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Ichnology of Upper Cretaceous deep-sea thick-bedded flysch sandstones: Lower Istebna Beds, Silesian Unit (Outer Carpathians, southern Poland)

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Abstract: The Ophiomorpha rudis ichnosubfacies of the Nereites ichnofacies was recognized in thick- and very thick-bedded sandstones of the Lower Istebna Beds (Campanian–Maastrichtian), which were deposited mainly in deep-sea clastic ramps and aprons. It contains mainly *Ophiomorpha rudis* (produced by deeply burrowing decapod crustaceans) and rarely *Zoophycos* isp. and *Chondrites* isp. The impoverished Paleodictyon ichnosubfacies of the Nereites ichnofacies is present in the medium- and thin-bedded packages of flysch sandwiched between the thick- and very thick-bedded sandstones. They contain *Chondrites* isp., *Phycosiphon incertum*, *Planolites* isp., *Arthrophycus strictus*, *Thalassinoides* isp., *Ophiomorpha annulata*, *O. rudis*, *Scolicia strozzii* and *Helminthorhaphe flexuosa*. The relatively low diversity of this assemblage is influenced by limited areas covered by muddy substrate, which favours deep-sea tracemakers, and partly by a lowered oxygenation in the sediment.

Key words: Upper Cretaceous, Polish Carpathians, Silesian Nappe, flysch, trace fossils, *Ophiomorpha rudis*.

Introduction

Most of ichnological studies on flysch deposits concern thin- and medium-bedded turbiditic sediments, in which the diversity of trace fossil is generally high. Less attention is paid to shaly flysch (e.g. Mikuláš et al. 2009) or thick-bedded sandstone-dominated deep-sea deposits (e.g. Heard & Pickering 2008; Phillips et al. 2011), mostly because they are less attractive due to their general low trace fossil diversity, and often in the Carpathians due to their poor exposure, except for quarries. However, it is expected that such deposits with sand-dominated substrate represent a specific paleoenvironment for burrowing organisms, which needs closer characterization, because most flysch trace fossils represent mud-dwellers adapted to muddy substrates (Kern 1980).

The Lower Istebna Beds (Campanian–Maastrichtian) is a peculiar Late Cretaceous lithostratigraphic unit of the Silesian Nappe in the Flysch Carpathians, which occupies large areas and is dominated by thick-bedded sandstones (e.g. Unrug 1963, 1968). The sandstones have been quarried for a long time as a building stone and the quarries together with some natural outcrops give an opportunity to study their trace fossils and ichnofabrics.

The aim of this paper is to present and interpret trace fossils and ichnofabrics of the Lower Istebna Beds in selected outcrops (Figs. 1–7), mainly in the middle sector of the Polish part of the Silesian Nappe. The collected and illustrated specimens (collection prefix INGUJ181P) are housed in the Institute of Geological Sciences of the Jagiellonian University in Cracow.

The Lower Istebna Beds have not been ichnologically investigated in detail. The occurrence of *Spirorhaphe* and *Cosmorhaphe* was mentioned by Unrug (1963), who also noted vertical burrows that pass downward into horizontal systems on the soles of thick beds, which are described as *Ophiomorpha rudis* in this paper. Książkiewicz (1968) described *Gyrophyllites*, mentioned occurrence of a few types of trace fossils (Książkiewicz 1975) and noted sixteen ichnotaxa in eleven outcrops (Książkiewicz 1977) (Table 1), indicating that this is one of the poorest lithostratigraphic unit in the Polish Carpathians concerning trace fossils. Rajchel & Uchman (2008) presented ichnology of the Łęki section, and Rajchel & Uchman (2009) described *Ophiomorpha rudis* from the Lower Istebna Beds building stones in the architecture of Cracow.

Geological setting

The Istebna Beds, distinguished by Hohenegger (1861), were split (Liebus & Uhlig 1902) into the Lower Istebna Beds (thick-bedded sandstones and conglomerates) and the Upper Istebna Beds (thick-bedded sandstones and conglomerates, dark shales with sideritic concretions, black mudstones with exotic blocks). In the eastern part of the Polish Carpathians (Krosno region), the Upper Istebna Beds are distinguished (Zuber 1915) as the Czarnorzeki Beds (see also Świdziński 1947). In the Beskid Śląski range (western part of the Polish Carpathians), where the Istebna Beds are thickest (at least 1600 m), and also in other areas, they are subdivided into the Lower Istebna Beds (thick-bedded conglomerates and sandstones, pebble mudstones, packages of thin-bedded calcareous sandstones and shales) and the Upper Istebna Beds (mostly dark non-calcareous shales of the Lower Istebna Shale, mostly thick-bedded sandstones and debris-flow deposits of the

