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Occurrence of the trace fossil *Zoophycos* from the Upper Viséan Paprotnia Beds of the Bardo Structural Unit (Sudetes, SW Poland)

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Abstract This paper presents evidence for the first confirmed occurrence of the trace fossil *Zoophycos* from any geological unit of the Polish Sudetes. The *Zoophycos* specimens were found in the Lower Carboniferous fossil-rich Paprotnia Beds, which are located in the Bardo Structural Unit of the Sudetes. The beds belong to *Goniatites crenistria* Zone of the Upper Viséan and are thought to represent shallow-water platform deposits. Several dozen *Zoophycos* specimens were studied in detail, and two morphotypes (termed A1 and A2) of different sizes were distinguished. There was a marked concentration of *Zoophycos* trace fossils in the lower part of the Paprotnia section, the sediments of which we interpret as probably having been formed between storm wave base and fair-weather wave base within oxygenated water.

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INTRODUCTION

Zoophycos is a term that describes a common trace fossil formed of a large number of three-dimensional, helically coiled spreiten structures that can have very variable detailed morphologies and that have been described from marine sediments ranging in age from Cambrian to Quaternary (see Bradley, 1973; Wetzel & Werner, 1981; Kotake, 1989, 1997; Miller, 1991; Olivero, 2003; Löwemark *et al.*, 2006; Knaust, 2009). *Zoophycos* have also been rarely described from Precambrian rocks (Crimes, 1987; Uchman, 1998). This enigmatic and cosmopolitan ichnofossil has challenged generations of geologists and ichnologists for over a century (for the earlier papers see Olivero, 2007; Olivero & Gaillard, 2007; Knaust, 2009). The *Zoophycos* ichnofacies is one of the four original ichnofacies pioneered by Adolf Seilacher (Seilacher 1963, 1964; see Frey *et al.*, 1990; Bromley & Asgaard, 1991). Traditional interpretations place *Zoophycos* within Seilacher's ethologic category *fodinichnia* (Seilacher, 1986), which includes the semi-permanent structures produced by endobenthic deposit feeders (see Miller & D'Alberto, 2001).

The broad collection of related forms presently grouped as *Zoophycos* are covered by the ichnofamily Alectoruridae (see Bromley & Hanken, 2003). According to Miller (2003) and Olivero (2007), *Zoophycos* is a very complex trace fossil and there is still no real agreement concerning its taxonomy and significance. Thus, Uchman (1995) proposed the term "Zoophycos group" to include all the trace fossils that share some common morphological "Zoophycos" characteristics.

Despite *Zoophycos* being common in both ancient and modern sediments, the animal or animals responsible for these traces have yet to be discovered; and a behavioural explanation is still strongly debated (e.g. Bromley, 1991). *Zoophycos* (*sensu lato*) is generally assumed to be the trace of an as-yet undiscovered deposit feeder (see Uchman, 1998; Rodríguez-Tovar & Uchman, 2006). *Zoophycos* producers have been variously hypothesized to be sipunculids (Wetzel & Werner, 1981), polychaete annelids, arthropods (Ekdale & Lewis, 1991) or echiuran worms (Kotake, 1992).

Zoophycos have been described from a diverse range of sediments, including sandstones, mudstones, shales, limestones, marly limestones, marls, chalk (Olivero, 2007) and hemipelagic mud (Leuschner *et al.*, 2002). These rock types represent a very wide range of palaeoenvironments, from the infralittoral to the abyssal (Frey *et al.*, 1990). *Zoophycos* have even been described from restricted lagoon environments (Osgood & Szmuc, 1972) and from a glaciomarine environment (Bhattacharya & Bhattacharya, 2007; Gong *et al.*, 2008).

Zoophycos have been recorded from subtidal to basinal environments: yet there is evidence that the bathymetric range of *Zoophycos* has increased over time (see Kotake, 1997). Most Palaeozoic *Zoophycos* were recognized from shallow-water deposits, whereas Mesozoic–Cenozoic specimens seem restricted predominantly to deep-water sediments (e.g. Ekdale & Bromley, 1984; Seilacher, 1986; Kotake, 1989, 1997; Miller, 1991; Bromley, 1996; Leuschner *et al.*, 2002; Olivero, 2003; Wetzel *et al.*, 2007; Knaust, 2009). And in modern seas, *Zoophycos* is only known from middle bathyal to abyssal sediments (Wetzel & Werner, 1981; Kotake, 1989).

The real sedimentological value of the *Zoophycos* ichnofacies is still enigmatic (Ekdale, 1992; Goldring, 1993). According to Frey & Pemberton (1985) and Frey *et al.* (1990), the *Zoophycos* producer could live in circalittoral to bathyal environments, in quiet waters, and be active in relatively oxygen-deficient conditions.

