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Middle Turonian trace fossils from the Bystrzyca and Długopole sandstones in the Nysa Kłodzka Graben (Sudetes, SW Poland)

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The Middle Turonian sediments of the Nysa Kłodzka Graben (Bystrzyca Sandstone in the Stara Bystrzyca outcrop and the Długopole Sandstone in Długopole Górne Quarry) contain trace fossils, which include *Curvolithus simplex*, ?*Macaronichnus* isp., *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Palaeophycus tubularis*, *Thalassinoides* cf. *paradoxicus*, *T. suevicus* and *Thalassinoides* isp. The assemblage of trace fossils points to the proximal *Cruziana* ichnofacies, that characterizes the distal lower shoreface and the archetypal *Cruziana* ichnofacies, typical of upper offshore settings. The trace fossils evidence implies that sedimentation took place in a shallow basin with periods of a sudden sediment input, good oxygenation and normal salinity. The Bystrzyca and Długopole sandstones are deposits of the shallow epicontinental sea that were deposited between the fair-weather and storm-wave base, in the distal lower shoreface–upper offshore setting. The Bystrzyca Sandstone is recognized as storm-originated deposits, whereas the Długopole Sandstone is probably the part of prograding “accumulation terrace”. The source of material for the sandstone was the East Sudetic Island and probably also the Orlica–Bystrzyca Uplift. The studied sandstones are related to a regression that started in the early/middle Middle Turonian and caused a relative uplift of the surrounding land.

Key words: trace fossils, ichnofacies, Cretaceous, palaeoenvironments, Middle Turonian, Sudetes.

INTRODUCTION

The study of trace fossils is very useful for palaeoenvironmental reconstructions. Ichnological analysis is a well-known source of information on the behaviour of the tracemaker as well as the sedimentary conditions (Seilacher, 1967, 2007; Bromley, 1996; Pemberton et al., 2001; McIlroy, 2004; Bromley et al., 2007; Miller, 2007; Buatois and Mángano, 2011; Knaust and Bromley, 2012). Trace fossils are very good tools in reconstruction of environment because they are preserved *in situ* and their distribution in environments is controlled by different environmental factors.

This paper provides the first detailed ichnological study of trace fossil assemblage found in the Middle Turonian sandstone (Stara Bystrzyca, Długopole Górne) in the Nysa Kłodzka Graben (Żelaźniewicz and Aleksandrowski, 2008; Figs. 1–3). Until now, the only published record was a short communication by Don and Wojewoda (2004) and Chrząstek (2012), concerning the Upper Cretaceous trace fossils from the Nysa Kłodzka Graben. Presence of trace fossil assemblage within Bystrzyca and Długopole sandstones, which are devoid of macrofossils, enables reconstruction of the environment and provides information on sedimentary conditions of their deposition during the Middle Turonian. In the Stara Bystrzyca and Długopole Górne outcrops, only some bivalves (mostly internal moulds of *Lima canalifera* Goldfuss and *Lima* sp.) and one fragment of an ammonite were recorded.

The studied assemblage of trace fossils is very rich in specimens, well-preserved but low-moderately diverese. The most abundant trace fossils are *Ophiomorpha nodosa* and *Ophiomorpha* isp., *Thalassinoides* cf. *paradoxicus*, *T. suevicus* and *Thalassinoides* isp. occur less frequently. Less common are *Curvolithus simplex*, *Palaeophycus tubularis* and ?*Macaronichnus* isp. (Table 1). The majority of specimens were not collected because they occur on the surfaces of large sandstone blocks, especially in the Długopole Górne Quarry. Therefore, they are documented mainly by field photographs.

Ichnological analysis of palaeoenvironment during the deposition of the Bystrzyca and Długopole sandstones in the Nysa Kłodzka Graben was used to interpret the sedimentary conditions: sedimentation rate, environment energy, palaeobathymetry, water salinity, levels of oxygenation of pore waters and consistency of the substrate. Thus, the trace fossils represented a basis for the reconstruction of the depositional environment and the palaeogeographic interpretation.

GEOLOGICAL SETTING

The Nysa Kłodzka Graben is one of the youngest tectonic units in the Sudetes (Don and Gotowała, 2008), that started to develop during the Coniacian (Wojewoda, 1997; Don and

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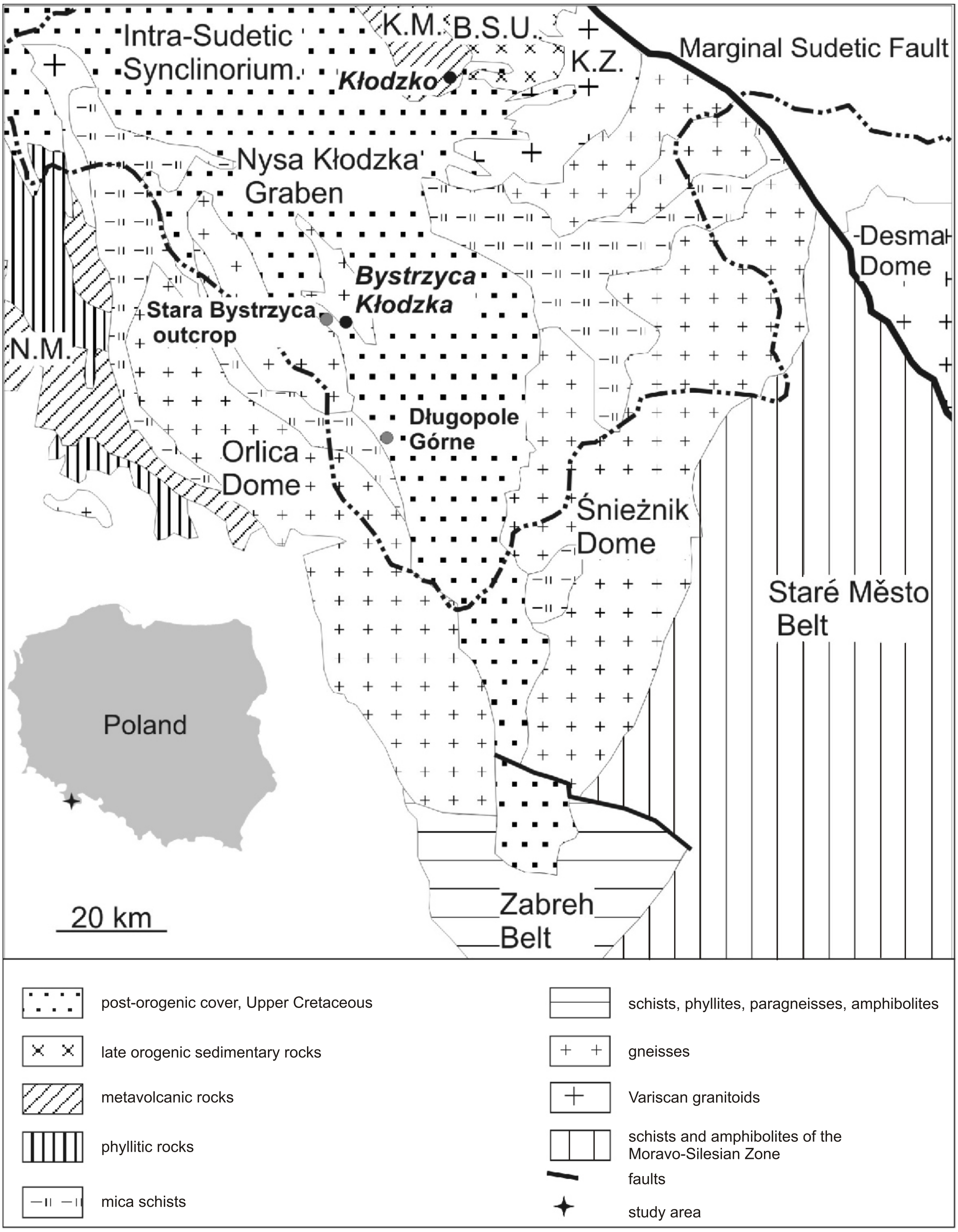
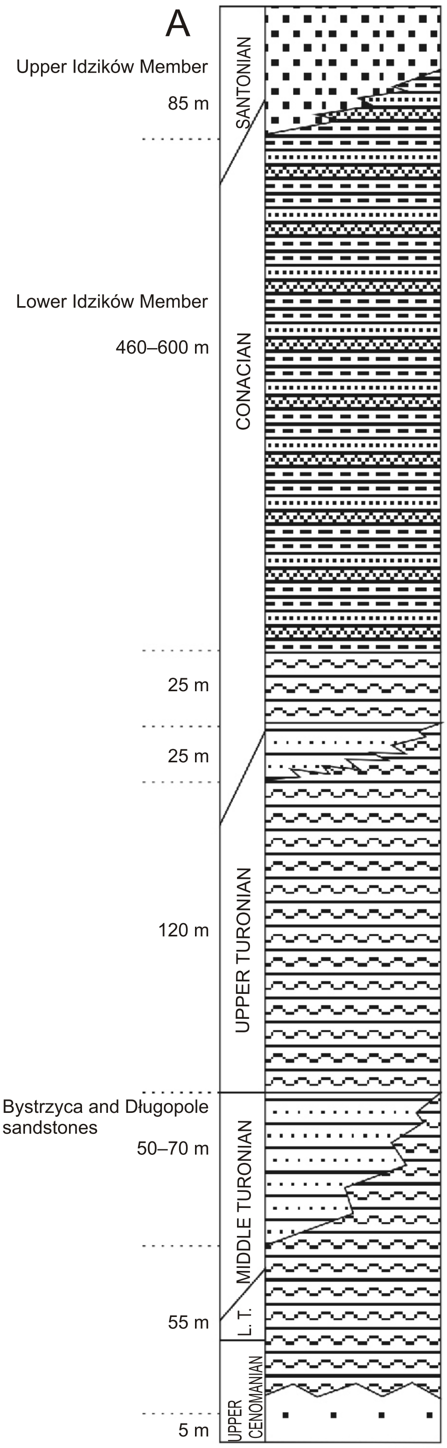


Fig. 1. Tectonical sketch of the Nysa Kłodzka Graben (after Żelaźniewicz and Aleksandrowski, 2008)

B.S.U. – Bardo Structural Unit; K.M. – Kłodzko Metamorphic Massif; K.Z. – Kłodzko–Złoty Stok Granite Pluton; N.M. – Nové Město Slate-Greenstone Belt



▨ Coniacian–?Santonian sandstones and conglomerates

▨ Coniacian calcareous claystones and mudstones intercalated by sandstone; intercalations of spongiolites in the bottom part of the section, in the Upper Cenomanian and in the Coniacian

▨ Lower to Upper Turonian calcareous mudstones, siliceous-calcareous mudstones, calcareous claystones, sandy limestones

▨ Middle and Upper Turonian sandstone, sublithic arenite, glauconitic sublitharenite

