nereites ichnofacies, without graphoglyptids. The lithological features of mudstones, trace fossil assemblage and poverty of macrofauna, testify to their deposition in a deeper sedimentation zone below storm wave base, most likely in dysoxic-pro-delta conditions. This study suggests that rocks containing D. liebeana may form a correlative horizon in the Świebodzice Unit.

Key words: Świebodzice Unit, Pogorzała Formation, Mississippian, trace fossils, fish trails, ichnofacies.

INTRODUCTION

The Świebodzice Unit (or Świebodzice Depression) is a small, rhomboidal, fault-bounded geological unit (Fig. 1) in the central Sudetes, which was de facto defined in the 1950s (Teisseyre, 1956b). Before the Second World War, German researchers (e.g., Berg et al., 1910; Cramer et al., 1921) recognised the same lithological units in the area as in the neighbouring Intra-Sudetic Synclinorium (named after Żelazniwicz et al., 2011). Porebski (1987, 1990) and Wojewoda (2014, 2016a, b) explained the rhomboidal shape of the Świebodzice Unit and referred it to a pull-apart basin. The Świebodzice Unit comprises ~3300–4500 m of sedimentary rocks, predominantly conglomerates, the so-called Świebodzice succession (Porebski, 1981). This succession generally is divided into two parts, a heterolithic succession and coarse-grained conglomerates, with their age determined variously since the 19th century.

The detailed history of geological investigations in the Świebodzice Unit was summarized by Gunia (1968). Most maps of German authors (e.g., Berg et al., 1910) considered the heterolithic deposits to be older than the coarse-grained conglomerates. This opinion was accepted by later researchers (e.g., Teisseyre, 1948, 1952, 1956b; Nemec et al., 1980; Porebski, 1981). But there was an opposing opinion, of Cramer et al. (1924), suggesting that the gneiss conglomerates (presently the Książ Formation) were older than the heterolithic rocks (currently the Pogorzała Formation).

Biostratigraphic documentation of this geological unit has been based on macrofossils, which have been found since the 19th century (see Gunia, 1968 and references therein). They represent Devonian (mainly in limestones) and Carboniferous taxa of fauna and flora. The macrofossils are generally poorly preserved and most of them are long-ranging taxa. They are also unevenly distributed and some Devonian fossils are re-worked (they occur in pebbles; Gunia, 1968). For these reasons, interpretation of the stratigraphy is complicated. Extensive stratigraphic studies of the rocks of the Świebodzice Unit, based on marine macrofauna, were undertaken by Gunia (1968). This author, like others before him, assumed that all the fossils found occur "in situ". Based on relatively rare index fossils, Gunia (1968) concluded that both parts of the unit...
(heterolithic and coarse-grained conglomerates) are stratigraphically equivalent and were deposited from the late Frasnian to the Tournaissian. Only one Carboniferous taxon Lepidodendron sp. from the Książ conglomerates found by Zimmerman (1936) was taken into account by Gunia (1968). This author rejected all other Carboniferous dates (see Pluta and Górecka-Nowak, 2018). Significant, but often overlooked results were provided by Krawczyńska-Grocholska (1973), which documented miospores of Visean–Namurian age in the Chwaliszów region. There were no subsequent stratigraphic investigations for nearly a half century. Recently, Halamski (2013) published new palaeontological and biostratigraphical studies of Devonian brachiopods from limestones of the Świebodzice Unit.

The view of Porębski (1981, 1990) has been the most frequently cited and commonly accepted. This author, based on sedimentological studies and the general stratigraphical scheme of Gunia (1968), proposed a formal lithostratigraphic division of the Świebodzice succession. According to Porębski (1981, 1990), the lower, heterolithic, part of the succession (1200–1500 m in thickness; the Pogorzała Formation and the Pełcznica Formation), is represented by polymictic conglomerates interbedded with thick fossiliferous mudstones with sandstones and rare organogenic limestone lenses. The age of this part was regarded as Upper Devonian (upper Frasnian–Famennian). In contrast the upper part of the Świebodzice succession, in the opinion of Porębski (1981, 1990), is represented by thick-bedded and coarse-grained conglomerates with sandstones of the Książ Formation (2000 m in thickness; with the presence of gneiss pebbles) and the Chwaliszów Formation (3000 m in thickness; polymictic conglomerates). These deposits were referred to the lower Tournaissian and probably in part to the Upper Devonian (see Gunia, 1968, Porębski, 1981). The Świebodzice succession is considered synorogenic and reflects mostly gravity-flow sedimentation in a marine slope-type fan-delta complex of a rapidly subsiding basin (Nemec et al., 1980; Porębski, 1981, 1987, 1990).

Recently, Wojewoda (2014, 2016a, b) presented a different developmental model of the Świebodzice Unit on the basis of cartographic and structural/sedimentological investigations using LIDAR methods. According to this, the conglomerates of the Książ and Chwaliszów formations, found in the central part of this unit, are older than the heterolithic Pogorzała and Pełcznica formations from its marginal parts and represent the Tournaissian–Namurian interval. In contrast the heterolithic formations are of the Namurian–Westphalian age and within them this author distinguished turbidites, hemipelagic and pelagic facies including olistoliths and slumps of older rocks (e.g., upper Devonian limestones) occurring near basin edges. This model explains well the occurrence of age-different taxa (Devonian and Carboniferous) in the heterolithic formations. Therefore, the age of the Pogorzała Formation cannot be correctly determined on the basis of redeposited Devonian body fossils.

The latest results of miospore studies of the Pogorzała Formation (Pluta and Górecka-Nowak, 2018) are important to discussion of the stratigraphy of this unit. These authors docu-

![Fig. 1. Geological map of the Świebodzice Unit (based on Kaczorowski and Wojewoda, 2011) with location of the exposures studied in the Witoszów region](image-url)
mented the Upper Visean–Serpukhovian age for rocks from the Pogorza³a Formation in the Witoszów and Lubiechów regions, formerly interpreted as the Upper Devonian (Ginia, 1968). The presence of Asturian (Westphalian) miospores in a few samples of these rocks, they interpreted as reflecting redeposition of stratigraphic leakage type. These new data support the model of Wojewoda (2014, 2016a, b). Pluta and Górecka-Nowak (2018) also conducted a detailed discussion of stratigraphic problems. They cited the pre-Second World War finds of Carboniferous macrofauna and macroflora from the Pogorza³a Formation, which were not taken into account by Gunia (1968). As these authors emphasized, present-day understanding of the geological setting and stratigraphy remains unsatisfactory, indicating that the geological history of the unit is more complicated than previously thought. According to them, the age of the rocks of the Œwiebodzice Unit has fundamental importance for the interpretation of geological history of the Central Sudetes.

Until now, no trace fossils have been reported from the Œwiebodzice Unit. Initially, individual undetermined trace fossils, described formerly by Prof. T. Gunia as sedimentary structures, were noticed by the author in 2019, while organizing the Gunia collection from Witoszów. Then, fieldwork revealed many more finds and the preliminary results of these studies were reported by Muszer (2019). This contribution provides the first comprehensive ichnological study of the Œwiebodzice Unit, focusing on mudstones of the Pogorza³a Formation. Based on ichnological investigations, some important stratigraphic and palaeoenvironmental conclusions can be drawn. Trace fossils are important, commonly being used to reconstruct palaeoenvironments because they represent the in situ record of biogenic activity and cannot be easily reworked (Minter et al., 2016).

Mississippian trace fossils from the central part of the Polish Sudetes are best known from the Upper Visean of the Bardo Unit (Muszer and Haydukiewicz, 2009, 2010; Muszer and Uglik, 2013). For many years they were mentioned, without description, from the Intra-Sudetic Synclinorium (Zakowa, 1958, 1960; Teissaye, 1968a; Nemec et al., 1982; Mastalerz, 1987, 1995). Recently, two reports of trace fossils from the Szczawno Formation of the Intra-Sudetic Basin were provided by Muszer (2013, 2020) and further studies are in preparation.