Specifically with respect to Lower Carboniferous deposits, *Zoophycos* is common in South Wales (Wu, 1982), Belgium (Gaillard *et al.*, 1999), the Moravian–Silesian Zone (Zapletal & Pek, 1999; Mikuláš *et al.*, 2004), Texas (Yurewicz, 1977), New Mexico (Cooper & Dutro, 1982), West Virginia (Bjerstedt, 1988), northwest Alberta (Sirman & Pemberton, 2003) and Japan (Kotake, 1997). This ichnogenus occurs either in low-energy carbonate facies (Yurewicz, 1977; Gaillard *et al.*, 1999), or in the Culm facies, deposited from inner- to the middle-deep-sea fans (Zapletal & Pek, 1999; Mikuláš *et al.*, 2004), or in shales, which represent a fully marine environment (Sirman & Pemberton, 2003). *Zoophycos* trace fossils have also been recognized from Lower Carboniferous deltaic facies (Bjerstedt, 1988).

In Poland, *Zoophycos* ichnospecies have been described mainly from the Tithonian–Miocene flysch formations of the Carpathians (e.g. Książkiewicz, 1977, Wetzel & Uchman, 1998; Uchman, 1998) and from the Jurassic carbonates of the Pieniny Klippen Belt (Tyszka, 1994). Rotnicka (2005) cited possible *Zoophycos* from the fine-grained Upper Cretaceous rocks of the Stołowe Mountains (Sudetes). Paszkowski & Uchman (1992) and recently Hoffmann *et al.* (2009) recognized *Zoophycos* from the carbonate deposits of the Rudawa Group (Middle-Upper Tournaisian) of the Kraków Block.

To date, ichnogenera have not been described from the Palaeozoic deposits of Sudetes. The first discovery of *Zoophycos* from the Palaeozoic strata of the Polish Sudetes has been shortly repoprted by Muszer & Haydukiewicz (2010). This paper specifically describes *Zoophycos* that occurrence from the Upper Viséan Paprotnia Beds of the Bardo Structural Unit.

GEOLOGICAL SETTING

The Bardo Unit is a separate complex structure within the central Polish Sudetes (Fig. 1). According to the tectono-stratigraphic model proposed by Wajsprych (1995), this unit is built up of both allochthonous and autochthonous/parautochthonous successions. The allochthonous rocks are assigned to the Upper Ordovician–Devonian and occur as large olistoliths in the uppermost part of the autochthonous sequence. The autochthonous/parautochthonous succession comprises Upper Devonian–Lower Carboniferous rocks. The lower part of Carboniferous succession is represented by several different facies, whereas its upper part consists of flysch and wildflysch sediments with olistoliths (see Wajsprych, 1995).

The deposits containing the trace fossil *Zoophycos* belong to the Paprotnia Beds, which occur only in the western part of the Bardo Unit and probably underlie the flysch strata. The Paprotnia Beds (formerly termed the Paprotnia Series – see Haydukiewicz & Muszer, 2002) are an informal unit belonging to an autochthonous/parautochthonous platform-to-foreland succession. The outcrop of these beds is situated about 500 m SE of Paprotnia Hill.

The exposed section is 13.7 m thick, contains claystones and mudstones in its lower part (Fig. 2) and a few intercalations of thin dark-grey micritic limestone beds. These deposits are overlain by dark-grey and dark-olive mudstones that are successively intercalated upwards with thin (2–4 cm thick) layers of grey claystones and greywackes. These mudstones also contain several bentonite layers and irregularly distributed small (centimetre-scale) mudstone nodules (intraformational sub-rounded concretion fragments) that can be found within the 5.3 m thick shale package (Fig. 2). The middle part of the section comprises sandy mudstones and greywackes with lenses and nodules of dark-grey organodetrital limestones, which usually form distinct horizons. The sediments are overlain by greywackes containing rare sandy and mudstone intercalations. These greywackes form the highest parts of the Paprotnia Beds and pass gradually into the polymict Wilcza Conglomerates (Fig. 2).

The Paprotnia Beds contain a very rich palaeontological record that has been studied by geologists and palaeontologists for more than 170 years (e.g. von Buch, 1839; Schmidt, 1925; Haydukiewicz & Muszer, 2002). Brachiopods and corals dominate the benthic fauna; goniatids and nautiloids represent the less common nektonic fauna; and marine microfossils include ostracods, foraminifers, numerous fragments of calcareous algae, and various kinds of calcareous tubes and spines. Within this marine assemblage are terrestrial plant debris that are dispersed throughout the deposits. Haydukiewicz & Muszer (2002) suggested that the Paprotnia Beds belong to the *Goniatites crenistria* Zone, which corresponds to the Upper Asbian (regional substage) of the Upper Viséan (V3b). Haydukiewicz & Muszer (2002) noted ichnofossils in the Paprotnia Beds, but they did not describe any ichnogenera.