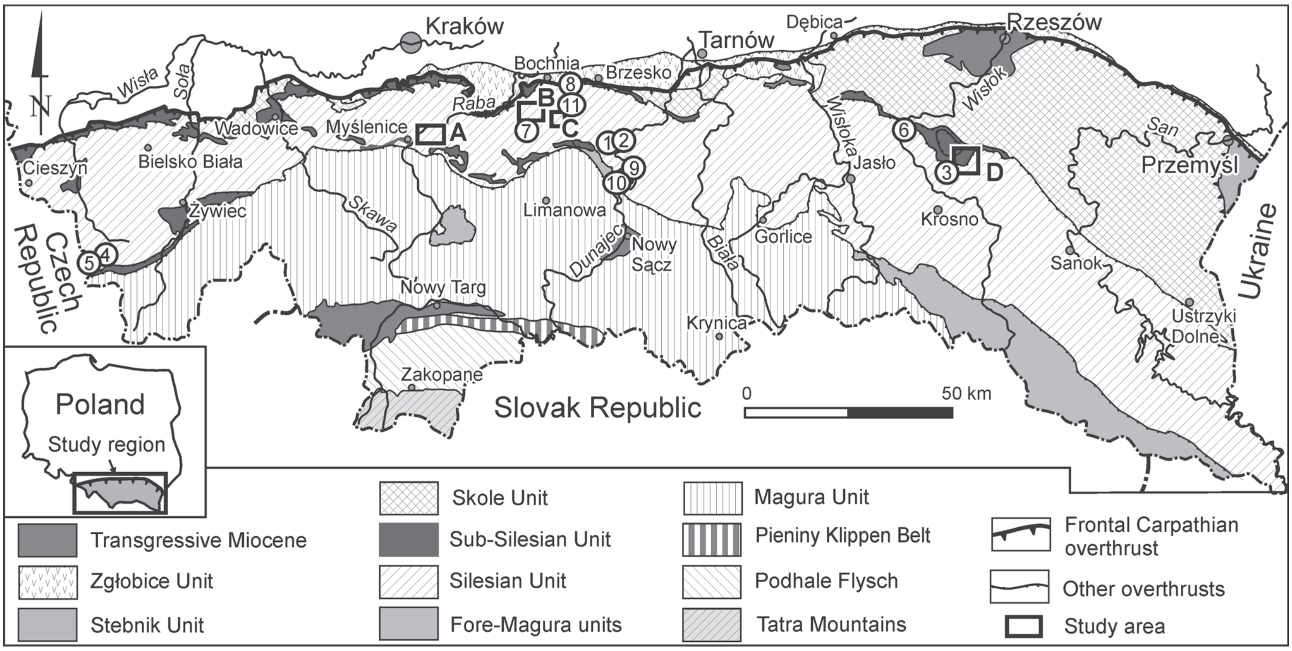

Fig. 1. Geological sketch map of the Polish Carpathians (based on Żytko et al. 1989; changed, simplified) with indication of the study areas. **A–D** refers to the maps in Fig. 3. Numbers in circles refer to the localities in Table 1.

Table 1: Published data on occurrence of trace fossils in the Lower Istebna Beds (compiled from Książkiewicz 1977). Original names in quadrangle parentheses; revised names by Uchman (1998). Localities: **1** — Będzieszyna, **2** — Czchów (in a package of the "Inoceramian type flysch"), **3** — Czarnorzeki, **4** — Istebna, **5** — Istebna — river Olza, **6** — Kobyle n. Jasło, **7** — Łapanów, **8** — Łazy, **9** — Rożnów, **10** — Tabaszowa, **11** — Wiśnicz. The localities are indicated in Fig. 1 (numbers in circles).

Ichnotaxa\outcrops	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Ophiomorpha annulata (Książkiewicz) [*Sabularia simplex* Książkiewicz]			x								
Ophiomorpha rudis (Książkiewicz) [**Sabularia rudis* Książkiewicz]	x		x	x		x					
Chondrites intricatus (Brongniart) [*Chondrites aequalis* Sternberg]			x								
Chondrites targionii (Brongniart [*Chondrites affinis* (Brongniart), *Chondrites arbuscula* Fischer-Ooster, *Chondrites furcatus* (Brongniart)]			x								
Cladichnus fisheri D'Alessandro & Bromley [*Taenidium isseli* (Squinabol)]			x								
Scolicia strozzii (Savi & Meneghini) [*Taphrhelminthopsis auricularis* Sacco]			x								
?*Scolicia prisca* de Quatrefages [*Scolicia vertebralis* Książkiewicz]		x									
Helminthorhaphe isp. [*Helminthoida crassa* Schafhäutl]		x	x								
Gyrophyllites rehsteineri Fischer-Ooster [*Gyrophylithes kwassizensis* Glocker]					x		x	x	x		
Spirophycus bicornis (Heer)					x						
Cardioichnus isp. [*Pararusophycus oblongus* Książkiewicz]									x		
Spirorhaphe involuta (De Strefani)										x	
Lorenzinia kuzniari Książkiewicz											x
Paleodictyon strozzii Meneghini [*Paleodictyon tellini* Sacco]			x								
Paleodictyon miocenicum Sacco		x									
cf. *Beaconites caprinus* Frey & Howard [*Keckia hoessi* Sternberg)]			x								

Upper Istebna Sandstone, mostly dark non-calcareous shales of the Paleocene Upper Istebna Shale; Unrug 1968; Fig. 2). Strzeboński (2001) included the Lower Istebna Shale in the Lower Istebna Beds, which are not considered in this paper.

The Lower Istebna Beds (Campanian–Maastrichtian) are composed mostly of thick- and very thick-bedded, mainly medium- to coarse-grained, locally conglomeratic sandstones, which occupy large areas of the Silesian Nappe (Unrug 1963, 1968; Bromowicz et al. 1976). In the study area, they are developed as 700–800 m thick (Leśniak & Słomka 2000), mostly poorly sorted oligomictic quartz arenites, arkoses or greywackes (Kamieński et al. 1967; Bromowicz et al. 1976; Bromowicz 2001), which are dirty white with rusty spots, pale yellow, rusty cream or brownish in colour. The sandstones are highly porous, weakly cemented by clay minerals, locally with silica. Stronger, concretionary carbonate cementation is present in some beds. Thickness of the beds attains 5 m or rarely even more. Many beds are amalgamated and display an erosive, commonly channelized base.