GEOLoGICAL SETTING

The research area is located in the southeastern part of the Œwiebodzice Unit, in the “synclinal block” of Pogorza³a, which is fault-bounded (Fig. 1; see Teissaye, 1956a; Porêbski, 1981). This block extends across the Pogorza³a, Witoszów, Mokreszów and Lubiechów regions (Teissaye, 1956a). The Pogorza³a block is built of conglomerates, greywackes and shales with rare, small “bodies” of organogenic limestone (considered either lenses or olistoliths according to various authors, cf. Porêbski, 1981 and Wojewoda, 2016a), which belong to the Pogorza³a Formation (Porêbski, 1981). The total thickness of this succession was estimated at 1200–1500 m (Teissaye, 1956a).

In the Witoszów Górny area there are a number exposures of the Pogorza³a Formation represented by mudstones with intercalations of sandstone (greywacke) and conglomerate. The mudstones are grey to dark and green grey, commonly thinly laminated (up to a few mm), with rare pyrite concretions. Alternating light and dark laminae occur. Marine fossils have been sporadically noted in these mudstones and less frequently in the greywackes. Plant fossils (mainly debris) are slightly more common than macrofaunal fossils.

In these rocks, some Carboniferous taxa were noted in 19th and 20th centuries, especially from a “roofing slate” quarry (e.g., the bivalves Posidonia becheri, Edmondia, Protoschizodus by Dames, 1868 and Bederke, 1924; the land plants Mesocalamites roemerii, Calamites tenuissimus and Sigillaria minitissima by Cramer et al., 1924). However, most studies have suggested that the Pogorza³a Formation is Devonian, because of numerous marine macrofaunal remains, found in limestone “bodies” occurring in mudstones in neighbouring regions (Zobell and Carnall, 1831; Dames, 1868; Gürich, 1909; Rózkowska, 1962). Pawlik (1939) considered the mudstones at Witoszów as younger than the calcareous deposits and include them to the “stufe Hemberg” (Famennian, Prolobites and Pronoceras Zones). According to Gunia (1968), these mudstones represent the Upper Devonian (Famennian), but their palaeontological documentation is poor (a few bivalve, brachiopod and cephalopod taxa). Porêbski (1981) included the Pogorza³a Formation in the Upper Devonian (upper Frasnian–Famennian). According to Wojewoda (2014, 2016a, b) the Devonian limestone fragments with body fossils are redeposited. The latest palynostratigraphic data (Pluta and Górecka-Nowak, 2018) shed new light on the stratigraphy and rejected the upper Devonian age of the Pogorza³a Formation in the southern part of the Œwiebodzice Unit. These authors documented the Upper Visean–Serpukhovian age for the mudstones from Witoszów Górny and Lubiechów regions and considered all older rocks and fossils as redeposited.

Four mudstone exposures in the Pogorza³a Formation in the Witoszów Górny area (Wit I, Wit II, Wit III, Wit IV) were studied (Figs. 1 and 2). They are the same as the localities studied by Gunia (1968), but were not analysed by Pluta and Górecka-Nowak (2018). All studied exposures are heavily covered with weathered material (Fig. 3).

The exposure Wit I (outcrop no. 30 of Gunia, 1968) is situated ~300 m S of the historic 17th-century manor house (GPS coordinates 50° 48' 58.8"N; 16° 23' 30.1"E). The exposure is ~10 m long and 5 m high (Figs. 2 and 3A). Grey shales with thin (up to 3 cm) intercalations of fine-grained sandstone are ex-
posed on the slope, on the right bank of the stream. The orientation of the bedding is 3/60. In this exposure numerous trace fossils have been found, besides fragments of land plants (Calamitaceae) and rare undetermined bivalves (Fig. 4D, H). The mudstones are probably overlain by conglomerates with rounded pebbles, and greywackes, which occur in blocks, but the contact with these rocks is not seen.

The exposure Wit II (GPS coordinates 50°48'55.6"N; 16°23'24.0"E) is located ~150 m SW of Wit I, on the northwestern slope of Mrowina Hill (Fig. 2). This locality seems to be the same as outcrop no. 4 of Gunia (1968), but its dimensions are different (now 10 m long, 7 m high). On the right bank of the stream, grey, green grey and dark grey shales with thin (up to 1–2 cm) intercalations of fine-grained greywacke are exposed. The strata dip ~40° to the north. These rocks are gently folded in the upper part of the exposure (Fig. 3B). Abundant trace fossils, rare plant fragments and undetermined cephalopods (Fig. 4E) occur in these mudstones.

Exposure Wit III (no. 3 of Gunia, 1968) is a large, old and disused quarry, known as the “roofing slate” quarry. It is situated ~750 m NW of the former manor (GPS coordinates 50°48’18.3”N; 16°22’53.3”E), on the wooded slope (Fig. 2). The quarry is now strongly overgrown and covered with weathered material (Fig. 3C). It exposes mainly dark grey shales, intercalated with layers (up to 20 cm) of greywacke. The bedding orientation is 10/40. Trace fossils occur only in the uppermost part of the quarry. Additionally, only an undetermined fish scale was found (Fig. 4G).

Exposure Wit IV (outcrop no. 11 of Gunia, 1968) is located 150 m N from the western end of the village of Witoszów Górny, on the southern slope of the hill, near the ruins of a former forester’s lodge (GPS coordinates 50°48’56.0”N; 16°22’12.2”E). The exposure is ~15 m long and 3 m high (Figs. 2 and 3D). In this profile dark grey, green grey and light grey shales with intercalations of fine-grained greywacke (up to 5 cm) are exposed. The rocks are locally gently folded. Measurements of bedding plane are 335/25, 345/30 in the eastern part of the outcrop and 350/40 in its western part. These rocks contain many trace fossils, some plant fossils (Calamitaceae) and rare bivalves (Fig. 4A–C, F, I).

MATERIALS AND METHODS

Almost all material studied in this paper was found during fieldwork in 2019 (Figs. 2, 4, 5B, D–H and 6–10). Fifty-eight samples were taken from mainly mudstones in the Witoszów region. Some samples were assembled from talus material. Additionally, five samples with trace fossils come from the collection of Gunia (1968; outcrops no. 4, 30 from Witoszów, no. 41 from Lubiechów; Fig. 5A, C).
Several rock samples were cut and the ichnofabric was observed on polished surfaces using a Nikon SMZ-2T microscope (Fig. 10). Photographs of trace fossils were taken with a Nikon Coolpix P5100 camera. The material collected is housed in the Institute of Geological Sciences of the University of Wrocław with the prefix Wit (catalogue numbers I-1/1 – I-2/4b, I-2/1 – I-z/3; II/1 – II/12; III/1 – III/3; IV/1 – IV/20), together with five samples from the Gunia collection (samples 4, 30, 41).

**DESCRIPTION OF THE TRACE FOSSILS**

**INVERTEBRATE TRACE FOSSILS**

*Ichnogenus Archaeonassa* Fenton and Fenton, 1937

*Archaeonassa fossulata* Fenton and Fenton, 1937

(Fig. 5A)
**Material and occurrence.** – Two specimens from the collection of Gnia (1968) (outcrop no. 30 = Wit I) and one specimen from talus of exposure Wit I.

**Description.** – Simple, unbranched, straight to meandering, narrow traces up to 92 mm long and 2.0–5.7 mm wide. Epichnial furrows are parallel to bedding. Margins of the furrow on both sides are bound by irregular and slightly raised levees. One specimen is looping and has a median groove flanked by ridges (Fig. 5A). The loop of this specimen is 40 mm wide.