Both the lithological and palaeontological features of the Paprotnia Beds reflect a gradual environmental change from offshore to onshore conditions (Haydukiewicz &

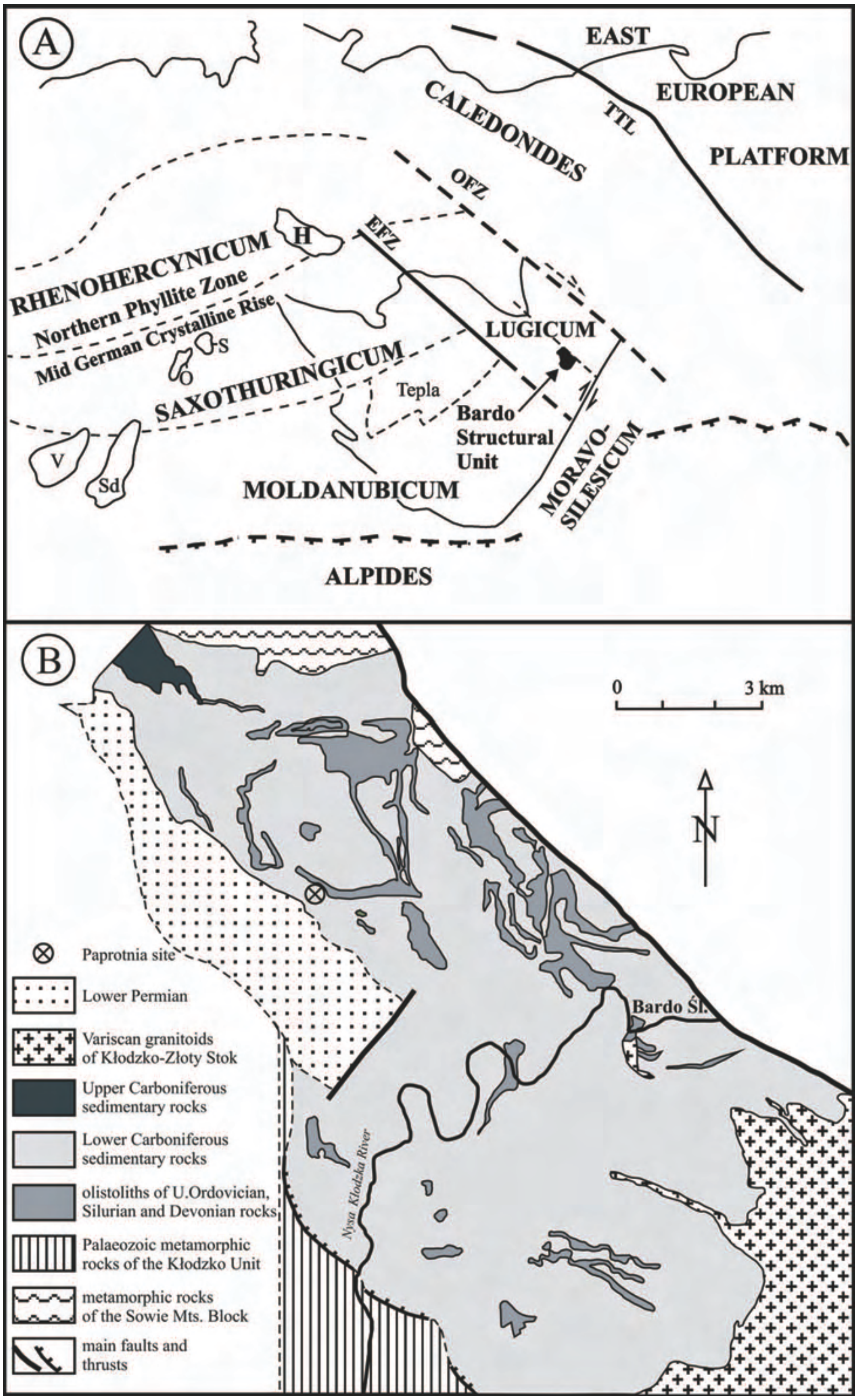

Fig. 1. **A** – Location of the Bardo Unit in the Mid-European Varsicides. Abbreviations are as follows: EFZ (Elbe Fault Zone), H (Harz), O (Odenwald), OFZ (Odra Fault Zone), S (Spessart), Sd (Schwarzwald), TTL (Teisseyre–Tornquist Line), V (Vosges). **B** – Generalized geological map of the Bardo Unit (modified after Oberc, 1957 and Haydukiewicz, 2002) including the location of the Paprotnia Beds.

Muszer, 2002). These platform deposits are interpreted as the shallower-water equivalent of the pelagic *crenistria* limestone, which is widespread in the Culm facies of Variscan Europe.

A recent U–Pb SHRIMP geochronological study of volcanic zircons from a bentonite within the Paprotnia Beds gave an age of 334 ± 3 Ma (Kryza *et al.*, 2007; Kryza *et al.*, 2008; Kryza *et al.*, 2010). This date is in perfect agreement with current age of the (lower) Asbian (see Menning *et al.*, 2006).