The thick-bedded sandstones can be ascribed to a few lithofacies determined as sandy conglomerates, sandstones and sandstones with mudstones, rarely to sedimentary deformed deposits (Strzeboński 2003). They originated from non-turbulent gravitational flows, sandy-debris or turbiditic

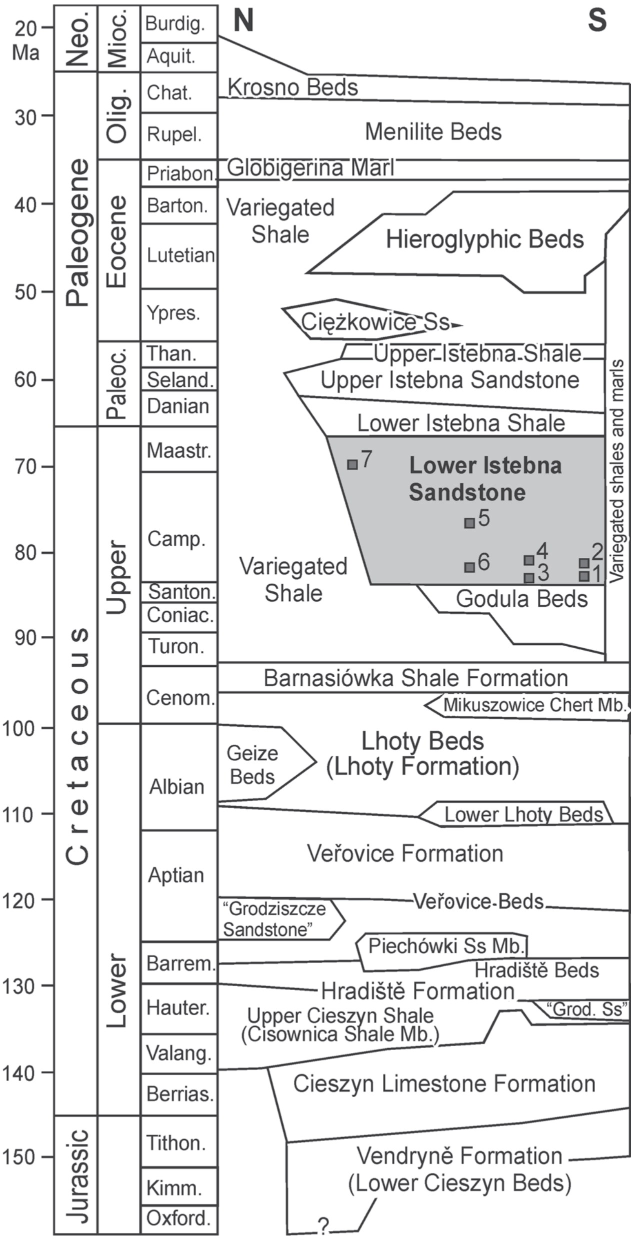

Fig. 2. General stratigraphic scheme of the Cretaceous–Paleocene in the Silesian Nappe (compiled from Oszczypko 2004 and Vašíček et al. 2010, and references therein). The Lower Istebna Beds shaded. Position of the studied outcrops: **1** — Łęki quarry, **2** — Łęki-river and Łęki-klippe sections, **3** — Czaslaw 1 quarry, **4** — Czasław 2 quarry, **5** — Sobolów quarry, **6** — Zonia quarry, **7** — Wola Komborska quarry.

flows (for origin of such deposits see Shanmugam 2000). The pebble mudstones were deposited as cohesive debrites (Strzeboński 2005). A transition from debris flow to turbiditic sandstones has been observed in some thick and very thick beds (Felix et al. 2009). The deposits of the Lower Istebna Beds can be ascribed mainly to the channel (Stanley & Unrug 1972) and overchannel, rarely depositional lobe facies in terms of the classical fan system (e.g. Mutti & Ricci Lucchi 1972; Walker 1978). However, lately, they are referred to a siliciclastic ramp or apron (Stow et al. 1996), that has been fed from multiple-points in proximity to their clastic material source (Strzeboński 2003). The source was situated on the Silesian Ridge (the so-called Silesian Cordillera) rimming the Silesian Basin from the south (Książkiewicz 1962; Unrug 1963, 1968; Strzeboński 2003). Taking in account several million years lasting sedimentation of the Lower Istebna Beds, activity of the source can be referred rather to a tectonic activation of the Silesian Ridge than to a eustatic sea-level fall.

Thin- and medium-bedded, non-calcareous flysch occurs as packages between the dominating thicker beds (Fig. 8B), usually with gradual transition from thick-bedded packages at the base (Wola Komborska quarry; Fig. 6) or vice versa (Czasław 2 quarry; Fig. 5). Moreover, rare packages of generally calcareous thin- and medium-bedded flysch are sandwiched between thick-bedded non-calcareous sandstones (Łęki-river section; Fig. 7). They are called the "Inoceramian-type flysch" in the Istebna Beds (Skoczylas-Ciszewska & Kamieński 1959). Such sediments contain grey, mostly fine-grained, horizontally and/or ripple laminated sandstones and dark grey, light grey, greenish-grey and greenish spotty mudstones. The non-calcareous greenish-grey and greenish mudstones are locally present also between some non-calcareous thick-bedded sandstones. Judging from the generally non-calcareous background shales, the Lower Istebna Beds were deposited below the calcium compensation depth (CCD) (Koszarski & Żytko 1965; Książkiewicz 1975; Geroch & Koszarski 1988), probably at the depth of 3500 m (Słomka et al. 2006) or at least 4000 m (Uchman et al. 2006). They contain the flysch-type agglutinated foraminifers (Olszewska & Malata 2006), which are typical of the bathyal and abyssal zones below the CCD (Gradstein & Berggren 1981).