**Remarks.** – The traces are most similar to Archaeonassa fossulata described by Buaotois and Mángano (2002: fig. 7A) from the Carboniferous floodplain deposits of Argentina, but a V-shaped cross-section is not clear in the specimens from Witoszów. They are also similar to Archaeonassa cf. fossulata described by Demircan and Uchman (2016: fig. 4A, B) from the prodelta facies of the Paleogene of Turkey, but their external margin is more even.

This ichnogenus was reviewed by Buckman (1994) and re-defined by Yochelson and Fedonkin (1997). Archaeonassa generally is interpreted as a grazing trail or pascichnion, produced by crustaceans, annelids or molluscs (e.g., Yochelson and Fedonkin, 1997; Buaotois and Mángano, 2002; Mángano et al., 2005; Carmona et al., 2006; Sarkar et al., 2009). Knaust (2007) regarded A. fossulata as a gastropod burrow (fodinichnion).

This ichnogenus has been described from lake, shallow marine and delta deposits (Buaotois and Mángano, 2002; Knaust, 2007; Sarkar et al., 2009; Mángano et al., 2013). It is a common element of the Cruziana and Memia ichnofacies (Buaotois and Mángano, 2002; Melchor et al., 2012). Archaeonassa is known from the Ediacaran (Häntschel, 1975; Buckman, 1994; Buaotois and Mángano, 2002) to the Recent (Netto et al., 2012a), but mainly from the Paleozoic (e.g., Mángano et al., 2005; Pazos et al., 2007).

**Archaeonassa isp.**
(Fig. 5B, C)

**Material and occurrence.** – Nine specimens from two exposures, Wit I (= outcrop 30 of Gnia) and Wit IV.

**Description.** – Horizontal, straight to curved, unbranched traces with narrow parallel ridges preserved as negative epirelief. They are semicircular or usually V-shaped in cross-section, occasionally flat. Their length is up to 9.2 cm, width is 1.5–0.4 mm.

**Remarks.** – The material is poorly preserved and incomplete, due to the fragile and fractured host rock. Some specimens show a sudden change of a movement direction (Fig. 5B, C).

**Ichnogenus Chondrites** Sternberg, 1833
Chondrites cf. intricatus (Bromniart, 1823)
(Figs. 5F and 6A, C)

**Material and occurrence.** – One incomplete specimen from exposure Wit I; several tunnel cross-sections exposed on the bedding surface (exposure Wit IV).

**Description.** – System of thin tunnels branching at sharp angles, which look like roots. The length of the tunnels range from 10–20 mm, and their diameter is ~0.2 mm. Tunnels are filled with darker material, differing from the host rock. They are slightly inclined to the bedding surface. Branching angle is <45°, which is a characteristic feature of Chondrites intricatus (Bromniart, 1823), but branches are not so straight as in this ichnospecies. The diameter and width of the burrow system resembles this ichnospecies (see Uchman et al., 2012). Cross-sections of the tunnels are visible on the bedding surface (Fig. 6A, C).

**Remarks.** – Chondrites has been interpreted as a fodinichnion (feeding structure) produced by an unknown infaunal deposit feeder (e.g., Seilacher, 2007). Other authors classified this trace fossil as a chemichnion (e.g., Bromley, 1996; Mikulás, 2006; Rodriguez-Tovar et al., 2010). Recently Baucon et al. (2020) re-evaluated Chondrites and considered it as a fodinichnion (created by vermiform deposit-feeders searching for food), agrichnion (when trace-makers cultivate asymbiotic bivalves and ingest bacteria) and chemichnion (produced by chemosymbiotic bivalves to provide symbionts with chemical agents).

This ichnogenus is one of the most common in Phanerozoic marine deposits (Uchman and Wetzel, 1999) and its stratigraphic range is from the Cambrian (Crimes, 1992) to Holocene (Loewemark et al., 2004). It occurs in a variety of ecological conditions, from nearshore to deep-sea and from highlyoxic (Wetzel, 1991) to oxygen-depleted sediments, rich or poor in organic matter (Wetzel and Uchman, 2001; Uchman et al., 2003). However, most workers cite Chondrites from low-energy environments (Seilacher, 2007) and substrates with oxygen-poor pore waters (e.g., Tyszka, 1994).

Ichnogenus Curvolithus Fritsch, 1908
Curvolithus simplex Buaotois et al., 1998
(Figs. 5D and 9A)

**Material and occurrence.** – Two fragmentarily preserved specimens from exposures Wit I and Wit II.

**Description.** – Horizontal, curved, flattened and unbranched trace with trilobate upper surface. The central lobe on the upper surface is smooth and much wider than the outer lobes, which are separated by shallow furrows. The specimens described are 5–6 mm wide and 15–40 mm long. They are preserved as positive epirelief on the bedding surface.

**Remarks.** – The ichnogenus Curvolithus was revised by Buaotois et al. (1998), who distinguished only two ichnospecies, C. multiplex Fritsch and a new species C. simplex. Specimens from the Witoszów region are most similar to C. simplex described by Buaotois et al. (1998: figs. 4.2–4.3, 7.1–7.6) and by Kroblicki and Uchman (2003: fig. 3). Curvolithus is commonly interpreted as a locomotion trace (repichnion) of endostratal invertebrate carnivores (see Buaotois et al., 1998 and references therein). The potential trace-makers are gastropods, wormlike polychaetes, flatworms, oligochaetes, nemerteans and holothurians (e.g., Lockey et al., 1987; Seilacher, 2007; Knaust, 2010).

Curvolithus is a common element of the Cruziana ichnofacies sensu Seilacher (1967). Lockley et al. (1987) defined the Curvolithus ichnofacies, which now is considered to be a subset of the Cruziana ichnofacies (Bromley, 1996). Mclory, 2008, this ichnogenus is commonly associated with shallow-marine deposits (Buaotois et al., 1998). It also occurs in fan-deltaic to offshore deposits (Webby, 1970; Fürsich and Heinberg, 1983; Heinberg and Birkelund, 1984; Maples and Suttner, 1990).
Fig. 5. Trace fossils from the Witoszów region

A – Archaeonassa fossulata (Arf) and Archaeonassa isp. (Ar) preserved as epirelief on the top of the bedding plane, outcrop no. 30 (coll. Gunia, 1968); B, C – Archaeonassa isp. preserved as negative epirelief on the top of the bedding plane: B – cat. No. Wit I-1/1a, C – outcrop no. 30 (coll. Gunia, 1968); D – Diplopodichnus biformis (Db) and Curvolithus simplex (Cu) preserved as positive epirelief, cat. No. Wit II/1a; E – Diplopodichnus biformis preserved as convex hyporelief, cat. No. Wit I-2/1; F – Chondrites cf. intricatus preserved on the surface slightly oblique to the bedding plane, cat. No. Wit I-1/4b; G, H – Dictyodora liebeana: G – horizontal cross-sections of the spreiten structure preserved as epirelief, cat. No. Wit IV/1, H – visible vertical wall of D. liebeana on the surface oblique to the bedding plane, cat. No. Wit I-1/1b
First discovery of Mississippian trace fossils in the Świebodzice Unit from the Witoszów region (SW Poland)

Fig. 6. Trace fossils from the Witoszów region

A–F – Dictyodora liebeana and Chondrites cf. intricatus, cross-sections on the bedding surface: A, C – abundant Dictyodora liebeana (Di) and tunnel cross-sections of C. cf. intricatus (Ch), cat. No. Wit IV/2a; C – enlarged view of the area marked by the square in A; B, D, E – Dictyodora liebeana cross-sections of the spreite; B – cat. No. Wit I-1/1a; D – cat. No. Wit I-1/3; E – cat. No. Wit I-1/2a; F – visible vertical walls of D. liebeana marked by arrows, Cal – undetermined Calamitaceae, cat. No. Wit I-1/4b
The stratigraphic range of *Curvolithus* is from the Proterozoic (Webby, 1970) to the Miocene (Buatois et al., 1998; Krobicki and Uchman, 2003; Hofmann et al., 2011). This ichnogenus commonly occurs in Carboniferous and Jurassic deposits (Eagar et al., 1985).