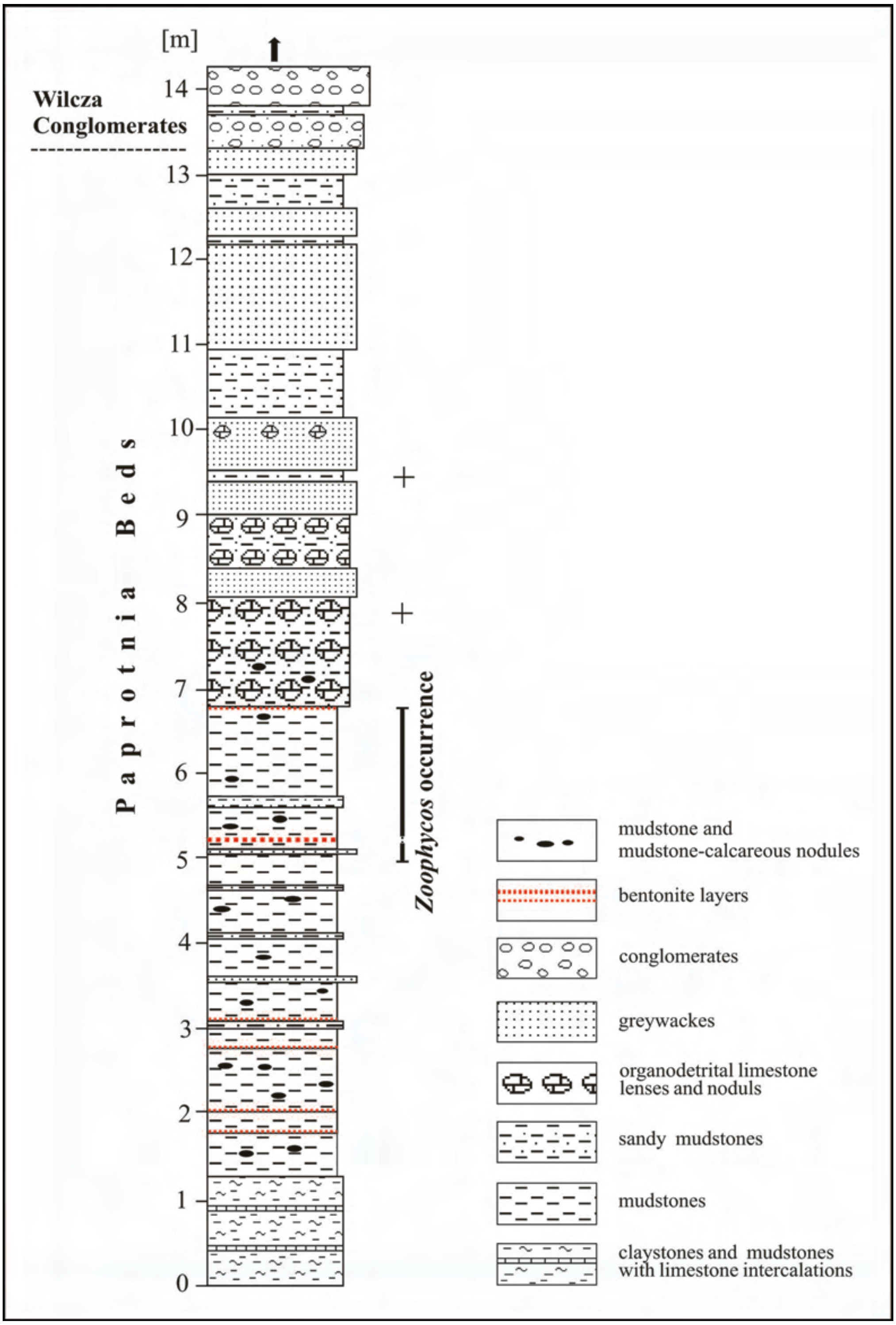

Fig. 2. Lithological column of the Paprotnia section (based on Haydukiewicz & Muszer, 2002) showing stratigraphic position of the *Zoophycos* occurrence.

SYSTEMATIC ICHNOLOGY

Ichnogenus Zoophycos Massalongo, 1855
Zoophycos ichnospecies
Figs 3–5

Material: Several dozen incomplete specimens, catalogue numbers ING/P-1 to ING/P-35, housed at the Institute of Geological Sciences, University of Wrocław.

Description: Large spreiten burrow structures with either simple flat forms or unilobate helical forms preserved parallel to bedding. Most specimens are parts of larger structures whose architecture is unknown. Some helical forms have downward growth. The spreiten have a simple morphology comparable to the morphotype A as described by