▨ Upper Cenomanian glauconitic arcosic arenite

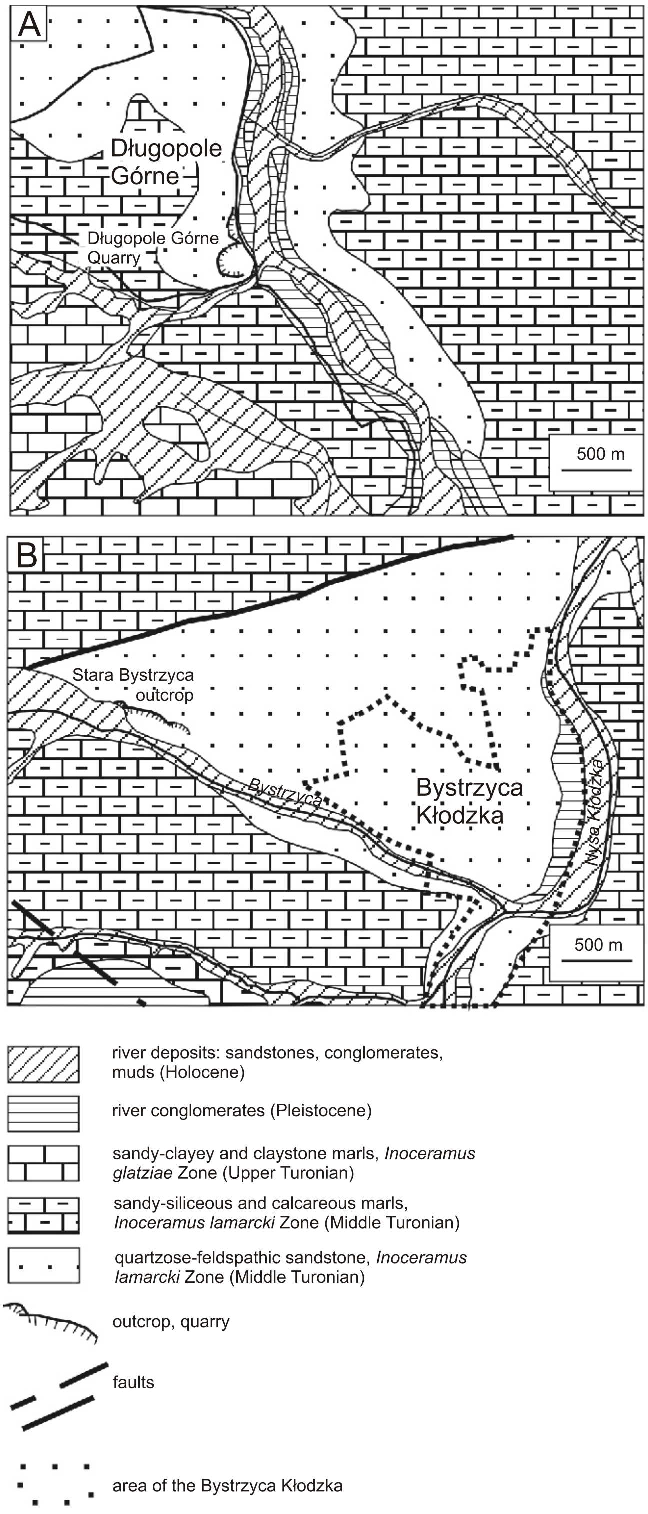
▼ age of the Bystrzyca and Długopole sandstones

B

Period/ epoch	Age	Subage	Inoceramid zonation (Walaszczyk, 1992; Walaszczyk and Wood, 1998)	Ammonite zonation (Walaszczyk, 1988, 1992; Kędzierski, 2008)
Late Cretaceous	Turonian	Late	*Cremnoceramus waltersdorfensis*	*Subprionocyclus neptuni*
			Mytiloides incertus	
			Inoceramus costellatus	
		Middle	*Inoceramus lamarcki* ▼	*Collignoniceras woollgari*
			Inoceramus apicalis	
		Early	*Mytiloides* ex. gr. *labiatus*	*Mammites nodosoides*

Fig. 2A – lithostratigraphic section of the Upper Cretaceous deposits in the Nysa Kłodzka Graben (after Wojewoda, 1997; Don and Gotowała, 2008, slightly changed by the author); B – chronostratigraphic table showing Turonian inoceramid and ammonite zonation (after Kędzierski, 2008)

L.T. – Lower Turonian



Długopole Górne Quarry 50°13.723′N 16°38.212′E

Stara Bystrzyca outcrop 50°18.117′N 16°37.839′E

Fig. 3A – geological map of the Długopole Górne vicinity (after Walczak-Augustyniak and Wroński, 1981); B – geological map of the Stara Bystrzyca neighbourhood (after Wroński, 1981)

Table 1

Ichnotaxonomical diversity in the Middle Turonian of the Bystrzyca and Długopole sandstones

Ichnotaxa	Bystrzyca outcrop	Długopole Górne Quarry
Curvolithus simplex	–	+
?*Macaronichnus* isp.	–	+
Ophiomorpha nodosa	+++	+++
Ophiomorpha isp.	+++	+++
Palaeophycus tubularis	+	+
Thalassinoides cf. *paradoxicus*	–	++
Thalassinoides suevicus	–	++
Thalassinoides isp.	–	++

+++ – abundant, ++ – common, + – rare, (–) – absent

Wojewoda, 2005; Kędzierski, 2005). It is approximately 55 km long and from 12 km (near Kłodzko) to almost 2 km wide in its southern part, lying in the Czech Republic (Fig. 1).

The Nysa Kłodzka Graben is filled with detrital sediments of the Cenomanian–?Santonian age, deposited on metamorphic rocks of the Orlica–Śnieżnik Dome (Fig. 1). The Upper Cretaceous sediments of the Nysa Kłodzka Graben passed into deposits of the same age from the Intra-Sudetic Basin. The Cretaceous succession ranges in thickness from 350 m in the Stołowe Mountains (Intra-Sudetic Basin) to over 1200 m in the Nysa Kłodzka Graben (Wojewoda, 1997).

The Cretaceous succession of the Nysa Kłodzka Graben consists of calcareous claystones, siliceous-calcareous mudstones, calcareous mudstones, separated by beds of sandstone, sandy limestone and spongiolite (Fig. 2A; Wojewoda, 1997; Don and Wojewoda, 2004, 2005; Niedźwiedzki and Salamon, 2005; Don and Gotowała, 2008). The German geologists, who investigated the Upper Cretaceous deposits of the Stołowe Mountains in the 19th century, termed the sandstones Quadersandstein, and fine-grained rocks as Plänermergel (see Geintiz, 1843; Rotnicka, 2005). These names are used in regional studies, in the Stołowe Mountains and the Nysa Kłodzka Graben, up to date.

The Quadersandstein Megafacies (e.g., Bystrzyca and Długopole sandstones) appears twice in the Turonian of the Nysa Kłodzka Graben: in the Middle and Upper Turonian (equivalents of the Radków Bluff Sandstone and the Skalniak–Szczeliniec Sandstone from the Intra-Sudetic Basin).

The Quadersandstein Megafacies in the vicinity of Stara Bystrzyca is 45–60 m thick (Don and Don, 1960; Komuda and Don, 1964; Radwański, 1965, 1975; Wroński and Cwojdziński, 1984). In the Długopole Górne, it is ca. 70 m thick (Wroński, 1982). These sandstones pinch out towards the south and the south-east and their grain size decreases in these directions. In the north and north-west parts of the Nysa Kłodzka Graben their thickness reaches ca. 110 m (Grocholska and Grocholski, 1958; Fistek and Gierwielaniec, 1964) and decreases to a few metres in the southern part of the graben.

The youngest deposits in the Nysa Kłodzka Graben – sandstones and conglomerates of the Upper Idzików Member (Fig. 2A) was earlier included in the Coniacian but currently is considered as being also Santonian in age (Don and Wojewoda, 2004; Wojewoda, 2004).

Biostratigraphy of the Upper Cretaceous deposits is usually based on inoceramids and ammonites. The Middle Turonian is subdivided into the following inoceramid zones: *Mytiloides* ex. gr. *labiatus* Zone, *Inoceramus apicalis* Zone, *I. lamarcki* Zone and *Collignoniceras woollgari* ammonite Zone (Walaszczyk, 1988, 1992; Walaszczyk and Wood, 1998; Kędzierski, 2008; Fig. 2B). The Bystrzyca and Długopole sandstones represents the *Inoceramus lamarcki* Zone and are probably of the middle Middle Turonian age, because they are overlain by the Bystrzyca limestones, that are dated, on the basis of inoceramids, as late Middle Turonian in age (Chrząstek, 2012; Fig. 2B). Additionally, Niedźwiedzki and Salamon (2005) found the crinoid *Bourgueticrinus* sp., within sandy siliceous mudstone of the *Inoceramus lamarcki* Zone; this is late Middle Turonian – earliest Late Turonian in age.

THE BYSTRZYCA AND DŁUGOPOLE SANDSTONES

The Middle Turonian sandstones from the Nysa Kłodzka Graben crop out at Stara Bystrzyca and Długopole Górne (Figs. 1, 3 and 4). The first outcrop is situated in Stara Bystrzyca, near the beginning of the village, on the right side of the road from Bystrzyca Kłodzka (Figs. 3B and 4B).

The Middle Turonian deposits cropping out in Stara Bystrzyca are a fine- to medium-grained, less frequently coarse-grained greyish sandstone; its beds are 0.5–1.0 m thick. Hummocky cross-stratification (HCS) was recognized in these deposits. The analysis of thin sections revealed that the Bystrzyca Sandstone contains over 50% of angular and subangular quartz grains and 5–15% of feldspar (microcline, plagioclases). This cement-matrix is clay-rich (<50% of clay minerals; 10–20% carbonates), yellow in colour and microcrystalline. Sparse grains of tourmaline were also observed.

In Długopole Górne, the Middle Turonian deposits are exposed in a quarry situated at the right side of the road from Bystrzyca Kłodzka to Długopole Górne (Figs. 3A and 4A).

The Długopole Sandstone beds lie almost horizontally (bedding planes from 5 up to 23°, see Don and Wojewoda, 2004). The sandstones are fine- to coarse-grained, cross-bedded, light grey-brown in colour. The Długopole Sandstone shows remarkable giant-scale cross-bedding (Don and Wojewoda, 2004). Their beds are from 0.5 to 3.0 m thick and contain gravel intercalations. Investigations of thin sections under the microscope, performed by the author, confirmed earlier descriptions of the Bystrzyca Sandstone (Fistek and Gierwielaniec, 1964). In thin sections of the Długopole Sandstone, a higher quantity of quartz grains and a smaller amount of feldspar grains (5–10%, locally <5%) was observed. Minor amounts of mica flakes are also present. The cement of these sandstones are clay rich, the clay minerals themselves constituting up to to 50% and carbonate ranges from 10 to 15%.

In agreement with the classification of sedimentary rocks (Lorenc, 1978), the Middle Turonian rocks from Stara Bystrzyca and Długopole Górne may be classified as a quartzose-feldspathic sandstone (subarcosic arenite and quartz arenite).

In the Stara Bystrzyca Quarry, a fragment of an ammonite was found (Fig. 5A), while in the Długopole Górne the bivalves *Lima canalifera* Goldfuss and *Lima* sp. (Fig. 5B, C) and a lot of moulds of bivalves were observed (Fig. 5D). In the collection of the Geological Museum of Wrocław University (MGUWr), the Turonian brachiopod (*Rhynchonella plicatilis* Sowerby specimen MGUWr-1883s) and the Middle Turonian bivalve (*Lima canalifera* Goldfuss, MGUWr-1499s) from the Długopole Górne outcrops are stored (Fig. 5E, F).