Studied sections

The Lower Istebna Beds were studied at Łęki near Trzemeśnia in a quarry and natural outcrops (Łęki-klippe and Łęki-river sections) and in the quarries at Czasław (Czasław 1 and 2) near Dobczyce, at Sobolów, Zonia and Leksandrowa in the Bochnia region, and at Wola Komborska near Krosno (Fig. 1).

The section at Łęki (Figs. 1, 3A), 112 m thick, starts in a quarry (GPS coordinates: N49°49.906′; E020°01.296′; ±6 m; Fig. 4); it continues in the right bank of the Trzemeśnianka River (Łęki-river section; thin-bedded flysch; Fig.7) and in a steep klippe near the bridge (GPS coordinates: N49°49.915′; E020°01.270′; ±6 m; Fig. 4) (Bromowicz 2001; Rajchel & Uchman 2008). The beds are inclined to the north in the southern limb of the Bulinka-Osieczany Syncline (Burtan 1984). In the quarry and in the klippe, the sandstones are thick- and very thick-bedded, medium-grained, poorly sorted, conglomeratic at the base of some beds, commonly amalgamated, massive or exceptionally large scale cross-laminated in the lower part or in the whole bed. They contain irregularly-distributed intraclasts, armoured (Fig. 8E) and non-armoured mudballs, which are up to more than a meter in diameter. Locally, the mudballs are distributed along the amalgamation surfaces, particularly within the thickest sandstone beds. Some larger intraclasts are composed of thin-bedded turbiditic sediments. Some smaller ones