Olivero (2003) from Mesozoic deposits in France. The specimens from the Paprotnia Beds represent two types that can be differentiated by the presence of secondary lamellae and size. The first type, termed here as morphotype A1, comprises the larger forms, which range in size between 110 mm and 160 mm. The second type, termed here as morphotype A2, includes the smaller forms, which have a length of up to 70 mm. Measurement of these trace fossils is often difficult because many specimens crosscut one another. Some slabs of *Zoophycos* are encircled by cylindrical marginal tubes, preserved only as fragments. This tubes are 1–2 mm (morphotype A2) to 3–5 mm (morphotype A1) wide. The minimal heights of the individual helical structures range from about 14 mm (the smaller forms) to about 20–35 mm (the larger forms). The lobes are filled with arcuate, well-marked primary lamellae, with the distance between two subsequent lamellae ranging from 1 to 2 mm (morphotype A2) and from 3 to 7 mm (morphotype A1). The secondary lamellae occur often only in the larger forms (morphotype A1) and the distance between each lamellae are in the range 0.7–1 mm. The acute angle between primary lamellae and secondary lamellae varies from 10° to nearly 30°, which is similar to *Zoophycos* described from the Kitakami Mountains by Kotake (1997). The laminae are spirally coiled around a vertical axis that is approximately perpendicular to bedding. The axial tunnel is oval in outline and its diameter ranges from 12–24 mm (morphotype A2) to 19–30 mm (morphotype A1). The angle between the bedding plane and the upper part of the lamina varies from 20° to 55°. The Paprotnia Beds specimens lack pellets in the spreite, features that are, by contrast, often preserved in Cenozoic *Zoophycos* (see Wetzel & Werner, 1981; Kotake, 1997).

Occurrence and vertical distribution: All the *Zoophycos* specimens described here are from the Paprotnia Beds of the Bardo Unit (Sudetes). These trace fossils are relatively common.

The ichnogenus *Zoophycos* is locally abundant in the lower part of the Paprotnia section. Distinct concentrations of this trace fossil occur within the 2.0 m-thick package of dark-grey and dark-olive mudstones that immediately underly the first horizon of nodules of organodetrital limestones. *Zoophycos* also occurs locally in mudstones between the limestones (Figs 2, 5B), but it has not been possible to discern any three-dimensional structures from these deposits. Locally, neighbouring burrow systems interpenetrate one another. We observed that morphotypes A1 (the larger forms) and A2 (the smaller forms) occur in the same horizon.

The local range of *Zoophycos* from the Paprotnia Beds corresponds to the uppermost part of taphocoenosis (II), an assemblage characterized by a dominance of epifaunal suspension feeders and the presence of bioturbational structures (see Haydukiewicz & Muszer, 2002). Other ichnofossils that occur in this taphocoenosis are rare, poorly preserved fragments that are difficult to identify: they are partly filled with a porous ferruginous substance (see Figs 10G and 10H in Haydukiewicz & Muszer, 2002). The fossils of this community are usually irregularly dispersed in mudstone that contain greywacke intercalations and thin bentonite layers (Fig. 2). Unfortunately, *Zoophycos* structures and other ichnofossils have not been observed within these bentonites.

This taphocoenosis (II) assemblage indicates oscillations in environmental conditions from storm wave base to the fair-weather wave base, but always in oxygenated water (Haydukiewicz & Muszer, 2002). The relative frequency of occurrence of particular taxonomical groups in the Paprotnia Beds varies depending on lithology. A distinct decrease in the amount of benthic fauna is noticeable in the greywacke intercalations, in the interval of mudstones within the thin bentonite layers, and just below the thickest bentonite layer in the sequence. Above this thickest bentonite layer, a progressive increase in benthic fauna is observed. The benthic organisms of this taphocoenosis could have existed in an environment whereby there was a gradual increase in the influx of terrigenous material and bottom water turbulence. Any rapid influx of terrigenous material, combined with increasing amounts of volcanic ash, would cause a short-term regress of benthic development (Haydukiewicz & Muszer, 2002).

Discussion: Specimens of *Zoophycos* ichnospecies in the Papronia Beds are well preserved but unfortunately incomplete. The host rock type itself (mudstone) is very fragile, and is a reason why precise description of the *Zoophycos* burrow system is impossible. Nevertheless, these *Zoophycos* clearly correspond to the constructional model of Gaillard & Olivero (1993) and are very similar to Tournaisian forms from Belgium (Gaillard *et al.*, 1999), despite the secondary lamellae of the Tournaisian specimens not being visible.

In comparison to the Lower Devonian specimens from Bolivia (Gaillard & Racheboeuf, 2006) the Paprotnia *Zoophycos* are similar, though much smaller. The acute angle between the major and minor lamella of the Paprotnia Bed specimens are similar to those of *Zoophycos* from the Lower Carboniferous of Japan (Kotake, 1997). Furthermore, the distance between two subsequent primary lamellae and the central axis of the Paprotnia *Zoophycos* are very similar to those from *Zoophycos* from the Middle Pennsylvanian of Nova Scotia (McIlroy & Falcon-Lang, 2006). In our specimens, however, the central axes are much smaller, possibly due to fragmentation. Pellets within the spreite are not present.

In contrast to the forms from the glaciomarine Talchir Formation in India (Bhattacharya & Bhattacharya, 2007) *Zoophycos* from the Paprotnia Beds are much larger, and this may be due to differences in climate and temperature of the local sea water.

It seems that the larger forms (our morphotype A1) are close to the ichnospecies *Zoophycos villae* Massalongo, 1855, and the smaller forms (our morphotype A2) are very similar to ichnospecies *Zoophycos brianteus* Massalongo, 1855 (see Olivero, 2007).