**Ichnogenus Dictyodora Weiss, 1884**

*Dictyodora liebena* (Geinitz, 1867)

(Figs. 5G–H, 6A–F and 10A–C)

**Material and occurrence.** – Numerous incomplete specimens found in three exposures in the Witoszów region (Wit I, Wit II, Wit IV; samples no 4, 30 of *Guria*, 1968 collection), one sample from the Lubiechów region (sample no. 41 of *Guria*, 1968 collection) and the *D. liebena* ichnofabric was observed on vertical polished sections. Several dozen specimens altogether.

**Description.** – Complex three-dimensional spreiten structures, which are oriented mostly obliquely to the bedding. Horizontal cross-sections of the spreite are the most common finds. In such cases, the traces have the character of variously shaped asymmetrical and less often nearly symmetrical meanders; complex meanders (third-order at maximum) also occur. Their meandering pattern is irregular. Spacing between meanders is 0.3–20 mm. Meanders often intersect (Figs. 5G and 6E). The spreite is 0.7–1.6 mm wide, generally ~1 mm. Typical basal burrow and mid-dorsal vertical walls are rarely preserved (Figs. 5H and 6A, B, F). The basal burrow is up to 10 mm wide (Fig. 6A). In side view, the wall shows fine longitudinal streaks (Fig. 5H). This ichnospecies is regarded as the most complex *Dictyodora* form (see Benton, 1982).

**Remarks.** – This ichnospecies represents the complex feeding trace of a shell-less mollusc (Benton and Trewh, 1980) or a worm-like animal (Benton, 1982). According to Seilacher (2007) the tracer of *D. liebena* explored deep tiers. Ethologically it is regarded as a fodininechium (Buatois and Mángano, 2011), or as a deep-tier paschichin (Uchman and Wetzel, 2012). This ichnospecies has been described mainly from deep-water strata of Europe, especially from the Lower Carboniferous Culm facies of Germany, Czech Republic and Spain (e.g., Roemer, 1870; Ruchholz, 1967; Benton, 1982; Stepak and Geyer, 1989; Pek and Zapletal, 1990; Orr et al., 1996; Mikuláš et al., 2004). *D. liebena* is typical of fine-grained, distal deposits with a high clay fraction and it is most often found in sediments of "roofing slate" type (Mikuláš et al., 2004). In the Sudetes, it has been recorded from the Mississippian Szczawno Formation of the Intra-Sudetic Basin (Zakowa, 1958; Muszer, 2013, 2019, 2020). This ichnospecies is of chronostratigraphic value, because its stratigraphic range is restricted to the Lower Carboniferous (Uchman, 2004, 2007a).

The ichnogenus *Dictyodora* ranges from the Ordovician to the Carboniferous and is considered typical of the deep-water *Nereites* ichnofacies (Benton, 1982; Buatois and Neto de Carvalho, 2008; Buatois and Mángano, 2011). Recently, it has also been described from Silurian and Devonian prodelta deposits in Argentina (Vieira de Luca and Basili, 2013; Pazos et al., 2015b). New ichnological investigations (e.g., Pazos et al., 2015b; Muszer, 2013, 2019, 2020) show that the Paleozoic ichnogenus *Dictyodora* is abundant in mudstone deposits rich in nutrients, that formed below wave base, but not necessarily on a continental slope or in a bathyal environment. The most important evolutionary change of *Dictyodora* was an increase in the height of the wall, which led to an increase in size overall, and in complexity (Benton, 1982). The increase in regularity of meandering has been seen as evolution towards greater efficiency of feeding where food distribution was patchy (Seilacher, 1974).

**Ichnogenus Diplopodichnus Brady, 1947**

*Diplopodichnus biformis* Brady, 1947

(Figs. 5D–E and 9A)

**Material and occurrence.** – Four specimens from exposures Wit I and Wit II.

**Description.** – Straight and curved horizontal trails, which are preserved as convex hyporeliefs, up to 7 cm long. One specimen is preserved as a single sinusoidal wave, which is slightly asymmetrical (Fig. 9A). Trails consist of two parallel ridges separated by a flat median groove, which is up to 2 mm wide. Median groove is wider than lateral ridges, which reach 1 mm width. Total trace width is 4 mm. Trails are rather smooth, but in two specimens a subtle transverse "segmentation" is partly visible.

**Remarks.** – The specimens from the Witoszów region are most similar to *Diplopodichnus biformis* described by Schatz et al. (2011: figs. 7, 8.2, 8.4, 9.1). This ichnogenus was originally defined by Brady (1947) from the Permian of Arizona, but Keighley and Pickrell (1996) emended the diagnosis. *Diplopodichnus* represents the repichnion ethological category (e.g., Pazos, 2002; Sadlok, 2008). According to many authors (e.g., Brady, 1947; Draganits et al., 2001; Getty et al., 2017; Lima et al., 2017) the producers of *biformis* were millipedes. As stated by Uchman et al. (2011) *Diplopodichnus* is similar to some variants of recent surface traces of isopods (bentic crustaceans). According to Brady (1998), there is a "Diplichnites-Diplopodichnus-Dendroidichnites" spectrum that could have been made by the same tracermaker.

This ichnogenus is usually known from continental and nearshore environments (Lucas et al., 2004) of the *Mermia* and *Scyphina* ichnofacies (Zhang et al., 1998; Lucas et al., 2013; Getty et al., 2017). It also occurs in the Upper Paleozoic diamictite and rhythmite facies in South America (Buatois and Mángano, 2011; Schatz et al., 2011; Neto et al., 2012b). The specimens from Witoszów are the first from a deep marine environment. The stratigraphic range of the ichnogenus is from the Ordovician to the Jurassic (Avanzini et al., 2011; Uchman et al., 2011a), and it covers a wide geographic area (Europe, USA, South America, India, China, see Zhang et al., 1998; Minter and Brady, 2009; Avanzini et al., 2011; Schatz et al., 2011; Uchman et al., 2011; Lima et al., 2017; Getty et al., 2017).

**Ichnogenus Lockeia James, 1879**

*Lockeia* isp.

(Fig. 7A)

**Material and occurrence.** – Four specimens from exposure Wit II.

**Description.** – Small, elongate, oval to almond-shaped moulds preserved as convex hyporeliefs, with clear margins and pointed terminations. The traces are 10–13 mm long and 4–5 mm wide (Fig. 7A). Three specimens occur serially, one after the other, and all of them on the same bedding surface together with *Protovirgularia* isp.
Remarks. — _Lockeia_ is usually interpreted as a bivalve resting trace (cubichnion; e.g., Häntzschel, 1975; Maples and Suttner, 1990; Ekdale and Bromley, 2001; Seilacher, 2007; Alonso-Murugaga et al., 2013), but some authors suggested its function as a domicile and escape trace (e.g., Buatois et al., 2005; Knaust, 2007). Other potential producers are ostracods and gastropods (e.g., Radley et al., 1998; Goldring et al., 2005). These traces occur in deposits representing a wide range of marine (from marginal to deep-sea) and freshwater environments from the Ediacaran to the Pleistocene (Kim, 1994; Radley et al., 1998; Goldring et al., 2005; Abbassi, 2007).

Ichnogenus _Lophoctenium_ Richter, 1850

Ichnogenus _Lophoctenium_ isp. (Fig. 7B)

Material and occurrence. — Two fragmentary specimens from exposure Wit II.