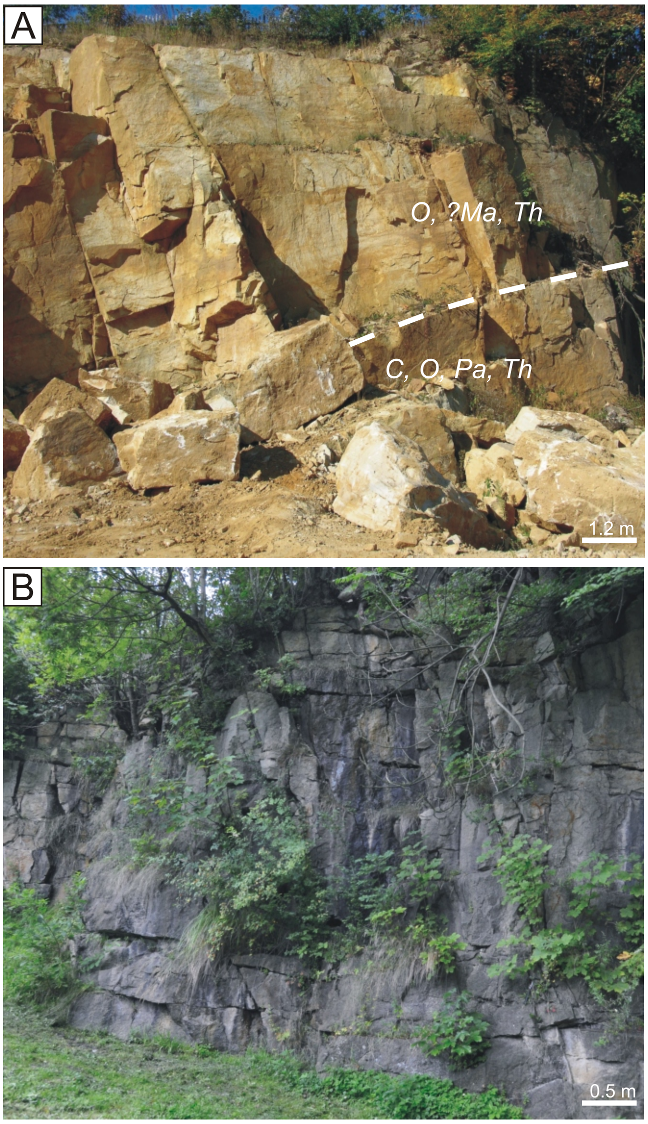


Fig. 4. Długopole Górne Quarry and Stara Bystrzyca outcrop

A – Długopole Górne Quarry (Middle Turonian sandstone); *C* – *Curvolithus*, ?*M* – *Macaronichnus* (questionable position due to occurrence in a sandstone block), *O* – *Ophiomorpha*, *Pa* – *Palaeophycus*, *Th* – *Thalassinoides*; **B** – Stara Bystrzyca outcrop (Middle Turonian sandstone)

DESCRIPTION OF TRACE FOSSILS

Middle Turonian sandstone outcropping at Stara Bystrzyca contains abundant *Ophiomorpha nodosa* and *Ophiomorpha* isp., whereas *Palaeophycus tubularis* is rare.

In the Długopole Górne Quarry, the Middle Turonian deposits contain trace fossils *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Thalasinoides* cf. *paradoxicus*, *T. suevicus*, *Thalassinoides* isp., *Palaeophycus tubularis*, ?*Macaronichnus* isp. and *Curvolithus simplex*. The most common are *Ophiomorpha* and *Thalassinoides* (Table 1).

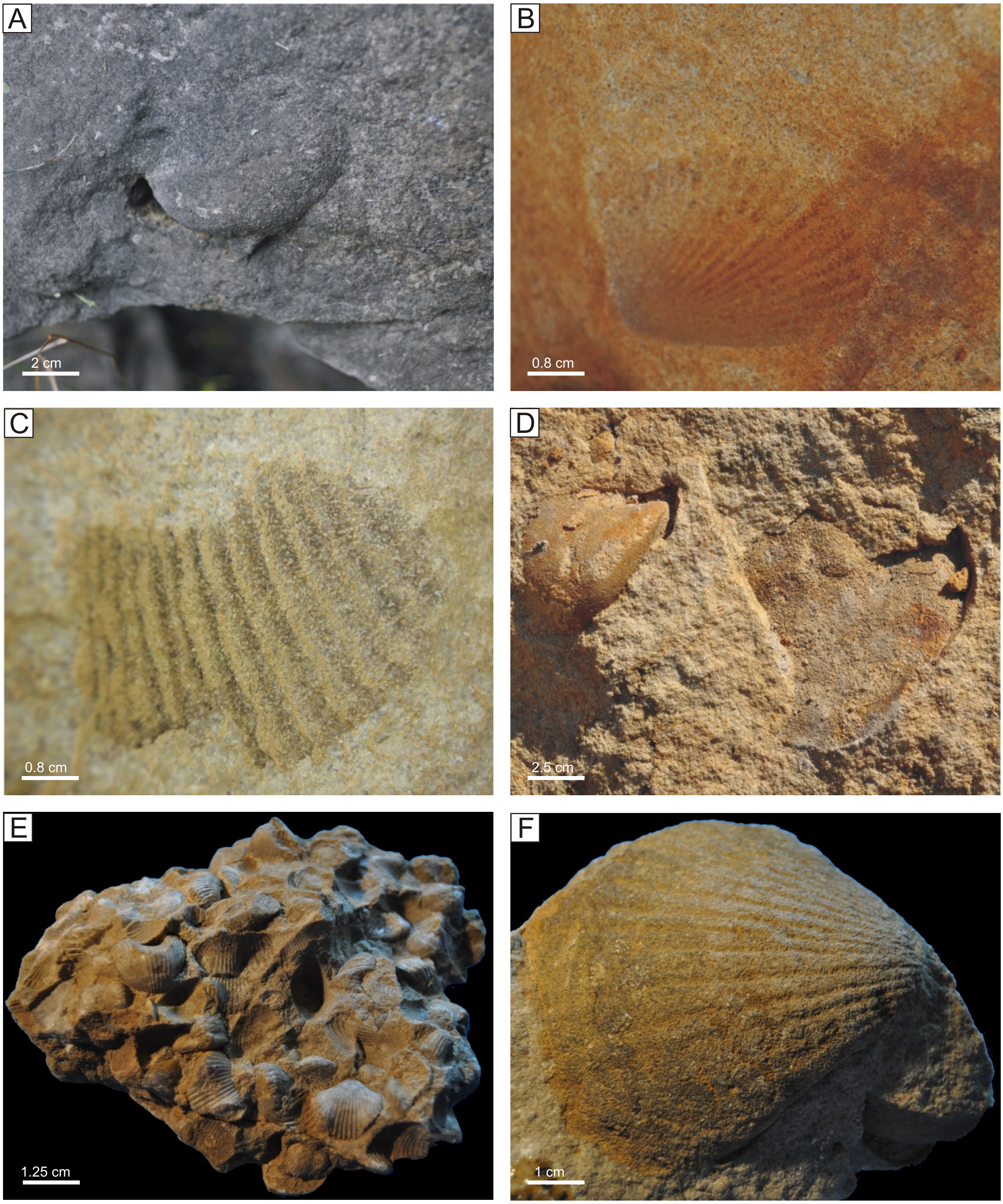


Fig. 5. Ammonites, bivalves and brachiopods from the Stara Bystrzyca and Długopole Górne outcrops

A – Ammonite? (Stara Bystrzyca); **B** – *Lima canalifera* (Długopole Górne); **C** – *Lima* sp. (Długopole Górne); **D** – moulds of bivalves (Długopole Górne); **E** – *Rhynchonella plicatilia* (MGUWr-1883s) from the collection of the Geological Museum of Wrocław University (Middle Turonian, Długopole Górne); **F** – *Lima canalifera* (MGUWr-1499s) from the collection of the Geological Museum of Wrocław University (Turonian, Długopole Górne)

Curvolithus simplex Buatois et al., 1998 (Fig. 6A) is a horizontal, epichnial straight to slightly winding, unbranched structure, 2 cm wide, 8 cm long, which is characterized by three rounded lobes. The central lobe is smooth, flattish, without ornamentation and is wider (1 cm) than lateral ones (0.5 cm).

Curvolithus has been usually interpreted as a locomotion trace (repichnion) of gastropods, wormlike polychaetes, oligochaetes, nemerteans, holothurians (Buatois et al., 1998 and references therein). According to Lockley et al. (1987), the tracemaker was probably an animal with a flattened cross-section. Seilacher (2007) and Knaust (2010) suggested that the tracemakers of *Curvolithus* could be flatworms (Platyhelminthes). According to Heinberg and Birkelund (1984), the *Curvolithus*-producing organism is very tolerant to grain-size changes that confirms production rather by a carnivore rather than a deposit-feeder.

Curvolithus belongs to the *Cruziana* ichnofacies *sensu* Seilacher (1967) or to the *Curvolithus* ichnofacies *sensu* Lockley et al. (1987), which is presently considered as a subset of the *Cruziana* ichnofacies (Bromley, 1996; McIlroy, 2008).

Curvolithus commonly occurs within shallow-marine deposits, from intertidal to shallow subtidal zones (Buatois et al., 1998; Mángano and Buatois, 2004).

This ichnogenus appears from the late Precambrian to Miocene (Buatois et al., 1998; Krobicki and Uchman, 2003; Uchman and Tchoumatchenco, 2003; Hofmann et al., 2011) but it is most common in Carboniferous (Eagar et al., 1985; Greb and Chesnut, 1994; Brettle et al., 2002) and Jurassic deposits (Wincierz, 1973; Fürsich and Heinberg, 1983; Bruhn and Surlyk, 2004).

?*Macaronichnus* isp. is more or less horizontal, straight or slightly winding, locally irregularly sinuous, unbranched burrow, 2.0–3.0 mm across, at least 15 mm long, observed within *Thalassinoides* filling in the Długopole Górne Quarry. The trace fossil filling is light-coloured in contrast with the darker host infill of *Thalassinoides*. Concentration of dark grains along the burrow margins suggests *Macaronichnus* (see Clifton and Thompson, 1978; Bromley et al., 2009), but the poor preservation prevents sure determination.

Macaronichnus can be produced by organisms that fed on epigranular microbial films (see Clifton and Thompson, 1978; MacEachern and Pemberton, 1992). It is interpreted as pascichnion (Savrda et al., 1998) or fodinichnion (Rindsberg, 2012). The tracemakers are deposit feeding polychaetes, most likely opheliids; analogies in modern environments: *Ophelia limacina* (Clifton and Thompson, 1978; D'Alessandro and Uchman, 2007; Seike et al., 2011) and *Euzonus mucronata* or *Euzonus* (Nara and Seike, 2004; Savrda and Uddin, 2005; Kotake, 2007; Seike, 2007; Dafoe et al., 2008).

Macaronichnus appears in the *Skolithos* ichnofacies (MacEachern et al., 2007a; Pemberton et al., 2001; Buatois and Mángano, 2011) and in the *Cruziana* ichnofacies (Maples and Suttner, 1990; Pemberton et al., 2001). This ichnotaxon has been reported also from the mixed *Skolithos-Cruziana* ichnofacies (Martini et al., 1995; Rossetti, 2000; Rossetti and Santos Júnior, 2004). The most common occurrences of *Macaronichnus* are in well-oxygenated foreshore and shoreface sands deposits (Clifton and Thompson, 1978; Pemberton et al., 2001; Gordon et al., 2010).

Macaronichnus is known since Permian to Holocene (Bromley, 1996; Quiroz et al., 2010).

Ophiomorpha nodosa Lundgren, 1891 (Figs. 6B–E, 7A, B, E, F and 8B–F) appears as single isolated shafts or tunnels or in some places as complex burrow system (complex network: mazes or boxwork; see Frey et al., 1978). Burrows are straight, usually vertical or subvertical but also inclined and horizontal. The traces have distinct knobby walls, which consist of agglutinated pelletoidal sediments. The walls are a characteristic and diagnostic feature of *Ophiomorpha* (Frey et al., 1978; Kamola, 1984). They are well-visible in the Middle Turonian deposits, in Długopole Górne Quarry (Fig. 6C, D) and Stara Bystrzyca outcrop (Fig. 7E). Pellets are usually interpreted as stabilizing the burrows and supporting the structure to prevent collapse of unconsolidated sediment (Ekdale and Bromley, 1984; Bromley, 1996; Rodríguez-Tovar et al., 2008).

Ophiomorpha is mostly elliptical, rarely circular in cross-sections, 0.5–2.5 cm across. Fragments of the burrows visible on the rock surface are 5.0–17.0 cm long, filled usually with sediment similar to the host rock. In some cases the fill is darker and coarser-grained (Fig. 6C, D). The burrow fill is rather structureless or meniscate (Figs. 7F and 8B). Burrows are rarely branched and exhibit mostly Y shaped branching. Swellings occur in some burrow segments, which are interpreted as turning chambers of the tracemaker (Figs. 6C, D and 7B; Frey et al., 1978; Bromley, 1996; Anderson and Droser, 1998; Monaco and Garassino, 2001).