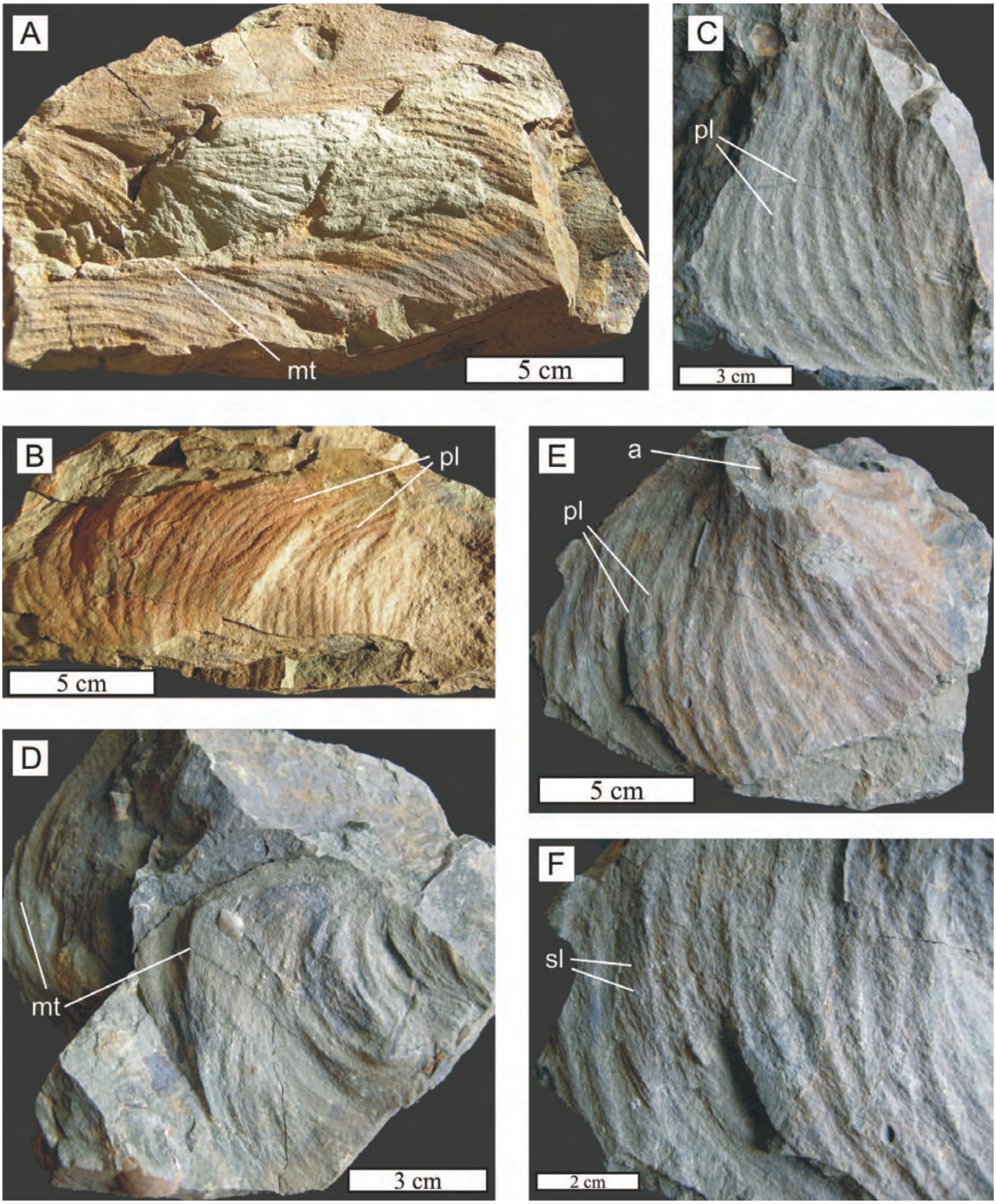

Fig. 3. Fragments of *Zoophycos* ichnospecies (morphotype A1) from the Paprotnia Beds showing primary lamellae and secondary lamellae. Abbreviations used in this figure are as follows: a (axil tunnel), mt (marginal tube), pl (primary lamellae), sl (secondry lamellae). **A, B** – Planar sprite with high length-to-width ratio (sample ING/P-1; A is lower bedding surface, B is upper bedding surface). **C** – Gently curved planar spreite with low length-to-width ratio (sample ING/P-9). **D** – Planar spreite with marginal tubes (sample ING/P-8). **E** – Spirally coiled structure with axial tunnel (sample ING/P-3). **F** – Primary and secondary lamellae (sample ING/P-3).