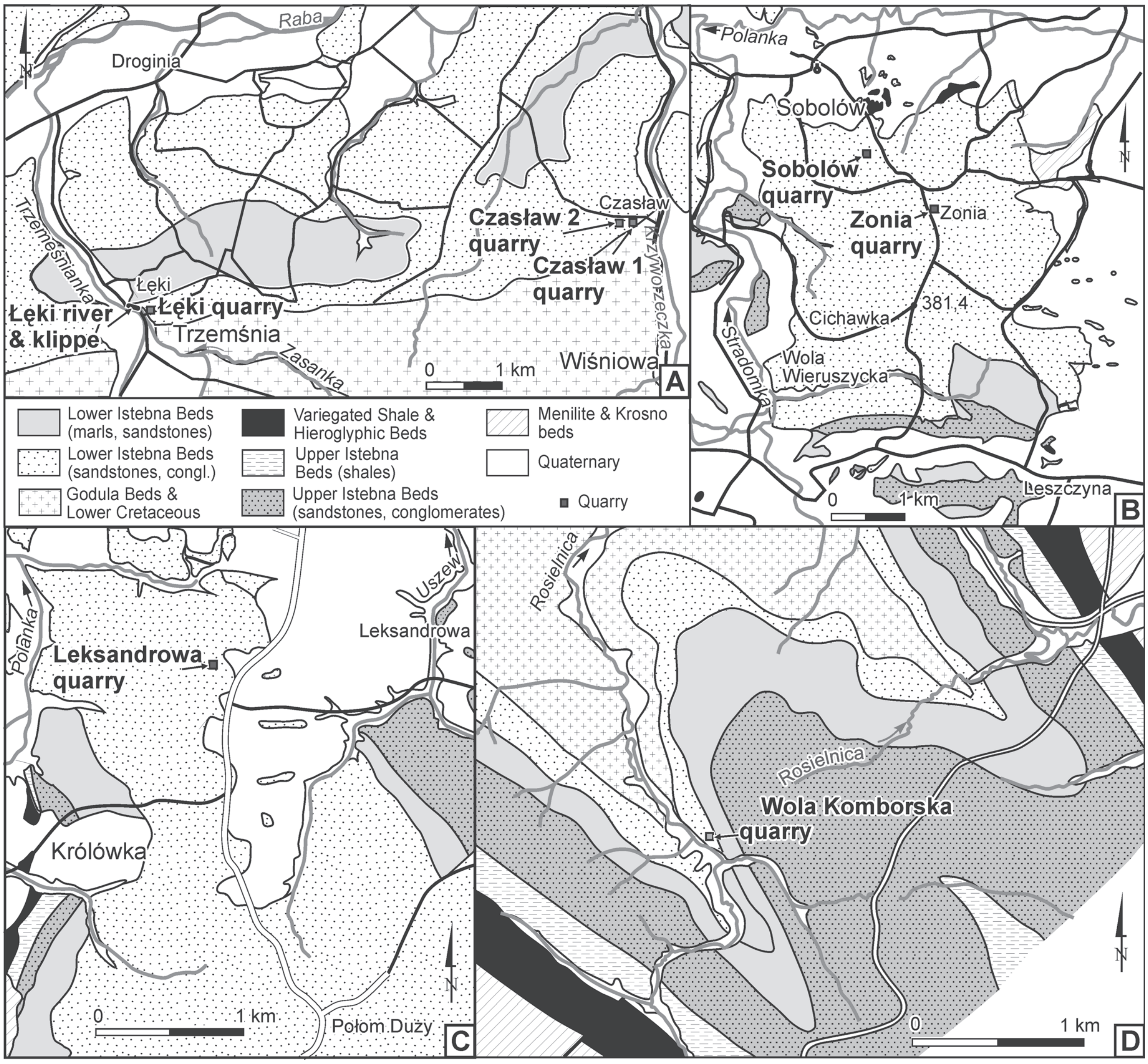

Fig. 3. Geological maps of the study areas. A–D correspond to the indications in Fig. 1. **A** — is based on Burtan (1954, 1974), **B** — on Skoczylas-Ciszewska & Burtan (1954), **C** — on Skoczylas-Ciszewska & Burtan (1954), and **D** — on Mitura & Birecki (1966); all changed and simplified.

are built of sideritic marly mudstones. The upper part of the Łęki-klippe section contains layers of conglomerates composed of mud intraclasts and muddy sand matrix (Fig. 8C). The bases of some sandstone beds are channelized or loaded. Individual scours, a few tens of centimeters wide and up to 10 cm deep, are filled with fine conglomerate or conglomeratic sandstones. Some beds are covered by ripplemarks at the top. Locally, dish and flame structures are present. Two sandstone-mudstone beds are involved in a submarine slump, which is about 1 m thick. At the top, some thick beds transit rapidly into a thin layer of horizontally and/or ripple-cross laminated sandy mudstones and mudstones, which contain abundant carbonized plant detritus (Fig. 8B,D) and are commonly covered by jarosite varnish.

In the Czasław 1 (Figs. 1, 3A, 5; GPS coordinates: N49°50.505′; E020°06.857′; ±11 m) and Czasław 2 (Figs. 1, 3A; GPS coordinates: N49°50.554′; E020°06.669′; ±5 m) quarries, thick-bedded, commonly amalgamated, coarse-grained, poorly sorted, arkosic sandstones with clayey, locally siliceous contact pore cement (Bromowicz 2001) crop out. They contain mud intraclasts and armoured mudballs, which are up to 20 cm in diameter. Amalgamation surfaces are underlined by a grain-size change. Dish structures and sand veins related to them are present. The veins, up to 10 cm thick, are manifested on the bedding surface as a polygonal network of ridges, which are up to a few centimeters high. The beds are massive, exceptionally horizontally laminated. The base of some beds is loaded. At the top, the grains are finer and a rapid transition to a thin layer of horizontally- or ripple-laminated sandy mudstones is common.

In the Sobolów quarry (Figs. 1, 3B, 5, 8A; GPS coordinates: N49°53.887′; E020°20.979′; ±5 m), thick-bedded, commonly