Burrow walls are in some cases incomplete or do not have visible peelleted walls. For these reasons some specimens were recognized at the ichnogenus level as *Ophiomorpha* isp. (Figs. 6F, 7C, D and 8A).

The ethology of *Ophiomorpha* is not fully understood (e.g., Uchman and Gaździcki, 2006). They are interpreted as domichnia or fodinichnia (Frey et al., 1978). Recent work also suggested that deep marine *Ophiomorpha* may represent agrichnia (Cummings and Hodgson, 2011). The tracemakers of *Ophiomorpha* are deposit and/or suspension-feeders or farmers (Bromley, 1996; Ekdale and Stinnesbeck, 1998; Fürsich et al., 2006). According to Frey et al. (1978), older parts of the burrows are used as domiciles whereas newer parts are feeding structures.

Ophiomorpha is produced by decapod crustaceans, mainly callianassid shrimps; crayfish and crabs are also considered as tracemakers (Frey et al., 1978; Gibert et al., 2006). Modern analogues of the *Ophiomorpha* producers include *Callichirus major* (former *Callianassa major*), *Protocallianassa*, *Axius* and *Neotrypaea* (Frey et al., 1978; Curran, 1984; Curan and White, 1991; Miller and Curran, 2001; Savrda et al., 2010).

Ophiomorpha is seen most commonly as a shallow-marine and marginal-marine trace fossil, typical for the *Skolithos* ichnofacies (Frey and Seilacher, 1980; Pemberton et al., 2001), but it occurs also in an offshore – *Cruziana* ichnofacies (Frey, 1990; Frey and Howard, 1990). *Ophiomorpha* should be interpreted on ichnospecific level because some ichnospecies (e.g., *Ophiomorpha annulata*, *O. rudis*) are known from deep-sea (Uchman, 1991). *Ophiomorpha* has a global distribution (Becker and Chamberlain, 2006) and is known from Permian to Holocene (Frey et al., 1978; Phillips et al., 2011). According to Anderson and Droser (1998) *Ophiomorpha* was found also in Pennsylvanian deposits.

Palaeophycus tubularis Hall, 1847 (Fig. 9A, B) from the Bystrzyca and Długopole sandstones are horizontal, straight to slightly winding, unbranched, cylindrical burrows, slightly elliptical in cross-sections, which are 3.0–5.0 mm across. Fragments of the burrows, visible at the rock surface, are 2.5–15 cm long. They possess distinct, smooth and unornamented walls and structureless fill, identical in lithology as the host rock.

Palaeophycus is interpreted as a dwelling burrow (domichnion) of suspension-feeders or predators (Pemberton and Frey, 1982). Virtasalo et al. (2006) and Lauridsen et al. (2011) interpreted *Palaeophycus* as feeding trace, combining deposit feeding and dwelling (fodinichnion) and speculated that *Palaeophycus* tracemaker is possibly a carnivore, a suspen-

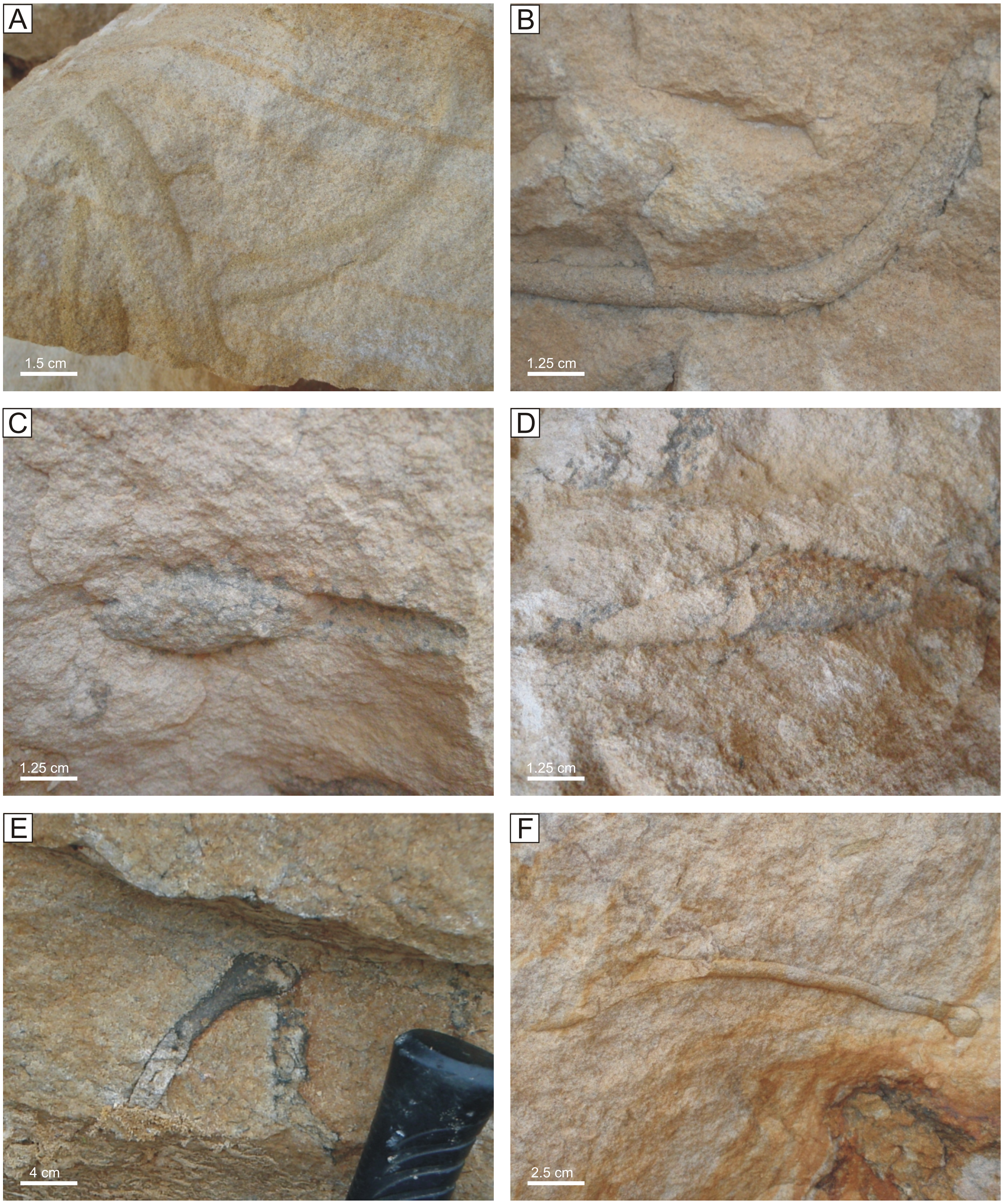


Fig. 6. Trace fossils from the Długopole Górne Quarry

A – *Curvolithus simplex* (Długopole Górne Quarry), horizontal surface; **B–E** – *Ophiomorpha nodosa* (Długopole Górne); well-visible pellets, which have built *Ophiomorpha* walls and swellings interpreted as turning chambers (C, D); **F** – *Ophiomorpha* isp. (Długopole Górne)

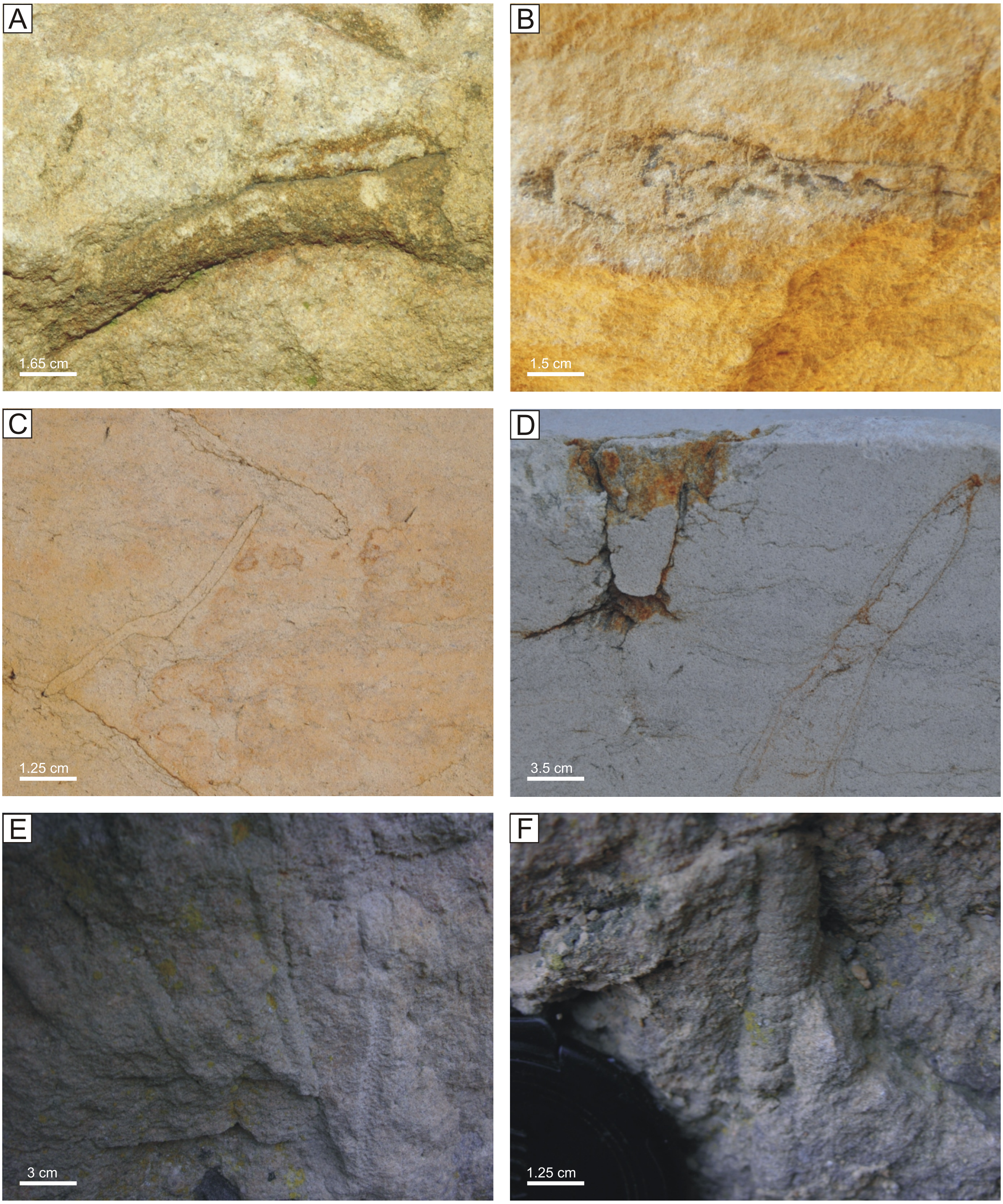


Fig. 7. *Ophiomorpha nodosa* and *Ophiomorpha* isp. from the Długopole Górne Quarry and Stara Bystrzyca outcrop

A, **B** – *Ophiomorpha nodosa* (Długopole Górne), well-visible swellings (B); **C**, **D** – longitudinal and cross-section of *Ophiomorpha* burrows (Długopole Górne); **E** – branched burrows of *Ophiomorpha nodosa* (Stara Bystrzyca), well-visible traces (holes) after pellets; **F** – meniscate filling of *Ophiomorpha nodosa* (Stara Bystrzyca outcrop)