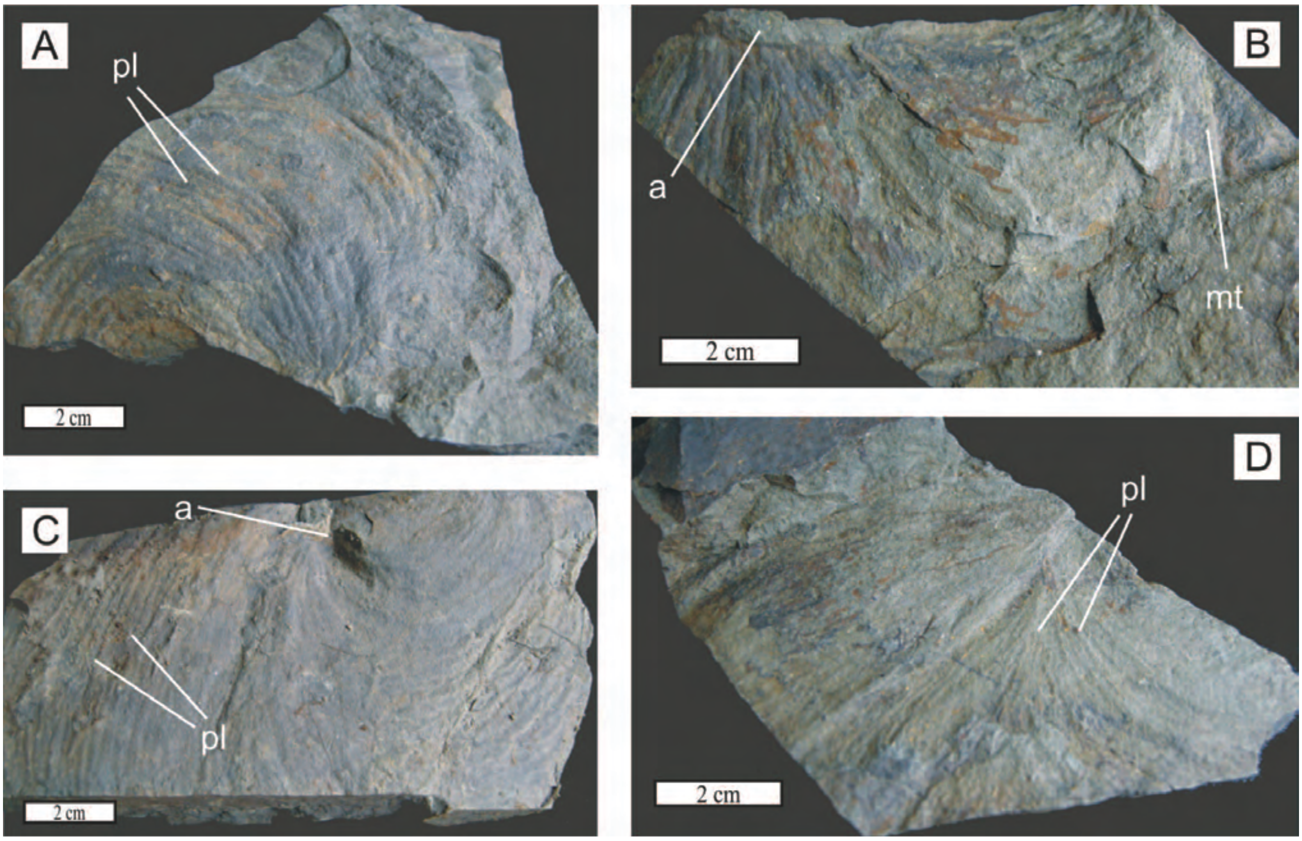

Fig. 4. Fragments of *Zoophycos* ichnospecies (morphotype A2) from the Paprotnia Beds showing primary lamellae. Abbreviations used in this figure are as follows: a (axil tunnel), mt (marginal tube), pl (primary lamellae). **A** – Sample ING/P-28. **B** – Sample ING/P-25. **C** – Sample ING/P-23. **D** – Sample ING/P-24.

CONCLUSIONS

The trace fossil *Zoophycos* from the Paprotnia Beds are simple in form and correspond to the morphotype A described by Olivero (2003). Our specimens closely resemble other Carboniferous forms of this ichnogenus (see Kotake, 1997; Gaillard *et al.*, 1999; McIlroy & Falcon-Lang, 2006). We have identified two morphotypes that can be differentiated by the presence of secondary lamellae and size: these we term A1 for the larger type with primary and secondary lamellae, which resemble *Zoophycos villae* Massalongo, 1855; and A2 for the smaller type with only primary lamellae, which resemble *Zoophycos brianteus* Massalongo, 1855. Both morphotypes occur in the same package of deposits.

Both the lithological and palaeontological features of the Paprotnia Beds indicate gradual environmental changes from offshore to onshore conditions. Concentrations of *Zoophycos* occur in the mudstones of the lower part of the section, just below the horizon of organodetrital limestones. Such a succession of sediments indicates distinct shallowing of the water body, from storm wave base to fair-weather wave base and to more oxygenated waters. The presence of *Zoophycos* in such deposits supports previous suggestions from the ichnological literature that the trace-making animal prefers shallow-water environments in the Early Carboniferous (*e.g.* Osgood & Szmuc, 1972; Yurewicz, 1977; Miller & Johnson, 1981; Wu, 1982; Bjerstedt, 1988; Ekdale & Mason, 1988; Gaillard *et al.*, 1999).