Description. — Epichnial structures fragmentarily preserved on the bedding plane. They consist of a series of concentric, curved and closely spaced asymmetrical burrow-fills with furrows, displaying a spreiten-like structure. The fragments are up to 4 cm long and up to 6 cm wide. The traces resemble _Lophoctenium comosum_ Richter described by Orr et al. (1996: fig. 8E, F) and occur in the same beds as _Lockeia_ isp. The specimens are poorly preserved and their assignment is uncertain.

Remarks. — According to Uchman (1998) _Lophoctenium_ needs a revision. This ichnogenus is regarded as a fodinichnion (trace of deposit-feeding organism, see Uchman et al., 2004). _Lophoctenium_ occurs in flysch deposits (e.g., Książkiewicz, 1977; Uchman, 1998; Uchman et al., 2004) from the Ordovician (Häntzschel, 1975) to the Miocene (Uchman, 1995) and is often described from the Lower Carboniferous Culm facies (e.g., Benton, 1982; Stepanek and Geyer, 1989; Orr et al., 1996; Lehotský and Zapletal, 2007).

Ichnogenus _Nereites_ Mac Leay in Murchison, 1839

_Nereites_ isp. (Fig. 10A, B)

Material and occurrence. — Two polished cross-sections of samples Cat. No. Wit II/8 and Wit IV/4 (exposures Wit II and Wit IV) with a _Nereites_ ichnofabric.

Description. — The _Nereites_ ichnofabric shows elongated, horizontal, dark “oval forms”, enveloped by claystone material. These “oval forms” are up to 2 cm long and are attributable to cross-sections of tunnels of _Nereites_. The filling is formed by dark, fine-grained material, which differs from the host rock. This claystone material, probably re-worked sediment, is a diagnostic feature of the ichnogenus _Nereites_ (Uchman, 1995).

Remarks. — _Nereites_ is interpreted as internal meandering grazing trails (pascichnia) (e.g., Seilacher and Meischner, 1989; Seilacher, 1986; Buatois and Mángano, 2011). The suggested possible producers were wormlike deposit-feeders, molluscs, arthropods or holothuroids (e.g., Häntzschel, 1975; Glaubek, 1998; Mángano et al., 2000; Joseph et al., 2012 and references therein).

This ichnogenus has been described from many occurrences ranging from the Late Precambrian (Crimes, 1987) to the Miocene (Uchman, 1995; Hu et al., 1998), or possibly Quaternary (Ekdale and Lewis, 1991).

It is a eurybathic form and a typical component of the _Nereites_ ichnosubfacies, which is distributed in distal flysch facies (e.g., Uchman, 2007b; Olivero et al., 2009; Joseph et al., 2012). It also occurs on tidal flats (Mángano et al., 2000), in shallow-marine deposits (e.g., Crimes and Anderson, 1985; Seilacher, 2007) and in fresh-water lakes (Wetzel, 2002).

Ichnogenus _Palaeophycus_ Hall, 1847

_Palaeophycus tubularis_ Hall, 1847 (Fig. 7D–F)

Material and occurrence. — Several specimens from all exposures studied (Wit I, Wit II, Wit III and Wit IV).

Description. — Predominantly horizontal to inclined endichnial burrows, distinctly lined, without ornamentation. They are preserved as convex epirelief and positive hyporelief. Tunnels are often branched, cylindrical, straight to curved or undulating. They are up to 10 cm long, with a diameter of 1.5–6 mm. The sediment fill is massive, similar to the host rock.

Remarks. — This ichnogenus is eurybathic and occurs in various environments from freshwater to marine. It is described from the Proterozoic to the Recent (Häntzschel, 1975; Pemberton and Frey, 1982; Buatois and Mángano, 2011). _Palaeophycus_ is ethologically interpreted predominantly as a dwelling burrow (domichnion) produced by deposit-feeders or predators, mostly by polychaetes, usually moving parallel to the bedding (e.g., Pemberton and Frey, 1982; Uchman, 1995; Mikuláš et al., 2013). Other authors have suggested fodinichnion/domicnichion (e.g., Rodriguez-Tovar et al., 2010), or replication/domicnichion (e.g., Chen et al., 2012).

Ichnogenus _Phycosiphon_ Fischer-Ooster, 1858

_Phycosiphon_ isp. (Fig. 10A, B)

Material and occurrence. — Two polished cross-sections of samples Cat. No. Wit II/8 and Wit IV/4 (exposures Wit II and Wit IV) with a _Phycosiphon_ ichnofabric.

Description. — In polished sections, _Phycosiphon_ resembles clusters of closely spaced elliptical spots and comma-shaped dots (0.2 mm thick) filled with darker sediment. In the specimens studied a narrow pale mantle was observed.

Remarks. — The specimens studied are very similar to specimens of _Phycosiphon incertum_ from the Eocene of Spitsbergen (Rodriguez-Tovar et al., 2014: fig. 3) and to small specimens of _Phycosiphoniform_ burrows from Cretaceous turbidites in Mexico (Bednarz and Mcllorey, 2009: fig. 1:1).

The ichnogenus _Phycosiphon_ has been variously described (for lists of synonyms see _Fu_, 1991; _Goldring_ et al., 1991; _Wetzel_ and _Bromley_, 1994). The _Phycosiphon_-producer generally colonized sediments enriched in organic matter (Wetzel, 2010) and was an opportunistic, highly selective deposit feeder (fodinichnion), but it remains unrecognized (Wetzel and Bromley, 1994; Wetzel and Uchman, 2001; Wetzel, 2008, 2010). According to Bednarz and Mcllorey (2009), producers of _phycosiphoniform_ burrows were small, probably vermiform organisms.
Fig. 7. Trace fossils from the Witoszów region

A – *Lockeia* isp. preserved as convex hyporelief, cat. No. Wit II/1b; B – *Lophoctenium* isp. preserved as epirelief, cat. No. Wit II/7; C – *Taenidium* isp. preserved as epichnial burrow, cat. No. Wit III/1; D–F – *Palaeophycus tubularis* preserved as positive hyporelief: D – cat. No. Wit I-2/1, E – cat. No. Wit III/1, F – cat. No. Wit II/8; G – *Protovirgularia* isp. preserved as positive hyporelief, cat. No. Wit II/1b; H – *Psammichnites* isp. preserved as positive hyporelief, cat. No. Wit II/1a
This ichnogenus is known from the Paleozoic to the Holocene from various marine environments (Seilacher, 1978; Fu, 1991; Goldring et al., 1991; Savrda et al., 2001; Naruse and Nifuku, 2008). It is most characteristic of the *Nereites* ichnofacies (Ineson, 1987) and the *Zoophycos* ichnofacies (Frey and Pemberton, 1984; Buatois and Mángano, 2011).

Ichnogenus *Protovirgularia* McCoy, 1850

**Protovirgularia isp.** (Fig. 7G)

**Material and occurrence.** – Fragment of one specimen from exposure Wit II.

**Description.** – Straight, unbranched, horizontal trail, which is poorly preserved (weathered) as convex hyporelief. It is 45 mm long and 4 mm wide. The internal structure consists of arcuate curved segments, highlighted by ribs. No visible median ridge. The trace is filled with sediment of the same type as the host rock. It occurs on the same bedding plane as *Lockeia* isp. and its width is similar to the width of *Lockeia* isp.

**Remarks.** – This ichnogenus is ethologically classified as a locomotion trail of a deposit-feeding (repichnion) bivalve (*Mángano et al., 2002b; Seilacher, 2007*). It is known from various marine (shallow to deep) and freshwater deposits (Han and Picken, 1994; Nara and Ikari, 2011) from the Arenig to the Miocene (*Uchman, 1998; Uchman and Gądzicki, 2006; Chen et al., 2011*).