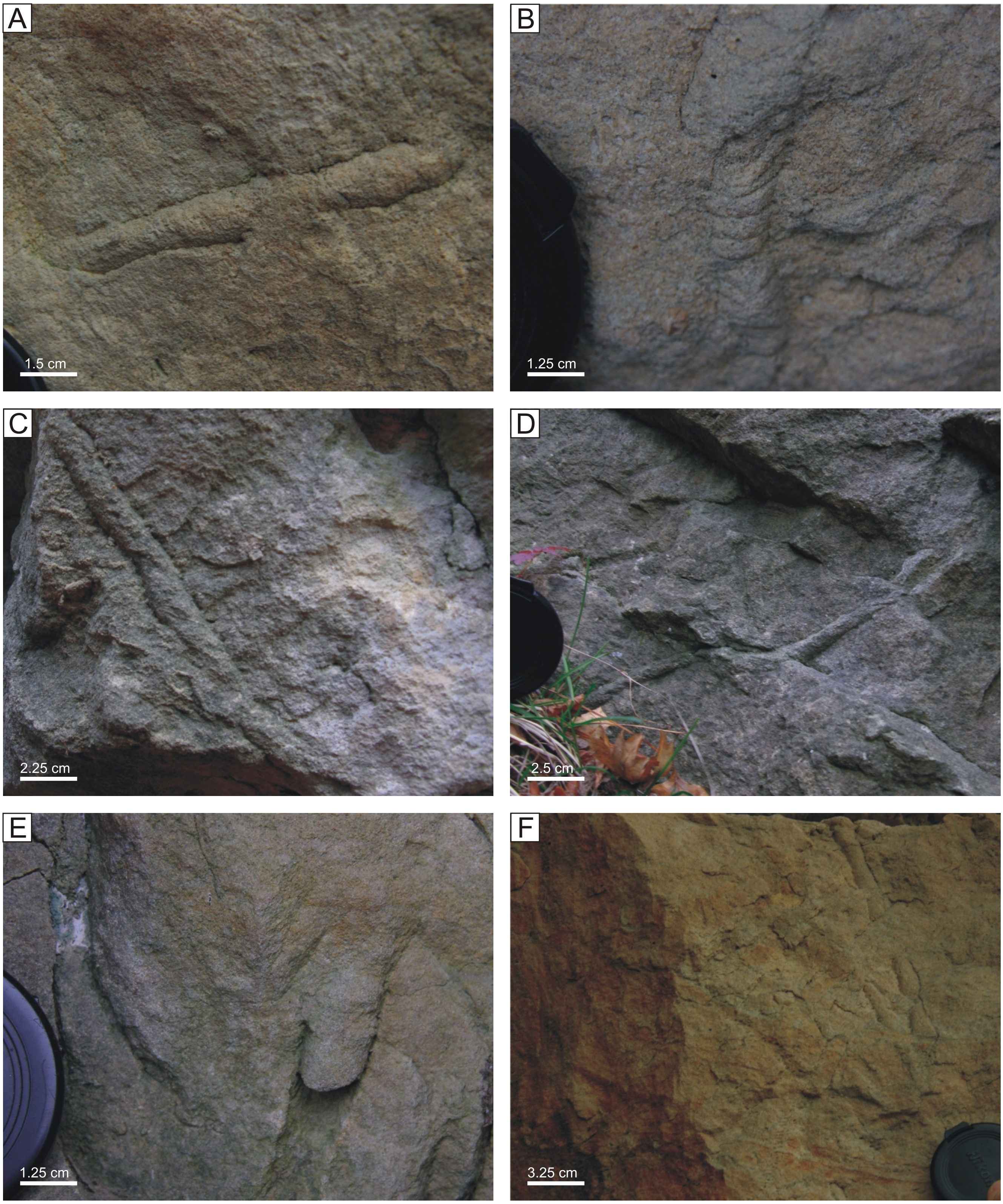


Fig. 8. *Ophiomorpha nodosa* and *Ophiomorpha* isp. from the Stara Bystrzyca outcrop

A – *Ophiomorpha* isp. (Stara Bystrzyca); **B** – meniscate structure of *Ophiomorpha nodosa* (Stara Bystrzyca); **C**, **D** – vertical *Ophiomorpha nodosa* (Stara Bystrzyca); **E** – *Ophiomorpha nodosa*, well-visible meniscate structures (Stara Bystrzyca); **F** – branched, vertical or inclined *Ophiomorpha nodosa* (boxwork, Stara Bystrzyca)

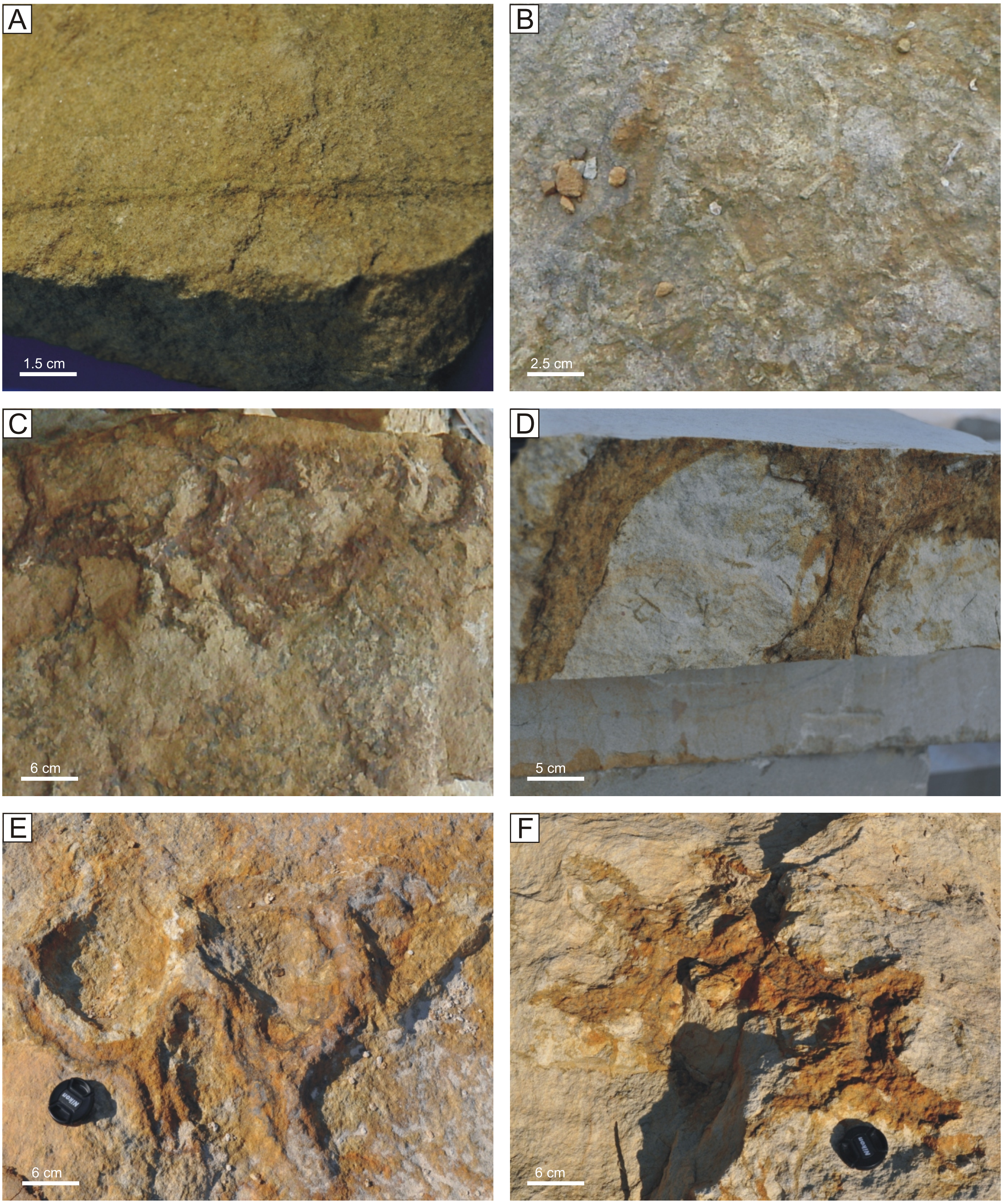


Fig. 9. *Palaeophycus tubularis* and *Thalassinoides suevicus* from the Stara Bystrzyca and Długopole Górne outcrops

A – *Palaeophycus tubularis* (Stara Bystrzyca outcrop); **B** – *Palaeophycus tubularis* (Długopole Górne Quarry); **C–F** – *Thalassinoides suevicus* (Długopole Górne) sion-feeder or a detritus-feeder. Schlirf (2003) also described *Palaeophycus* as domichnial/?fodinichnial burrow.

Palaeophycus is produced mostly by polychaetes or other "worms" (Pickerill et al., 1984; Keighley and Pickerill, 1995; Gibert and Ekdale, 2002; Mikuláš, 2006; Mikuláš and Martínek, 2006; Virtasalo et al., 2011; Hofmann et al., 2012). Zonneveld et al. (2010) suggested also arthropods as the *Palaeophycus* producers. Loughlin and Hillier (2010) speculated, that sipunculids and enteropneusts are tracemakers of *Palaeophycus*. Bradshaw (2010) suggested also small crustaceans.

Palaeophycus is an eurybathic form and appears in different ichnofacies (Seilacher, 1967; MacEachern et al., 2007a). It occurs both in shallow- and deep-sea environments (McCann and Pickerill, 1988; Uchman and Tchoumatchenco, 2003; Carvalho et al., 2005; Kumpulainen et al., 2006). *Palaeophycus* occurs from the Neoproterozoic to Recent (Häntzschel, 1975; Pemberton and Frey, 1982; Gradziński and Uchman, 1994; Uchman et al., 2005; Fernandes and Carvalho, 2006; Avanzini et al., 2011).

Thalassinoides* cf. *paradoxicus (Woodward, 1830) (Fig. 10A, B) – cylindrical, unlined, wide, T- rather than Y-shaped (80–110°) burrows. Colour of the lining is usually darker (yellow-brown) than the host rock, while burrow fill is the same or slightly lighter. Vlahović et al. (2011) suggested that the darker colour of the lining is caused by bacteria and algae. It is 4.0–6.0 cm across and individual tunnels between branching are 20–25 cm long. This burrow course is similar to *T. paradoxicus*.

Thalassinoides is interpreted as domichnion and/or fodinichnion and agrichnion of deposit-feeders (Gibert and Martinell, 1995, 1998; Myrow, 1995; Bromley, 1996; Ekdale and Bromley, 2003; Singh et al., 2008; Jaglarz and Uchman, 2010). Thalassinid shrimps, ghost shrimps or shrimp-like organisms, lobsters, crayfish, crabs (Frey et al., 1984; Ekdale and Bromley, 2003; Goldring et al., 2004, 2007; Tshudy et al., 2005; Knaust, 2007) as well as ceriantid sea anemones, enteropneusts and fish (Myrow, 1995; Bromley, 1996; Kim et al., 2002; Pruss and Bottjer, 2004; Chen et al., 2011) are suggested as producers of *Thalassinoides*.

In modern environments, *Callichirus* (*Callianassa*), *Glyphea* and *Mecochirus rapax* are considered as producers of *Thalassinoides* (Myrow, 1995; Bromley, 1996; Nesbitt and Campbell, 2006; Carvalho et al., 2007). *Upogebia affinis* was suggested as one of the possible tracemaker of *Thalassinoides*, however, recently Pervesler and Uchman (2009) reported that this taxon produced *Parmaichnus stironensis*. Similary, Nara and Kotake (1997), Nesbitt and Campbell (2002), Seike and Nara (2007) and Radwański et al. (2012) suggest also some upogebiid crustaceans are responsible for the *Psilonichnus* tracemakers.