We also note that ancient and present-day *Zoophycos*-group trace fossils that are similar to the *Zoophycos* trace fossils from the Paprotnia Beds often seem to occur in sediments that contain pebble lags, tuffs or volcanic ash (e.g. Chamberlain, 1975; Kotake, 1989, 1997; Löwemark *et al.*, 2004; Löwemark *et al.*, 2006; Gong *et al.*, 2008; Hoffmann *et al.*, 2009).

Thus, this report on the occurrence of *Zoophycos* trace fossils from the Paprotnia Beds of the Bardo Structural Unit, SW Sudetes, enriches our knowledge of the Carboniferous of the Sudetes and opens the way for geologists to study these sediments from an additional, and fresh, perspective.

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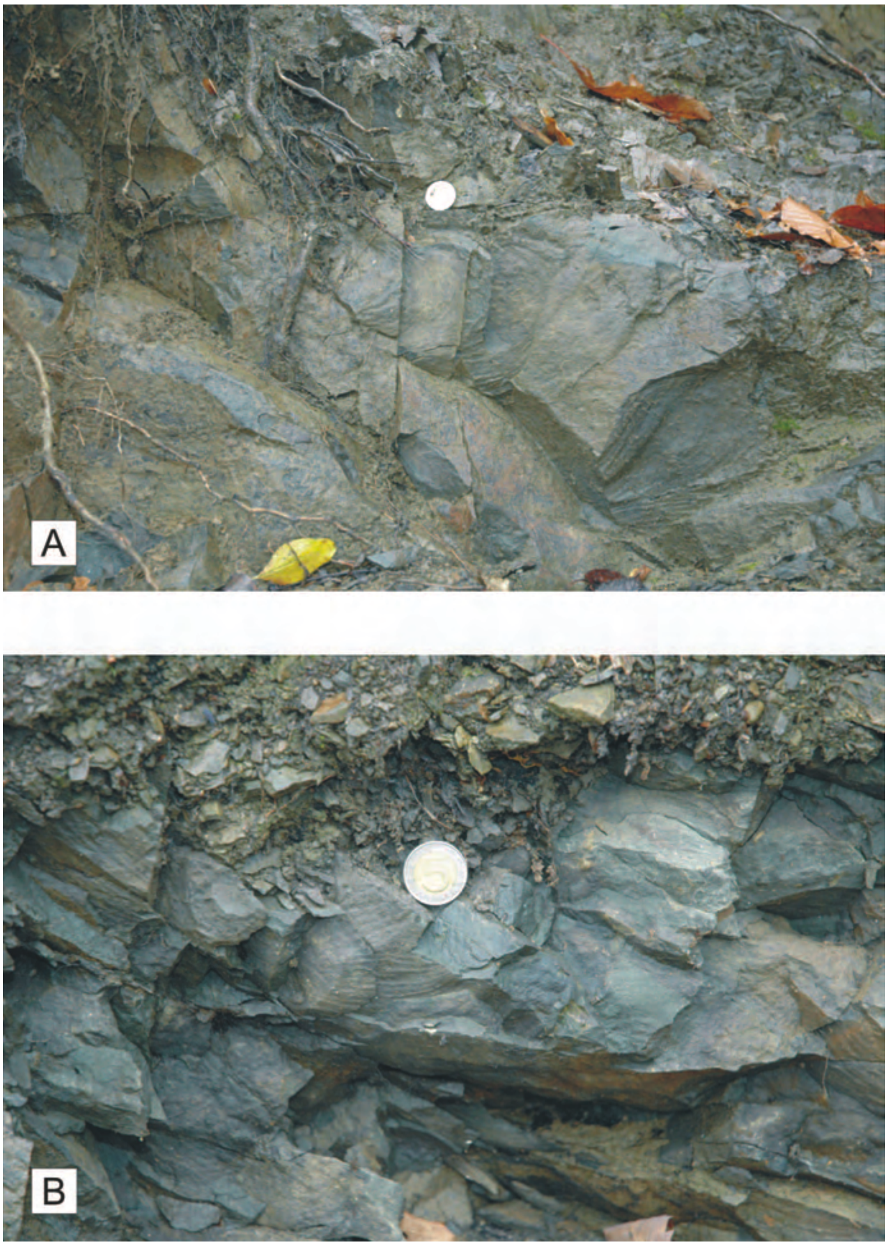

Fig. 5. Outcrop photographs of *Zoophycos* on lower bedding surface of the Paprotnia Beds (the Paprotnia section). **A** – In the lower part of *Zoophycos* occurrence; N 50°31'57.6''; E 16°37'27.26''. **B** – In the upper part of *Zoophycos* occurrence; N 50°31'57.11''; E 16°37'27.92''. Coin diameter = 2.3 cm.

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