Psammichnites was interpreted as a repichnion of large Paleozoic molluscs (*Häntzschel, 1975*). It is commonly referred to the feeding activity of a soft-bodied marine animal, moving through the sediment and being connected to the sediment surface by a snorkel device (e.g., *Seilacher, 1997; Acería and Acínolaza, 2006; Baucon and Neto de Carvalho, 2008*).

It ranges from the Lower Cambrian probably to the Permian (see *Mángano et al., 2002a*). *Psammichnites* is often reported from marginal-marine environments (*Mángano et al., 2002a; Buatois and Mángano, 2011; Desjardins et al., 2012*), while the Carboniferous *Psammichnites* is listed as a common element of lower estuarine settings (*Mángano et al., 2005; Buatois and Mángano, 2007*). It also occurs in shale substrates in offshore settings and thick turbidite successions (see *Álvaro and Vizcaíno, 1999*).

Ichnogenus *Psammichnites* Torell, 1870

*Psammichnites* isp.

(Fig. 7H)

Ichnogenus *Taenidium* Heer, 1877

*Taenidium* isp.

(Fig. 7C)
Material and occurrence. – Fragment of one specimen from exposure Wit III.

Description. – Horizontal, rather straight, slightly curved unwalled tunnel, preserved as an epichnial burrow on the bedding plane. It was actively filled, with a meniscate sandy core similar to the host rock, and a thin dark muddy lining. The lining is different than the host rock. The trace is 21 mm long and 2 mm wide.

Remarks. – The specimen resembles Taenidium barretti (Bradshaw, 1981) described by Baucon et al. (2014: fig. 4B), but is much thinner and menisci are less regular in shape and rather poorly preserved. The specimen studied is similar to Taenidium serpentinum Heer, 1877 in burrow width (see Keighley and Pickerill, 1994: fig. 3), but lacks well-spaced, arcuate menisci.

Meniscate burrows (ichnogenera Ancorichnus Heinberg, 1974; Beaconites Vialov, 1962; Taenidium Heer, 1877) were classified on the basis of the presence and type of wall, and differences in the type of meniscate backfilling (e.g., Bradshaw, 1981; Frey et al., 1984; D’Alessandro and Bromley, 1987). The ichnogeneric diagnosis of meniscate burrows was emended by Keighley and Pickerill (1994). Unwalled Beaconites barretti was included by these authors in Taenidium Heer, 1877 as T. barretti. A new species of Taenidium was also described by Bromley et al. (1999).

Taenidium was produced probably by deposit feeders (Uchman, 2007b). According to Baucon et al. (2014) this burrowing style is typical of worm-like organisms. Taenidium is a combination of locomotion and feeding trace and could be regarded as a pascichnion. Ichnogenus Taenidium is a facies-crossing form (from freshwater to deep marine environments), ranging from the Ordovician to the Pleistocene (Keighley and Pickerill, 1994; Abbassi, 2007). Ichnospecies T. barretti is typical of continental settings, while T. serpentinum occurs only in marine deposits (Keighley and Pickerill, 1994: fig. 5).

Vertebrate Trace Fossils

Ichnogenus Undichna Anderson, 1976
Undichna cf. britannica Higgs, 1988
(Fig. 8A, B)
First discovery of Mississippian trace fossils in the Świebodzice Unit from the Witoszów region (SW Poland)

Material and occurrence. – A few fragmentary specimens on one slab from exposure Wit I.

description. – Horizontal trails, preserved as epichnial grooves, up to 6 cm long. The grooves are sharply incised and commonly 1 mm wide. Trails are commonly discontinuous, consisting of two intertwined sinusoidal or slightly sinusoidal waves with different amplitude and being out-of-phase. Because of fragmentary preservation the exact determination of its parameters is not possible. The probable wavelength is ~30 mm and the amplitude is 7–10 mm. It is difficult to distinguish the wider (larger) wave from the narrower (smaller) wave and to determine the phase difference between waves. In addition, on the same slab there are short sections of other waves or scratches.

Remarks. – The morphotype of the trails described are most similar to specimens presented by Ronchi et al. (2018: fig. 7), but specimens from Witoszów are smaller. Similarly, specimens of Ronchi et al. (2018) are discontinuous and preserved only at the intersections of out-of-phase sinusoidal traces. The discontinuous and much larger specimens of U. britannica were also presented by Soler-Gijón and Moratalla (2001: fig. 3).

This ichnogenus was reviewed by Trewhin (2000) and Minter and Braddy (2006) and its stratigraphic range was originally restricted to the Late Paleozoic (see Gibert et al., 1999). Subsequently, Undichna was reported from the Upper Silurian to the Holocene as a common ichnotaxon in sub-aquatic continental and marine environments (Gibert et al., 1999; Minter and Braddy, 2006; Cardonatto and Melchor, 2014; Knaust and Minter, 2018; Knaust, 2019). According to Trewhin (2000), Undichna occurs also within glacially influenced rhythmites and turbidites in non-marine basins.

Most records of U. britannica are known from the Carboniferous to the Jurassic (Ronchi et al., 2018), but the entire stratigraphic range of this ichnospecies is from the Upper Mississippian (Fillmore et al., 2011) to the Holocene (Gibert et al., 1999).

This trace fossil is produced by fish swimming close to the sediment surface (repichnion). According to Cardonatto and Melchor (2014) the potential producers of this trace are palaeonisciforms with a subcarangiform locomotion type.

Other structures

Wave ripples influenced by microbial mats (Fig. 9C)

Material and occurrence. – One example from exposure Wit II.
Description. — The impression is preserved on the bedrock surface. It is ~60 mm long and 25 mm wide. It is preserved as a set of hypichnial ridges, of which three ridges are clearly visible, but the other three ridges occur only as fragments. Ridges are sinuously and bilaterally symmetrical, wavy and 2 mm wide. Waves are of low-amplitude (~5 mm). The distance between ridges is constant, distinctive, as is the amplitude (~4–5 mm).

Wavelength is ~22 mm.

Remarks. — This represents microbiologically induced sedimentary structures (MISS). This case of wave ripples. The specimen is very similar to the wave ripples described by Sarkar and Banerjee (2019) and Marriott et al. (2013: fig. 2a).

MISS are interpreted as mattracks, which involved substrate modification by microbial activity (Noffke et al., 2001, 2006; Marriott et al., 2013; Pazos et al., 2015; Vodrážková et al., 2019). According to Noffke et al. (2001) microbial mats dominated by cyanobacteria depend on photosynthesis. They are bathymetrically controlled and occur at the turning points of regression-transgression cycles from the Archean onwards. These structures, in modern times, are very common in shallow-marine to marginal-marine environments (Noffke et al., 2001, 2006). According to Davies et al. (2016), most of the fossil microbial mats have been reported from tidal and storm-influenced settings, and only sporadically from deeper water facies. Vodrážková et al. (2019) described microbially induced sedimentary structures from the Middle Devonian deep-water siliciclastic sequences of the Prague Basin and consider the origin of these structures as an effect of current and/or gravitational forces or of seismic shocks.

Zigzag scratches

( fig. 9B)

Material and occurrence. — Fragment of one specimen from the exposure Wit III.

Description. — The specimen is 4 cm long and ~3 cm wide. It consists of sets of parallel zigzag scratches preserved as epirelief. Distances between scratches are not equal and reach 5 mm. The specimen is poorly preserved and incomplete, and so determination is difficult.

Remarks. — These zigzag scratches shows some resemblance to the ichnogenus Parundichna Simon et al., 2003, but do not show characters typical characteristic of this ichnogenus. Parundichna is interpreted as the swimming trace (replacement) of a large coelacanth fish (Simon et al., 2003). The specimen studied may result from the motion of an unknown animal (fish or arthropod).