Thalassinoides belongs mostly to the *Psilonichnus*, *Cruziana* and *Glossifungites* ichnofacies but appears also in the *Zoophycos* and *Nereites* ichnofacies (Seilacher, 1967; MacEacher et al., 2007a). The environmental distribution of *Thalassinoides* ranges from tidal flat and shoreline environment to offshore outer shelf facies and deep-sea fans (Kim et al., 2002) and it is formed in firmground and hardgrounds (Myrow, 1995).

Thalassinoides occurs frequently from the Ordovician (Sheehan and Schiefelbein, 1984; Droser and Bottjer, 1989; Ekdale and Bromley, 2003; Carvalho et al., 2010) and in rarely cases also from the Cambrian (Miller and Byers, 1984; McCann and Pickerill, 1988; Mikuláš, 2000).

Thalassinoides suevicus (Rieth, 1932; Fig. 9C–F) appears as cylindrical, flattened tunnels, elliptical in cross-section, slightly curved, regularly branched, 2.0–4.5 cm wide. They usually exhibit a Y-shape of branchings (at 60–130°). In some places, they represent horizontal mazes or boxworks (see Frey et al., 1978). Cylinders are 20–45 mm across. Margin of the burrow is smooth. Filling of the burrows is locally darker and coarser-grained than the host rock (Fig. 9C–F). In some cases, the preservation of trace fossils did not allow to recognize their at the ichnospecific level and they are described as *Thalassinoides* isp. (Fig. 10C–F).

Thalassinoides is interpreted as a fodinichnial (Bromley, 1996), domichnial (Myrow, 1995) and occasionally agrichnial burrow (Ekdale and Bromley, 2003). Recently, *Thalassinoides* is interpreted mostly as a domichnial (dwelling) and fodinichnial (feeding) structure (Häntzschel, 1975; Miller and Knox, 1985; Rodríguez-Tovar and Uchman, 2006; Rodríguez-Tovar et al., 2009a, b, 2010, 2011; Monaco et al., 2012). Most authors suggest that the tracemaker of *Thalassinoides* was a deposit-feeder (Gibert and Martinell, 1998; Kędzierski and Uchman, 2001; Ekdale and Bromley, 2003). Kim et al. (2002) speculated on ?suspension-feeders as *Thalassinoides* producers.

Modern analogues of tracemakers are decapod crustaceans, probably thalassinid shrimps or shrimp-like organisms (Sheehan and Schiefelbein, 1984; Ekdale and Bromley, 2003). Lobsters and crabs are also proposed (Frey et al., 1984; Myrow, 1995; Bromley, 1996; Gingras et al., 2002; De, 2005; Rossetti and Netto, 2006). Ceriantid sea anemones, acorn worms and fish are also speculated as the possible tracemakers of *Thalassinoides* (Myrow, 1995). *Thalassinoides* represents a facies-crossing ichnotaxon being reported from deep marine environments (Uchman 1995, 1998) and more commonly, shallow-marine settings (Ekdale and Bromley, 2003; Rodríguez-Tovar and Uchman, 2004a, b; 2010; Malpas et al., 2005).

Thalassinoides is a dominant arthropod burrow in the geologic record and occurs from the Ordovician to Recent (Sheehan and Schiefelbein, 1984; McCann and Pickerill, 1988; Myrow, 1995; Ekdale and Bromley, 2003). *Thalassinoides* shows a high abundance in the Ordovician (Hembree et al. 2011; Jin et al., 2012), however, numerous authors often reported its occurrence since the Cambrian (Miller and Byers, 1984; Mikuláš, 2000).

RECONSTRUCTION OF THE MIDDLE TURONIAN ENVIRONMENT ON THE BASIS OF TRACE FOSSILS

DISTRIBUTION OF TRACE FOSSILS AND COMPARISON TO THE SHOREFACE MODEL

The dominant presence of the trace fossils typical of nearshore deposits in the Middle Turonian trace fossil assemblage at Bystrzyca and Długopole (*Curvolithus simplex*, ?*Macaronichnus* isp., *Palaeophycus tubularis*, *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Thalassinoides* cf. *paradoxicus*, *T. suevicus*, *Thalassinoides* isp.) confirms the interpretation that the examined deposits have been deposited in a shallow environment (Clifton and Thompson, 1978; Frey et al., 1978; Curran, 1985; Pollard et al., 1993; Myrow, 1995; Buatois et al., 1998). In shallow-marine siliciclastic facies only *Skolithos* and *Cruziana* Seilacherian ichnofacies (cf. Bromley, 1996) are distinguished (Frey and Seilacher, 1980; Frey et al., 1990). The *Skolithos* ichnofacies points to deposition above the fair weather wave base (i.e. foreshore, upper shoreface–proximal lower shoreface environment), while the *Cruziana* ichnofacies – below fair-weather wave base but above the storm wave base (distal lower shoreface–offshore settings; MacEachern and

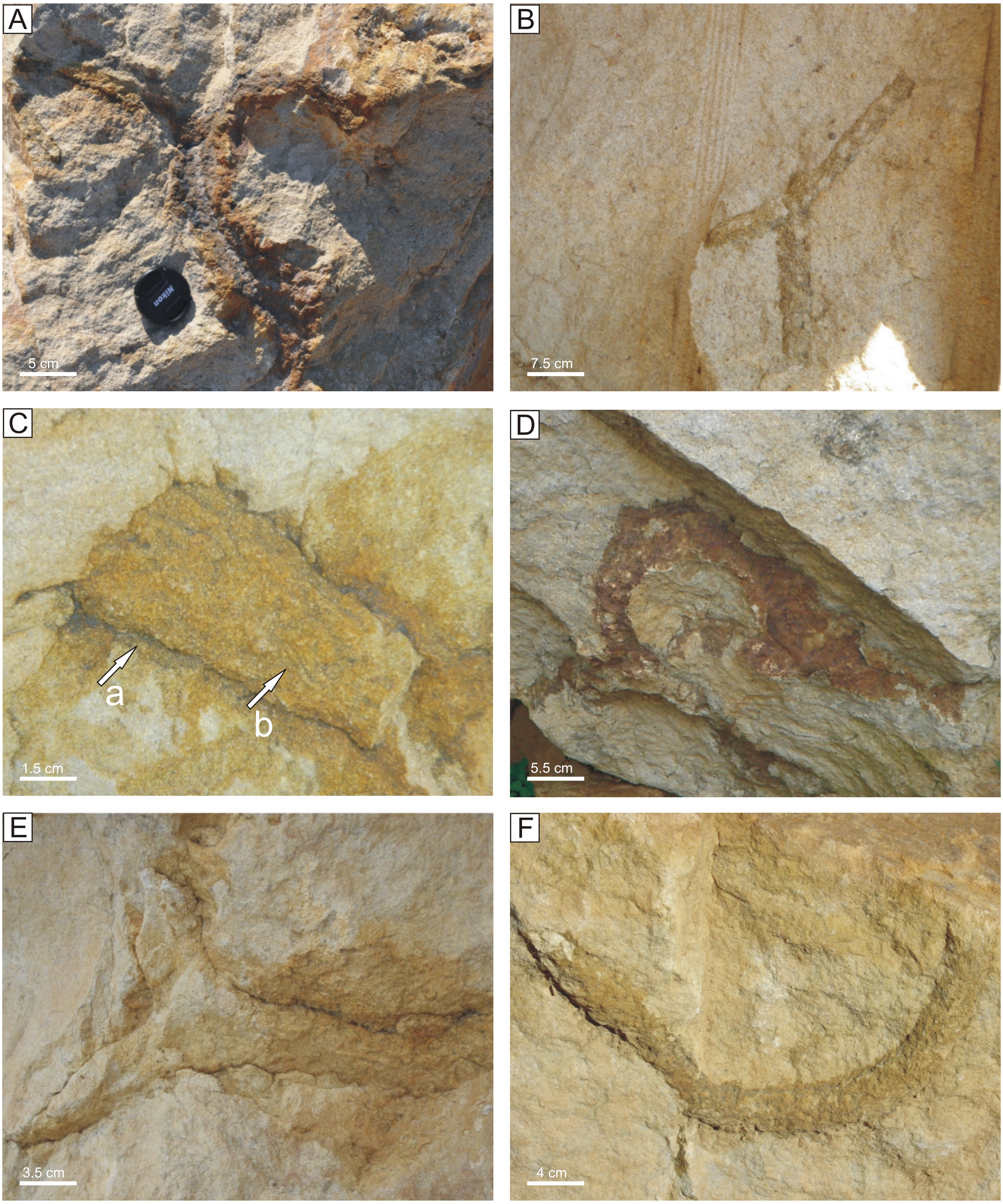


Fig. 10. Trace fossils from the Długopole Górne Quarry

A, B – *Thalassinoides* cf. *paradoxicus* (Długopole Górne); **C** – *Thalassinoides* isp. (a) and ?*Macaronichnus* isp. (b) (Długopole Górne); **D–F** – *Thalassinoides* isp. (Długopole Górne)

Bann, 2008; Pemberton et al., 2012) in soft substrates (Pemberton et al., 2004; MacEachern et al., 2007b). In the older shoreface model (MacEachern et al., 1999; Pemberton et al., 2001) the proximal *Cruziana* that characterizes the lower shoreface was lying above the fair-weather wave base.

In the Middle Turonian Bystrzyca and Długopole sandstones, trace fossils are abundant though the taxonomical diversity is moderate/low. In the studied trace fossil assemblage, horizontal to inclined burrows prevail that imply moderately-low energy conditions. Vertical burrows are subordinate, abundant especially in the Bystrzyca Sandstone. The trace fossil association contains a wide variety of ethological categories: repichnia (*Curvolithus simplex*), domichnia (*Ophiomorpha nodosa*, *Ophiomorpha* isp., *Palaeophycus tubularis*), domichnia/fodinichnia (*Thalassinoides* cf. *paradoxicus*, *T. suevicus*), and pascichnia (?*Macaronichnus* isp.). The trace fossil assemblage most closely resembles the *Cruziana* ichnofacies (MacEachern et al., 2007a, 2012; Buatois and Mangano, 2011).

Taking into account the great variety of as well-depositional subenvironments as the trace fossils assemblages occurring in shallow-marine siliciclastic, the classic model of ichnofacies (Seilacher, 1967; Frey and Seilacher, 1980) is often insufficient for the description of trace fossil distribution (see Uchman and Krenmayr, 2004). Vertical trace fossils that are abundant in the *Skolithos* ichnofacies, occur also in the proximal and the archetypal *Cruziana* ichnofacies, especially in the storm beds. MacEachern et al. (1999) and Pemberton et al. (2001), on the basis of the Cretaceous deposits of the Western Interior Seaway of North America, for an open shelf deposits, suggested a more refined model of ichnofacies (“shoreface model showing the distribution of ichnological assemblages”), based on increasing environmental energy level. These authors distinguished the *Macaronichnus* assemblage, the *Skolithos* ichnofacies and the proximal, the archetypal and the distal *Cruziana* ichnofacies. The proximal *Cruziana* ichnofacies is typical of lower shoreface settings above the fair-weather wave base, while the archetypal *Cruziana* ichnofacies characterizes offshore transition–upper offshore settings, below the fair-weather but above the storm-wave base. The distal *Cruziana* ichnofacies points to the lower offshore settings. The *Macaronichnus* assemblage indicates foreshore–upper shoreface and replaced the archetypal *Skolithos* ichnofacies under conditions of very high energy (Pemberton et al., 2001).

In this “shoreface model” for the wave-dominated seas, the foreshore–middle shoreface that is characterized by the *Skolithos* ichnofacies and the lower shoreface that is typified by the proximal *Cruziana* ichnofacies, occurs above the fair-weather wave base (MacEachern et al., 1999; Pemberton et al., 2001; Buatois and Mángano, 2011). On the other hand, some others authors (Bann and Fielding, 2004; MacEachern and Gingras, 2007; MacEachern and Bann, 2008), divide the lower shoreface into the proximal lower shoreface that occurs above the fair-weather wave base and the distal lower shoreface, lying below the fair-weather wave base.