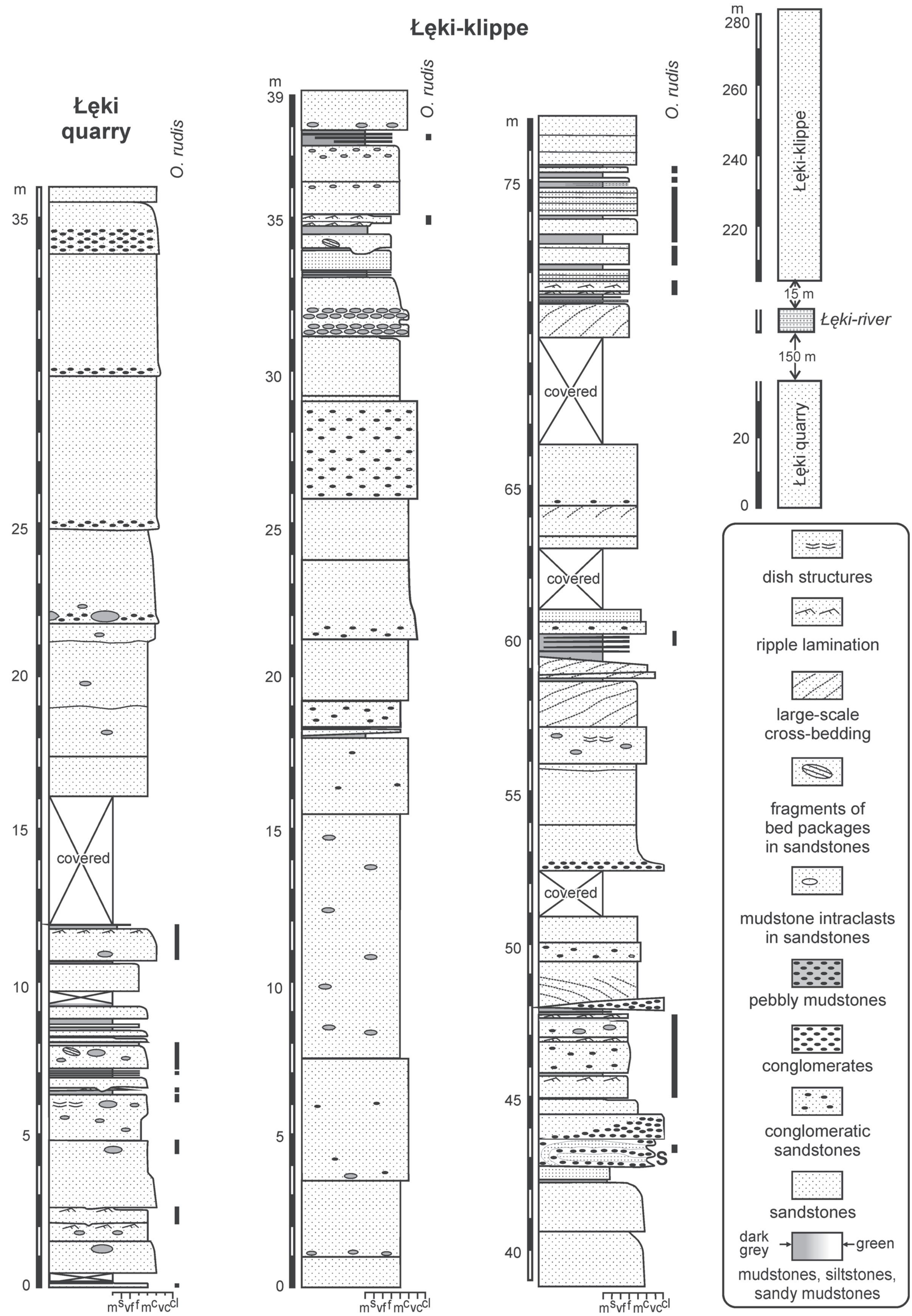

Fig. 4. Sections of the Lower Istebna Beds at Łęki (based on Rajchel & Uchman 2008, modified). **Łr** — Łęki-river section (see Fig. 7).

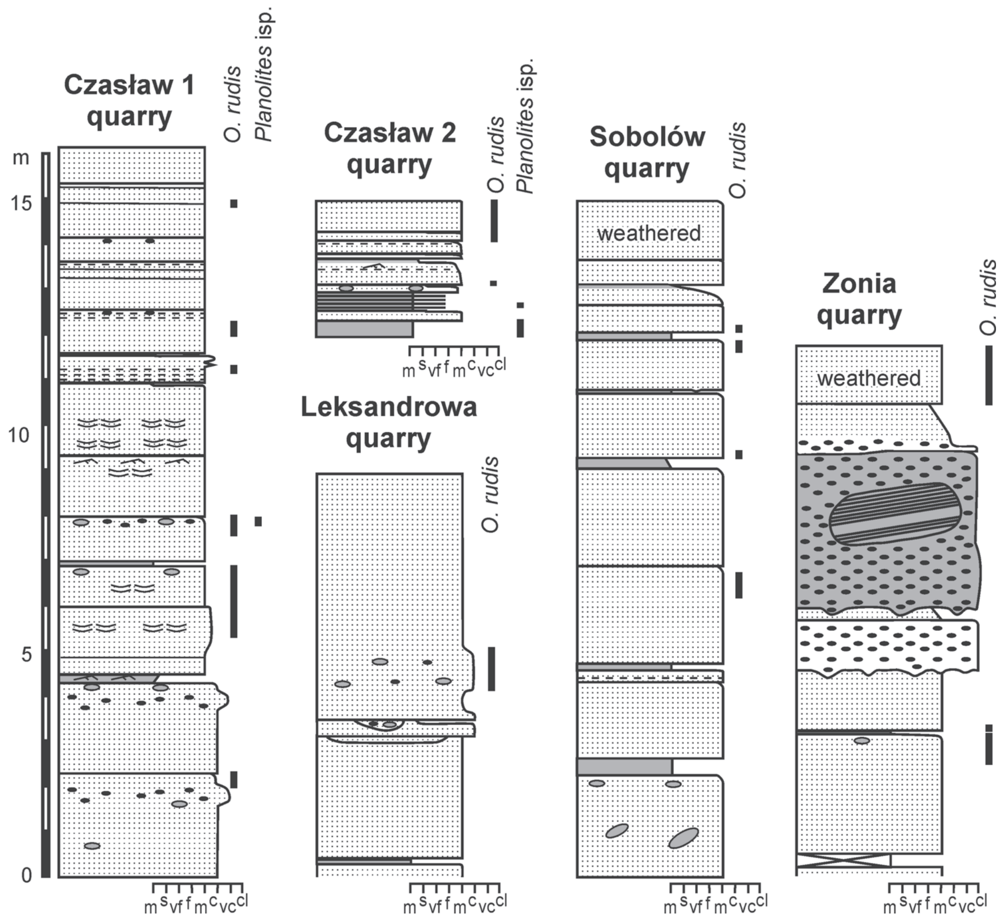

Fig. 5. Sections of the Lower Istebna Beds in the Czasław 1, Czasław 2, Sobolów, Zonia and Leksandrowa quarries. Legend as in Fig. 4.

amalgamated, mostly medium-grained, poorly sorted sandstones crop out. Their bases are sharp, locally covered by flute casts. The cement is clayey, locally calcareous in the lower part. The beds at the top change from muddy sandstone to grey or greenish grey horizontally laminated sandy mudstones with plant detritus. In the lower part of the section, large intraclasts of sideritic mudstones are present (Fig. 8F). Close to the top, small mudballs occur.