ICHNOASSEMBLAGE AND PALAEOENVIRONMENTAL INTERPRETATION

The ichnological material described from the Witoszów Górny region belongs to the Pogorza Formation. Detailed sedimentological interpretations of this lithostratigraphic unit were made by Teisserey (1956a) and Porębski (1981). The heterolithic succession was interpreted as reflecting deltaic-marginal marine environments (Cramer et al., 1924; Teisserey, 1968b; Gunia, 1968b). Other authors consider the Pogorza Formation as deposits of a fan-delta slope/basin plain depositional system (Nemec et al., 1980; Porębski, 1981, 1987). According to Wojewoda (2014, 2016a, b), the heterolithic succession represents turbidites, hemipelagic and pelagic facies with complexes of redeposited older rocks (often Devonian).

The mudstones from Witoszów Górny have a characteristic dark colour (dark grey, grey, green grey), and include pyrite concretions and well-developed thin parallel lamination. Other sedimentary structures were not observed, with the exception of one specimen of wave ripples. The mudstones are intercalated with thin fine-grained greywackes 1–20 cm thick. These rocks correspond to association I described by Porębski (1981). Such lithological features of mudstones are characteristic of low-energy lower-offshore settings (see Pemberton et al., 2012) and deeper settings (slopes and deep-sea fans; see Hubbard et al., 2012; Uchman and Wetzel, 2012). Their sedimentation took place in low-energy and low-oxygenated waters below storm wave base, with periodically anoxic conditions. The fine-grained greywackes may represent storm deposits. Some plant fossils (Fig. 4A–D), poor preserved benthic (bivalves) and nektonic (cephalopods, fish) macrofauna (Fig. 4E–I) also occur. The macrofauna indicate an open marine environment and the plant fragments were probably transported from land to sea by rivers or by floating.

An abundant and moderately diverse ichnofauna (fifteen ichnospecies, Table 1), found in four exposures studied (Wit I–Wit IV) in the Witoszów Górny region allows additional palaeoenvironmental conclusions. Among these trace fossils fodinichnia and repichnia dominate, while pasichnia, dromichnia and cubichnia are subordinate. Dictyodora liebeana is the most common trace fossil and occurs in three exposures (Wit I, Wit II and Wit IV). This ichnospecies was also found in the collection of Gunia (1968), including his outcrop 41 (Dubiech region, the Pogorza Formation), which was not studied here. Palaeophycus tubularis occurs frequently in all exposures studied. Other invertebrate trace fossils were occasionally found: Archaeonassa fossulata, Archaeonassa isp., Chondrites cf. intricatus, Curvolithus simplex, Diplopodichnus biforis, Lockeia isp., Lophochitonium isp., Nereites isp., Phycosiphon isp., Protovirgularia isp., Psamminichites isp. and Taenium isp. In exposure Wit I fish swimming trails Undichna cf. britannica were also found. An uncertain zigzag structure was discovered only in exposure Wit III.

The trace fossil assemblages from individual exposures differ from each other to varying degrees, but three of them are quite similar, primarily due to abundant D. liebeana. The highest ichnotaxonomic diversity (Table 1) was observed in shales from the exposures Wit II (10 ichnotaxa) and Wit I (8 ichnotaxa). In mudstones from exposure Wit IV 7 ichnotaxa were found. Trace fossil assemblages from these 3 exposures show the greatest similarity (4 or 5 common ichnotaxa) and display a Dictyodora liebeana ichnoassemblage. A very poor trace fossil assemblage with the lowest ichnotaxonomic diversity occurs in exposure Wit III (only 3 ichnotaxa, 1 ichnospecies common), the only exposure in which D. liebeana was not discovered.

Ichnological studies from Witoszów Górny also included ichnofabric analysis of some mudstone samples with D. liebeana. This involved observation of all structural and textural aspects of the deposits, especially bioturbation. In several polished cross-sections Nereites, Phycosiphon and D. liebeana ichnofabrics are observed (Fig. 10A–C). The Phycosiphon ichnofabric (small, dark, flattened “spots” and strings) manifests deeper tiering than the Nereites ichnofabric (horizontal, elongated and dark “forms”, enveloped by claystone material; Fig. 10A). In contrast to the observations of Mikuláš et al. (2002), the Dictyodora ichnofabric (the deepest tiering) from Witoszów shows clearly visible courses of these traces, which are oriented obliquely to the bedding surface (Fig. 10C). They are lined with a thin dark coating.
**List of trace fossils from the Witoszów Górny region**

<table>
<thead>
<tr>
<th>Trace fossils</th>
<th>Wit I</th>
<th>Wit II</th>
<th>Wit III</th>
<th>Wit IV</th>
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<tr>
<td>Archaeonassa fosculata</td>
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<td>Archaeonassa isp.</td>
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<td>Chondrites cf. intricus</td>
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<td>Curvolithus simplex</td>
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<tr>
<td>Dictyodora liebeana</td>
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<td>Diplopodichnus biformis</td>
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<td>Lockeia isp.</td>
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<td>?Lophoctenium isp.</td>
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<tr>
<td>Nereites isp.</td>
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<td>Palaeophybus tubularis</td>
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<td>Phyciosiphon isp.</td>
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<tr>
<td>Protovirgularia isp.</td>
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<tr>
<td>?Psammichnites isp.</td>
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<td>Taenidium isp.</td>
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<tr>
<td>Undichna cf. britannica</td>
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<tr>
<td>Zigzag structures</td>
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</table>

+++ – very abundant, ++ – abundant, + – rare

The palaeoenvironmental interpretation of sedimentary conditions of Witoszów mudstones is primarily based on the most common and distinctive trace fossil, *D. liebeana*. This ichnospecies has specific palaeoenvironmental requirements. Uchman (2004) stated that Ordovician to Carboniferous deep-marine ichnofaunas typically contained *Dictyodora*. According to Buatois and Mángano (2011 and references therein) this ichnogenus is considered as typical of deep-water *Nereites* ichnofaunas, but later research proved that *Dictyodora* occurs also in mudstones in a prodelta setting (see Pazos et al., 2015b). According to Pazos et al. (2015b), *Dictyodora* is not a direct indicator of deep-sea environments and most *Dictyodora* ichnospecies from the Silurian of Argentina are probably frequent in muddy substrates rich in nutrients below storm wave base, but not necessarily slope or bathyal.

In the Witoszów region, *D. liebeana* coexists with *Nereites* isp. The ichnogenera *Lophochtenium, Chondrites* and *Undichna* are also present in the *Nereites* ichnofaunas (Buatois and Mángano, 2011; Knaust, 2019). Other trace fossils from the Witoszów mudstones show varying environmental preferences. The ichnogenera *Palaeophybus, Lockeia* and *Protovirgularia* are eurybathic, while *Archaeonassa, Curvolithus* and *Psammichnites* mainly characterize shallow water *Cruiziana* ichnofaunas, but may also be present in deeper sedimentation zones. Only *Diplopodichnus* has so far been described from continental and near marine environments from the *Memria* and *Scyenia* ichnofaunas (Lucas et al., 2004; Buatois and Mángano, 2011). These ichnogenera, with the exception of *Dictyodora* and *Palaeophybus*, occur sporadically. According to Uchman and Wetzel (2011), co-occurrence of deep-sea and shelf trace fossils may be caused by the transport of trace-makers by storm and other currents from the shelf to the deep sea.