Recently, Pemberton et al. (2012) suggested an “...integrated ichnological/sedimentological model for shoreface settings, with positions of the subenvironments...” (redefined after MacEachern et al., 1999; MacEachern and Bann, 2008). In this model, the distal lower shoreface is lying below the fair-weather wave base and represents the proximal *Cruziana* ichnofacies, whereas the proximal lower shoreface that characterizes the distal *Skolithos* ichnofacies, occurs above the fair-weather wave base. Foreshore–middle shoreface settings are typical of the archetypal *Skolithos* ichnofacies. According to these authors, because the ”offshore transition” zone does not reflect a depositional subenvironment, is not subdivided and the boundaries between the upper, the middle, the lower and the offshore zones are not clearly defined, due to a lowered the effective wave base during storm events.

Generally, all collected trace fossils indicate the proximal and the archetypal *Cruziana* ichnofacies that characterize distal lower shoreface–upper offshore, below the fair-weather wave base but above the storm-wave base (see Pemberton et al., 2001, 2012; Buatois and Mángano, 2011).

Ophiomorpha appears in foreshore–offshore deposits, especially in shoreface, whereas *Thalassinoides* characterizes lower shoreface–offshore environments (Pemberton et al., 2001; Uchman and Krenmayr, 2004; Buatois and Mángano, 2011; Higgs et al., 2012). Both *Curvolithus* (Fürsich and Heinberg, 1983; Maples and Suttner, 1990; Buatois and Mángano, 2011) and *Palaeophycus* (Pemberton et al., 2001; Bressan and Palma, 2009) are most typical of shoreface–offshore settings.

Although *Macaronichnus* may be regarded as most typical of foreshore to shoreface (especially upper shoreface) environments (Clifton and Thompson, 1978), but it can occur also in lower shoreface (Curran, 1985; D’Alessandro and Uchman, 2007; Rygel et al., 2008; Vakarelov et al., 2012), offshore settings (Maples and Suttner, 1990; Pollard et al., 1993) and even deep-sea (Greene et al., 2012). Uchman and Kenmayr (2004) and Bromley et al. (2009) noticed problems with environmental interpretation of *Macaronichnus*. Pemberton et al. (2001) distinguished the *Macaronichnus* assemblage in foreshore (moderately energy) and foreshore–middle shoreface settings (high energy level). These autors stated that *Macaronichnus* can appear in the distal and the proximal lower shoreface after storm deposition, when high “oxygen window” occurred (see also Uchman and Krenmayr, 2004).

In the “shoreface model” for an open shelf deposits, Pemberton et al. (2001) related *Thalassinoides* to the lower shoreface–offshore settings (see also Buatois and Mángano, 2011; Pemberton et al., 2012). Thus, the presence of *Thalassinoides* indicates the proximal *Cruziana* ichnofacies (Uchman and Kenmayr, 2004; Pervesler et al., 2011a, b) and the archetypal *Cruziana* ichnofacies (MacEachern et al., 2007a; MacEachern and Bann, 2008). *Ophiomorpha* can occur in the lower shoreface and the upper offshore (Frey, 1990; Frey and Howard, 1990; Pollard et al., 1993; Li et al., 2011). Bann et al. (2004, 2008), Bann and Fielding (2004) and MacEachern and Bann (2008) reported *Macaronichnus* from the proximal *Cruziana* ichnofacies and the archetypal *Cruziana* ichnofacies (lower shoreface–upper offshore).

DŁUGOPOLE SANDSTONE PALAEOENVIRONMENT

In the Długopole Sandstone, *Thalassinoides* and *Palaeophycus* appear in fine-grained sandstone, whereas *Ophiomorpha* appears in coarser-grained sandstones. *Thalassinoides* is often filled by the coarser sand from the overlying beds.

Thalassinoides suevicus, *Thalassinoides* isp., *Palaeophycus tubularis* and *Curvolithus* isp. prevail in the lower part of the Długopole Górne section (Fig. 4A), whereas *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Thalassinoides* cf. *paradoxicus* and *T. suevicus* in the upper part. ?*Macaronichnus* has been found within a filling of *Thalassinoides* (Fig. 10C) that appears on the surface of a large sandstone block; therefore, its position in the section is questionable (?upper part).

In the lower part of the Długopole Górne section, the large *Thalasinoides* are common, forming mazes and boxworks (Fig. 9C), which suggests lower energy level (see Frey et al., 1978). *Thalassinoides* isp. is also abundant (Fig. 10D–F). The intense burrowing probably took place during a longer time interval of stabilization of the sea-floor, caused by the drop of accumulation rate, enough to produce the *Thalassinoides* galleries. *Curvolithus*, however, also occurs in environments with quiet water conditions (Heinberg and Birkelund, 1984; Baucon and Carvalho, 2008), but it also was reported in high energy, regressive settings (Lockley et al., 1987). The large *Thalassinoides* boxwork is typical of the archetypal *Cruziana* ichnofacies – upper offshore setting (MacEachern et al., 2007a; Buatois and Mángano, 2011; Pervesler et al., 2011b; Pemberton et al., 2001, 2012). *Curvolithus* and *Palaeophycus* are also common in this ichnofacies (Buatois and Mángano, 2011).

The trace fossils assemblage occurring in the lower part of the Długopole Górne section contains moderately diverse trace fossil assemblage, typical of open-marine environments, lying below the fair-weather wave base (*Thalassinoides suevicus*, *Thalassinoides* isp., *Curvolithus simplex*, *Palaeophycus tubularis, Ophiomorpha nodosa*, *Ophiomorpha* isp.) that characterizes the archetypal *Cruziana* ichnofacies, which is usually positioned in the upper offshore (Pemberton et al., 2012).

On the other hand, *Thalassinoides suevicus* (Fig. 9D–F), *Thalassinoides* cf. *paradoxicus* (Fig. 10A, B) and *Thalasinoides* isp. (Fig. 10C) occur also in the upper part, but *Ophiomorpha nodosa* and *Ophiomorpha* isp. dominate (Figs. 6B–F and 7A–D).

The more abundant vertical or inclined shafts of *Ophiomorpha nodosa* and *Ophiomorpha* isp. that are the most common in the upper part of the Długopole Górne section, indicates higher energy conditions (Frey et al., 1978; Martino and Curran, 1990; Pollard et al., 1993; MacEachern et al., 2007a). *Thalassinoides suevicus*, in some places forming boxworks, and *Thalassinoides* cf. *paradoxicus* are also present. ?*Macaronichnus*, occurring in the sandstone block, may represent the lower as well as the upper part of the section (Fig. 10C). The position of the block, however, suggests it is likely to have been the rather upper part of the section (Fig. 4A). *Macaronichnus* is usually common in high energy, wave or tidal dominated settings (Encinas et al., 2008; Pemberton et al., 2008; Aguirre et al., 2010; Quiroz et al., 2010; Buatois and Encinas, 2011).

The trace fossils assemblage occurring in the upper part of the Długopole Górne section (*Ophiomorpha nodosa*, *Ophiomorpha* isp., ?*Macaronichnus* isp., *Thalassinoides suevicus*, *Thalassinoides* cf. *paradoxicus*) corresponds to the fully marine and points to the proximal *Cruziana* ichnofacies, typical of the distal lower shoreface (follow MacEachern and Bann, 2008; Pemberton et al., 2012). For this ichnofacies *Ophiomorpha nodosa* and *Macaronichnus* are common (Pemberton et al., 2001, 2012). According to these authors, the *Thalassinoides* boxwork, also indicates the proximal *Cruziana* ichnofacies.

Based on the “food paradigm” (Pemberton et al., 2001) and the “ichnological-sedimentological model for shoreface” (Pemberton et al., 2012) in the distal lower shoreface suspension-feeders behaviour is subordinate, whereas in the upper offshore rare. MacEachern and Bann (2008) reported that conditions in the archetypal *Cruziana* ichnofacies typically range from moderate energy levels to lower energy and the tracemakers construct their burrows horizontally rather than vertically. In the proximal *Cruziana* ichnofacies the energy conditions are higher and vertical or inclined burrows occur more commonly.

The Długopole Sandstone shows giant-scale cross-bedding, which implies bedforms migration by currents (Don and Wojewoda, 2004). Jerzykiewicz and Wojewoda (1986) and Wojewoda (1997, 2011) interpreted the Middle Turonian sandstones of the Intra-Sudetic Synclinorium and the Nysa Kłodzka Graben as deposits of the “accumulation terraces”, that were deposited on the fault-controlled scarps. According to these authors, sand was entrained in the shoreface by storm events and offshore-directed current transported it across the shelf. The prograding “terrace” might have been probably reworked by storms.

According to the integrated ichnological/sedimentological model for shoreface settings (Pemberton et al., 2012), the lower part of the Długopole section was deposited in the upper offshore, whereas the upper part, probably in the distal lower shoreface, between the fair-weather and storm-wave base. The common crustaceans network, occurring especially in the lower part of the section, suggests low to moderately energy conditions (Buatois and Mángano, 2011).

Thus, the ichnologic data of the Długopole Sandstone show expressions of the archetypal and the proximal *Cruziana* ichnofacies and probably indicate shallowing trend from the upper offshore to the distal lower shoreface (cf. Pemberton et al., 2012).

The similar assemblages of trace fossils (*Ophiomorpha*, *Macaronichnus*, *Palaeophycus*, *Thalassinoides*) from the low to moderate energy nearshore facies, were described by Curran (1985), Buatois et al. (2002, 2012), Uchman and Krenmayr (2004) and Morris et al. (2006). Pemberton et al. (2001), who referred on a similar assemblage of trace fossils, placed the succession containing *Thalassinoide*s, *Palaeophycus* and *Ophiomorpha* in the upper offshore, whereas deposits rich in *Ophiomorph*a, *Macaronichnus* in the middle-lower shoreface. In comparison to other nearshore trace fossils assemblages (lower shoreface-upper offshore settings) including *Macaronichnus*, *Ophiomorpha*, *Palaeophycus*, *Thalassinoides*, the majority of them were recorded from the storm-originated deposits (Frey and Pemberton, 1991; MacEachern et al., 1999; Bann and Fieding, 2004; Bann et al., 2004; Gani et al., 2008; Rygel et al., 2008; Schwarz, 2012) or bar settings (Curran, 1985; Pollard et al., 1993; Olariu et al., 2012; Sullivan and Sullivan, 2012).

BYSTRZYCA SANDSTONE PALAEOENVIRONMENT

Bystrzyca Sandstone contains trace fossil assemblage that includes only *Ophiomorpha nodosa*, *Ophiomorpha* isp. and *Palaeophycus tubularis* (Table 1). *Ophiomorpha nodosa* is the most obvious trace fossil in the Stara Bystrzyca outcrop (Figs. 7E, F and 8B–F). Besides horizontal and inclined burrows, also vertical shafts of *Ophiomorpha* appear, especially in the bottom and the upper part of the section (Fig. 8B, F). The trace fossil asemblage shows low ichnodiversity, but high individual densities. It is dominated by dwelling burows generated by suspension-feeders and carnivores.

The predominance of boxwork and vertical shafts or inclined burrows of *Ophiomorpha* reflect the rapid sedimentation that is characteristic of storm events (Frey, 1990; Frey and Howard, 1990; Pollard et al., 1993; Anderson and Droser, 1998). The Bystrzyca Sandstone probably represent a main storm deposition (see Pemberton et al., 2001). These sandy layers (tempestites) are low to moderately bioturbated that pointing to a moderate-high energy level. The supplies of sands were abundant and the frequence of storm was probably moderate to high. Short-term colonization windows allowed us to establish the storm-related trace fossils suite that indicates colonization after the storm events, by an opportunistcic (r-selected) community, in this case, by *Ophiomorpha nodosa* and

Palaeophycus tubularis. In the idealized ichnological-sedimentological tempestite model (Pemberton et al., 2001), *Ophiomorpha* and *Palaeophycus* are typical of post-storm colonization, though *Palaeophycus* may also represent the fair-weather suite, especially in the lower shoreface and offshore transition (Pemberton et al., 2001; Buatois and Mángano, 2011). Some tracemakers (e.g., callianassid crustaceans) could be transported, from shallower settings, with the sediment, during storms or other events, and deposited within the sand beds that they subsequently colonized (Föllmi and Grimm, 1990; Bromley, 1996; Fürsich, 1998; Savrda and Nanson, 2003; Zonneveld et al., 2010).