In the Zonia quarry (Figs. 1, 3B, 5; GPS coordinates: N49°53.771′; E020°22.023′; ±7 m), a 2.5 m thick bed of pebble mudstone crops out in the SW limb of the Królówka Syncline (Skoczylas-Ciszewska 1952; Bromowicz 2001). It contains quartz, lydite, sandstone, gneiss and marlstone pebbles in muddy and sandy matrix, sandstone intraclasts, and a large block of thin-bedded flysch, which is about 3 m long and 1 m thick. The bed is underlined and overlaid by thick-bedded conglomerates and coarse-grained sandstones that display erosive bed bases. They contain shale intraclasts and mudballs, which are up to 35 cm long.

In the Leksandrowa quarry (Figs.1, 3C, 5; GPS coordinates: N49°53.636′; E020°26.788′; ±12 m), a 9.5 m thick section of very thick- and thick-bedded, medium- and coarse-grained, poorly sorted sandstones crop out in the NE limb of the Wiśnicz Nowy Anticline (Skoczylas-Ciszewska 1952). They contain shale intraclasts, which are up to a dozen cm thick, and lensoidal laminae of fine-grained conglomerate. The base of some beds is channelized and filled with coarser sediment.

In the Wola Komborska quarry (Figs. 1, 3D, 6; GPS coordinates: N49°44.091′; E021°53.566′), a 28 m-thick section crops out in the northern limb of the Wola Komborska Anticline, which is a part of the folded Czarnorzeki Anticline (Mitura & Birecki 1966). Thick-bedded, medium-grained sandstones prevail in the lower part. In the upper part, also thin- and medium-bedded fine-grained sandstones intercalated with grey siltstones-mudstones are present. Outcrop surface dirt due to exploitation did not permit observation of *Ophiomorpha* and possible other trace fossils in the lower part of the section; the trace fossils are, however, well visible in cut exploited blocks and also in the architectural elements in Cracow (Rajchel 2002, 2003, 2004; Rajchel & Uchman 2009).

Trace fossils in thick-bedded sandstones of the Lower Istebna Beds

The thick-bedded sandstones contain almost exclusively *Ophiomorpha rudis* (Książkiewicz, 1977). Very rarely, *Zoophycos* isp. and *Chondrites* isp. occur.

Ophiomorpha rudis (Figs. 8D, 9) was previously described by Książkiewicz (1977) as *Sabularia rudis*, but was

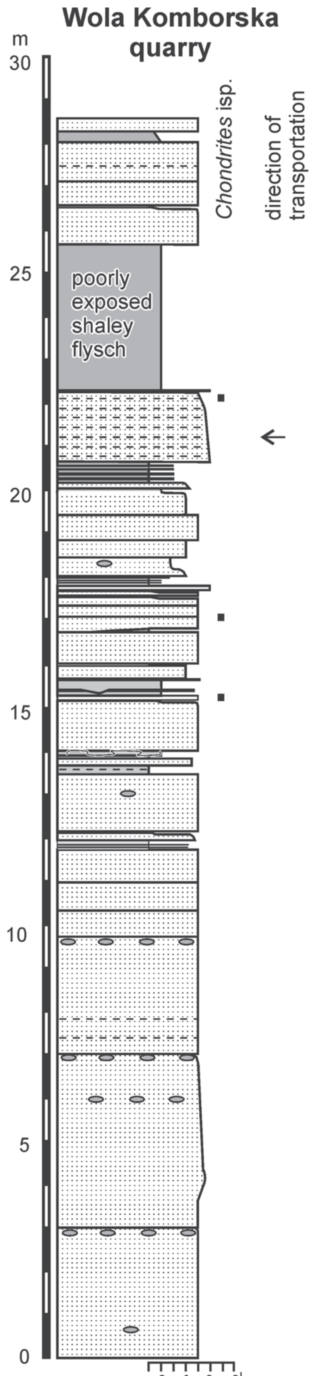

Fig. 6. Section of the Lower Istebna Sandstone in the Wola Komborska quarry. Occurrences of *Ophiomorpha rudis* are not indicated because of muddy dirt covering the exposure wall caused by exploitation. Legend as in Fig. 4.