The *Nereites* ichnofaunas, documented from flysch deposits (Buatois and Mángano, 2011, and references therein), is characterized by a dominance of graphoglyptids and the presence of sophisticated grazing trails, feeding traces and deposit feeders, the dominance of shallow-tier trace fossils, very high ichnodiversity and high ichnabundance, but low densities of individual ichnotaxa. This characteristic refers rather to the *Nereites* ichnofacies from the Mesozoic–Cenozoic. Some ichnogenera and ichnofacies showed evolutionary changes through the Phanerozoic (Buatois and Mángano, 2011). For example, the evolutionary trend of *Dictyodora* was manifested by increase in the height of the wall, which led to an increase in size overall and in complexity (Benton, 1982). In consequence, these changes resulted in increased efficiency of feeding where food distribution was patchy (Seilacher, 1974). The *Nereites* ichnofacies changed many times, including by progressive size decrease of its components, increase in diversity and increase in the degree of complexity of some of the trace fossils (Seilacher, 1974; Uchman, 2003, 2004). This ichnofacies occurs over a wide bathymetric range (see examples in Uchman and Wetzel, 2012). The deep-sea trace fossils have often changed (e.g., in the diversity and contribution of graphoglyptids) through the Phanerozoic (Uchman, 2003, 2004). Cambrian graphoglyptids are known only from shelf deposits, whereas in the Ordovician this group colonized the deep sea floor (Orr, 2001; Uchman and Wetzel, 2012).

**Table 1**

<table>
<thead>
<tr>
<th>Trace fossils</th>
<th>Wit I</th>
<th>Wit II</th>
<th>Wit III</th>
<th>Wit IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archaeonassa fossulata</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Archaeonassa isp.</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chondrites cf. intricus</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Curvolithus simplex</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Dictyodora liebeana</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Diplopodichnus biformis</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Lockeia isp.</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>?Lophoctenium isp.</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Nereites isp.</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Palaeophybus tubularis</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Phyciosiphon isp.</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Protovirgularia isp.</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>?Psammichnites isp.</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Taenidium isp.</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Undichna cf. britannica</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Zigzag structures</td>
<td></td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>
was formed in an environment intermediate between a lower offshore zone (the distal Cruziana ichnofacies) and a fan-delta slope (below wave base, the Zoophycos ichnofacies).

An ichnoassemblage described by Orr et al. (1996) from the Lower Carboniferous of Menorca shows great similarity to the ichnoassemblage described from Witoszów. It occurs in the Culum sediments (mainly in sandstones, siltstones, mudstones) interpreted mostly as deposits of an inner- to mid-fan palaeoenvironment. A diverse ichnofauna contains D. liebeana, Chondrites, Lophoctenium, Nereites, Neoneireites, Arthro- phycus, Phycosiphon, Tomaculum (formerly Syncropus). In this ichnoassemblage, graphoglyptids are also absent.

A similar ichnoassemblage with Dictyodora was described by Benton (1982) from the Lower Carboniferous of Thuringia. It occurs in rhythmically layered black sapropelic mudstones and greywackes (the Culm facies). This ichnoassemblage represents the Nereites ichnofacies and contains also Chondrites, Lophoctenium, Protovirgularia and Nereites, but also Phycosiphon and the graphoglyptid Paleodictyon.

Another similar Dictyodora-Nereites ichnoassemblage occurs in the Carboniferous of the Canic Alps (Bacoun and Neto de Carvalho, 2002) and is interpreted as corresponding to deep marine settings associated with delta-front, organic-rich muds. It includes Dictyodora, Nereites and Protopalaeodictyon as an accessory component. Additionally, this fine-grained deposit is also characterized by presence of plant remains.

Two Carboniferous ichnoassemblages with Dictyodora liebeana are also known from Moravia and Silesia (Zapletal and Pek, 1987; Mikuláš et al., 2002, 2004). In the first one, this ichnospecies is accompanied by the ichnogenera Chondrites, Phycosiphon, Planolites, Spirodemos, Falichnites, Pilichnus, Protomalaeodictyon and Zoophycos. The second ichnoassemblage contains, in addition to Dictyodora, Diplocraterion, Rhizocorallium, Cosmoraphe and Paleodictyon. Mikuláš et al. (2002) also described ichnofabrics of the Culm facies from Moravia and Silesia, containing D. liebeana.

The ichnoassemblages studied show some similarities (the presence of Dictyodora liebeana, Nereites, Chondrites and Phycosiphon) and differences (the lack of graphoglyptids) to other Mississippian ichnoassemblages from the European Culm facies. This may be the result of limited connection of the Świebodzice basin with the open ocean as well as unstable environmental settings caused by a rapidly subsiding basin (see Nemec et al., 1980; Porębski, 1981, 1987, 1990) in the Late Viséan–Serpukhovian.

The lithological features of the mudstones (e.g., dark colour, pyrite concretions, lamination) from Witoszów Górny, the poverty of benthiic and nektonic macrofauna and numerous trace fossils typical of the Nereites ichnofacies, but without graphoglyptids, testify to their deposition in a deeper sedimentation zone, below storm wave base, most likely in dysaerobic (and even anaerobic), pro-delta conditions. Dominance of deposit feeders in the Dictyodora ichnoassemblage and the absence of suspension feeders indicates a soft, easy-to-penetrable and organic-rich substrate.

CONCLUSIONS

This is the first comprehensive report of trace fossils from the Pogorzala Formation and the Świebodzice Unit. In four studied exposures in Witoszów Górny, abundant and moderately diverse (15 ichnospecies referred to 14 ichnogenera) ichnofauna were discovered and within them 1 ichnospecies of fish swimming trails. Wave ripples influenced by microbial mats and zigzag structures were also found. The Dictyodora liebeana ichnoassemblage, which occurs in dark green grey mudstones in three studied exposures (Wit I, Wit II and Wit IV) represents the non-standard Nereites ichnofacies (probably Nereites sub-ichnofacies) without complex agrichnial burrows. An absence of graphoglyptids may be the result of many factors: (1) low diversity and frequency of this group, (2) shallower conditions, which were not conducive to the development of graphoglyptids or their preservation, (3) unstable conditions caused by the rapidly subsiding Świebodzice basin in the Late Viséan–Serpukhovian and (4) limited connection of the basin with the open ocean. D. liebeana has also been found in the Lubiechów region (sample 41, coll. of Gunia, 1968). The above-mentioned four occurrences of D. liebeana have a zonal, latitudinal course and are located in the south of the Pogorzala block (Fig. 1).

Lithological features of the mudstones, the poverty of benthiic and nektonic macrofauna, plant remains and numerous trace fossils without graphoglyptids indicate deposition of these strata in a deeper marine settings, below storm wave base, most likely in dysaerobic (and even anaerobic), pro-delta conditions. A domination of deposit feeders and absence of suspension feeders in the ichnoassemblage described indicates a soft, organic-rich and easy-to-penetrable mud substrate. These mudstones represent distal flysch.

Among the trace fossils listed, the most important stratigraphically is D. liebeana, which is an index for the Lower Carboniferous (Uchman, 2004, 2007a). Occurrence of this ichnospecies in the Serpukhovian of the neighbouring the Intra-Sudetic Synclinorium (Zakowa, 1958; Muszer, 2013; 2020; Muszer et al., 2016) indicates that it is restricted to the Mississippian. An other ichnospecies which appeared in the Carboniferous is Undichna britannica (see Fillmore et al., 2011; Ronchi et al., 2018). The widespread occurrence of D. liebeana and presence of U. cf. britannica in-situ in the region of Witoszów Górny supports the latest suggestions of Pluta and Górecka-Nowak (2018) and provides additional evidence for referring the mudstones of the Pogorzala Formation to the Mississippian.

Many researchers have emphasized the difficulty of stratigraphic correlation of the rocks building the Świebodzice Unit, because of the lack of good biostratigraphic control, and of widespread correlative horizons (e.g., Teissaye, 1956a; Porębski, 1981; Pluta and Górecka-Nowak, 2018). The results of this ichnological study suggest that one such correlative horizon may be the strata containing Dictyodora liebeana. This ichnospecies, restricted to the Mississippian, is abundant and easy to recognize, especially in the field.

Further ichnological studies of the Pogorzala Formation (e.g., in the vicinity of Lubiechów), especially of the mudstones and sandstones, may provide additional palaeoenvironmental information. Likewise, ichnological studies of the Pelcznica Formation may be prospective.

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