Sedimentologic investigation in the the Bystrzyca Sandstone shows presence of the hummocky cross-stratification, that clearly points to a storm-origin for these deposits and sedimentation between fair-weather and storm wave base (shoreface-shelf; Dott and Burgeois, 1982; Myrow and Southard, 1996). On the other hand, the HCS-like structures occasionally have been recorded from deep-water turbidite sandstone beds (Mulder et al., 2009) and even fluvial deposits (Campbell and Oakes, 1973; Cotter and Graham, 1991; Quin, 2011). In the shoreface models, hummocky cross-stratification is described from shoreface and offshore settings (Pemberton et al., 2001, 2012; MacEachern and Bann, 2008; Buatois and Mángano, 2011). On the basis of sedimentologic data, the most probably setting for the Bystrzyca Sandstone is offshore transition, where can occur thin to thick fine-grained sandstones with hummocky cross-stratification can occur. On the other hand, the moderately or even high energy conditions, abundant sand supplies and low/moderately bioturbation of the sandstone beds, may imply shallower environment. According to Mángano et al. (2005) high energy conditions prevail in the lower and middle shoreface environments, where vertical burrows dominated, recording colonization after storm events.

The trace fossil assemblage (*Ophiomorpha nodosa*, *Ophiomorpha* isp., *Palaeophycus tubularis*) characterizes as well shoreface settings as well as upper offshore (offshore transition zone), but prevails in the middle-lower shoreface settings (Pemberton et al., 2001, 2012). According to Buatois and Mángano (2011), in the middle and lower shoreface the bulk of the suite consists mainly of ichnogenera such as *Ophiomorpha* (commonly vertical components) and *Palaeophycus*. In the shoreface model (Pemberton et al., 2001), *Ophiomorpha* is common in storm-dominated proximal and distal lower shoreface. Additionally, in the distal lower shoreface, suspension feeding organisms are common (subordinate behaviour), whereas in the upper offshore they are rare (minor behavior; Pemberton et al., 2012). The dominance of dwelling burrows of suspension-feeders clearly indicates moderate to relatively high-energy environment. In the Bystrzyca Sandstone, *Ophiomorpa* (dominant) and *Palaeophycus* (rare) represent opportunistic colonization of the storm beds (storm-related suite), whereas the fair-weather suites are not observed. In the lower shoreface, storms tend to destroy resident fair-weather benthic communities more commonly than in the deeper subenvironments (Pemberton et al., 2012) and in the contrast to the offshore, the preserved depositional record of the lower-middle shoreface successions is characterized by predominance of tempestite beds (Kumar and Sanders, 1976). On the other hand the absence of fair-weather suite can be also attributed to short transit time between storm events.

According to the integrated ichnological-sedimentological shoreface model by Pemberton et al. (2012), the trace fossil assemblage, occurring in the Bystrzyca Sandstone, indicates the proximal *Cruziana* ichnofacies, which is positioned in the distal lower shoreface. Taking into account the subdivision of the wave-dominated shorefaces, based upon the degree of storm-wave influence (storm-affected, storm-influenced, storm-dominated; MacEachern and Pemberton, 1992; Dashtgard et al., 2012) the Bystrzyca Sandstone, probably was deposited in the storm-influenced or even storm-dominated shoreface (moderately-high energy conditions). In the division of Pemberton et al. (2001) it can be defined as moderately storm-affected or strongly-storm dominated shoreface.

PALAEOECOLOGY

The Bystrzyca and Długopole sandstones contain the assemblage of fossils indicating a fully marine, well-oxygenated environment (Lockley et al., 1987; Ekdale and Mason, 1988; Miller, 2001; Gillette et al., 2003; Giannetti and McCann, 2010). In particular, both *Macaronichnus*, typical of well-oxygenated sand (Clifton and Thompson, 1978; Pemberton et al., 2001) and *Thalassinoides* (Savrda and Bottjer, 1986; Savrda, 2007) have been recognized as important indicators of fully oxic conditions. The large *Thalassinoides* galleries are common in the Długopole Sandstone, marking the well-oxygenation environment (e.g., Doyle et al., 2005; Gingras et al., 2011). The producers of trace fossils prefer normal salinity but can tolerate salinity fluctuation (stenohaline-polyhaline). *Ophelia*, one of the modern tracemakers of *Macaronichnus*, tolerates salinities lower than those of the open marine environments (Clifton and Thompson, 1978). The present-day *Callianassa biformis*, which is one of tracemakers of *Ophiomorpha* and *Thalassinoides*, penetrates estuaries and tolerates salinities from 12 to 30‰, even so low as 10‰ (Frey et al., 1978; Goldring and Pollard, 1995; Pervesler and Uchman, 2009). Some of tracemakers of *Ophiomorpha*, *Macaronichnus* and *Palaeophycus*, are strongly associated with high sedimentation rate settings (Gingras et al., 2011).

The other representatives of fauna, i.e. bivalves *Lima canalifera* Goldfuss (Fig. 5B) and *Lima* sp. (Fig. 5C) could also point to the shallow basin and a low energy, normal marine conditions (Wilmsen et al., 2007; Chrząstek, 2012; Mel'nikov et al., 2012). Brachiopods, i.e. *Rhynchonella plicatilis* (Fig. 5E) are also indicators of marine, usually well-oxygenated settings (Richardson, 1997; Curry and Brunton, 2007). The presence of ammonites (Fig. 5A) in the Bystrzyca Sandstone, which were probably stenotypic organisms, very sensitive to oxygenation and salinity changes (Landman et al., 2012; Olivero, 2012), suggests fully marine conditions. Although ammonites inhabited nearshore, intermediate and distal-shelf to upper-slope environments (Matsukawa et al., 2012) they are common in Mesozoic epicontinental seas (Zakharow et al., 2012).

COMPARISON TO OTHER SEDIMENTOLOGICAL INTERPRETATIONS

The Długopole Sandstone is interpreted (after Jerzykiewicz and Wojewoda, 1986) as a part of the “accumulation terrace” (hypothetical palaeobedform of the Cretaceous sea-floor), which was deposited, parallel to the shore, on the fault-controlled scarps. Earlier, the Middle Turonian sandstones from the Polish part of the Stołowe Mountains were recognized as subaqueous dunes (Skoček and Valečka, 1983), whereas those from the Bohemian Cretaceous Basin as deposits of probably coarse-grained, “Glibert-type”- deltas (Uličný, 2001). Laurin and Uličný (2004) suggested that the Middle Turonian, cross-stratified sandstones of the nearshore Jizera Formation (Bohemian Cretaceous Basin) are shoreface to shoal-water delta-front deposits, affected by both tidal and storm processes.

The Bystrzyca and Długopole sandstones of the Nysa Kłodzka Graben were formed during the regressive phase, which started in the early/middle Middle Turonian (Rotnicka, 2005) and caused relative uplift of the sediment source areas: East-Sudetic Island and Orlica Island (Orlica-Uplift according to Chrząstek and Wojewoda, 2011) (Don and Don, 1960; Radwański, 1964, 1968; Jerzykiewicz, 1975; Wojewoda et al., 2011). The trace fossil assemblage of the Bystrzyca and Długopole sandstones can be used to define in greater detail the depositional environment of these deposits. It might be generally in agreement with the palaeogeographic interpretation presented by Jerzykiewicz and Wojewoda (1986) and Wojewoda (1997, 2003, 2011) who suggested offshore environment for the Middle Turonian sandstones, but ichnological analysis showed slightly shallower environment (distal lower shoreface–upper offshore). Rotnicka (2005), who investigated trace fossils of the Upper Cretaceous equivalent deposits of the Stołowe Mountains (Intra-Sudetic Synclinorium), e.g. Radków Bluff Sandstone, suggested ?upper offshore setting (proximal *Cruziana* ichnofacies) as an environment for the Middle Turonian sandstones and connected these deposits with distal tongues of prograding “terraces” rather than with storm deposits.

The Bystrzyca and Długopole sandstones are overlain by mudstones, marlstones and limestones, containing macro- and trace-fossils (e.g., *Planolites* and *Chondrites*), deposited in the deeper, offshore environment (Chrząstek, 2012). Laurin and Uličný (2004), who investigated the Middle Turonian deposits (mudstones, marlstones) of the Bohemian Cretaceous Basin (offshore Izera Formation), reported the similar trace fossils assemblage: *Thalassinoides*, *Planolites* and *Chondrites*, typical of offshore shelf; they found *Ophiomorpha* and *Thalassinoides* in the nearshore Middle Turonian Izera Formation (sandstones of the shoreface–offshore transition).

Almost the same assemblage of trace fossils, including *Ophiomorpha*, *Thalassinoides* and *Planolites*, appears in the Cenomanian–Upper Turonian sediments of the Intra-Sudetic Basin (Rotnicka, 2005) and in the Middle and Upper Turonian deposits of the Bohemian Cretaceous Basin (Uličný, 2001; Mikuláš, 2006).

CONCLUSIONS

The moderately-low diverse, open-marine trace fossils assemblage found in the Middle Turonian sandstones of Stara Bystrzyca and Długopole Górne includes *Curvolithus simplex*, ?*Macaronichnus* isp., *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Palaeophycus tubularis*, *Thalassinoides* cf. *paradoxicus, T. suevicus* and *Thalassinoides* isp. (Table 1). The trace fossils evidence indicates that the studied sequence must have been deposited in a shallow-marine environment. Additionally a fragment of ammonite and bivalve shells (*Lima canalifera* Goldfuss, *Lima* sp.) were observed that also points to a shallow basin with normal marine conditions.

Trace fossils assemblage, which appears in the Bystrzyca Sandstone (*Ophiomorpha* and *Palaeophycus*), represents a close approximation to the proximal *Cruziana* ichnofacies, which is positioned in the distal lower shoreface. In the bottom part of the Długopole Górne section, *Thalassinoides*, *Ophiomorpha*, *Curvolithus* and *Palaeophycus* appear, whereas in the upper part *Ophiomorpha*, *Thalassinoides* and ?*Macaronichnus* prevail. The assemblage of trace fossils shows an upward progression from the archetypal to the proximal *Cruziana* ichnofacies. This probably indicates a shallowing trend from the upper offshore to the distal lower shoreface.

On the basis of ichnological studies, the Bystrzyca and Długopole sandstones are recognized as fully marine, shallow deposits, which were deposited from the distal lower shoreface to upper offshore, in water depths that were generally between fair-weather and storm-wave base. Ichnological study showed that the Bystrzyca Sandstone was deposited in the moderately-high energy conditions (storm-influenced or even storm-dominated shoreface; cf. MacEachern and Pemberton, 1992; Dashtgard et al., 2012).

Ichnological analysis of the Długopole Sandstone, is generally in agreement with the palaeogeographic scheme proposed by Jerzykiewicz and Wojewoda (1986), who recognized the Middle Turonian sandstones of the Nysa Kłodzka Graben as the “accumulation terraces” that were deposited on the fault-controlled scarps. The storm events might have reworked the prograding “terrace”. The Długopole Sandstone was deposited under low-moderately energy conditions.

Ichnological data provides significant new insights into the depositional environment of the Bystrzyca and Długopole sandstones, deposited in shallower distal lower shoreface–upper offshore environment. This environment was fully oxygenated, of normal salinity (stenohaline).

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