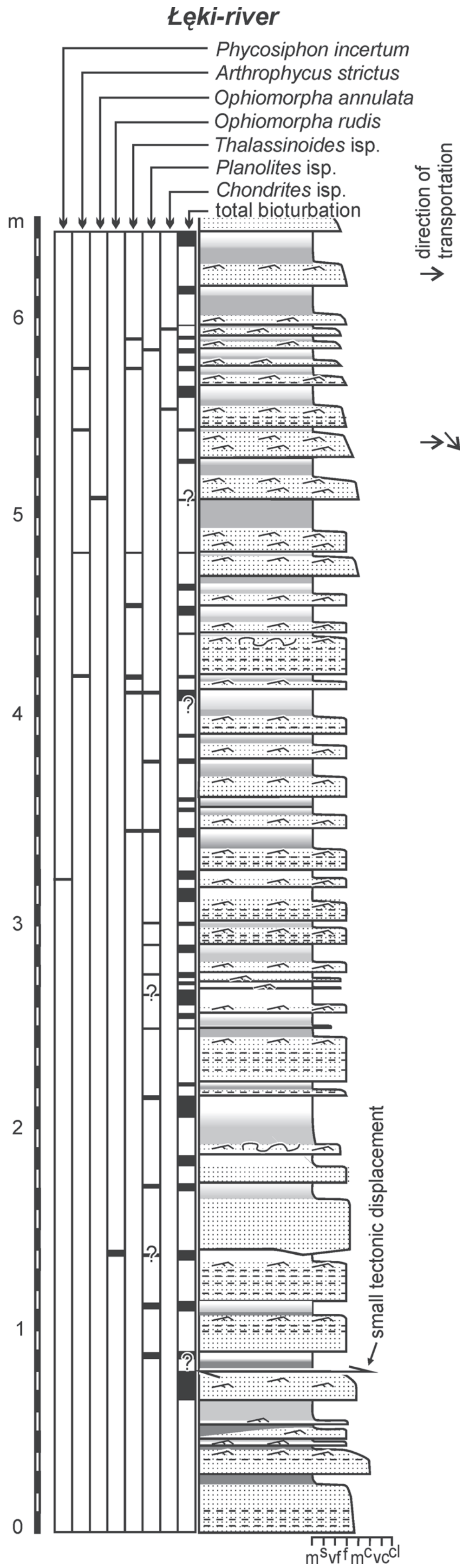

Fig. 7. Section of the "Inoceramian-type flysch" package of flysch within the Lower Istebna Beds at Łęki (Łęki-river section; for its location see Figs. 3A, 4). Legend as in Fig. 4.

included later in *Ophiomorpha* (Uchman 1995) and distinguished as *Ophiomorpha rudis* (Uchman & Demircan 1999; Uchman 2001). *Ophiomorpha rudis* (Książkiewicz 1977) is a burrow system composed of oblique to vertical shafts crossing the beds, and horizontal, irregular mazes concentrated close to bedding or amalgamation planes (Uchman 2009). The burrows are 5–18 mm in diameter, and up to at least a meter long.

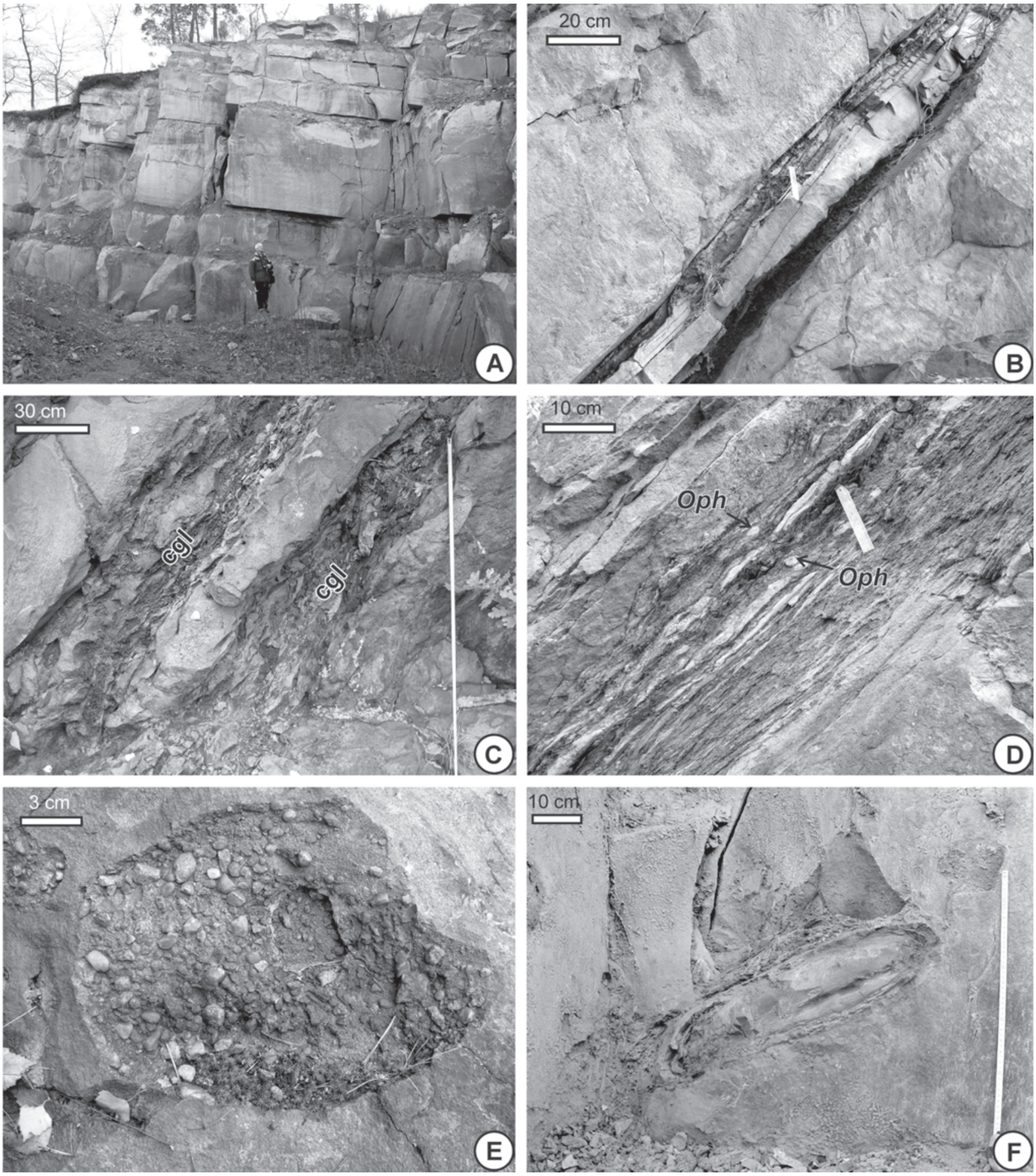

Fig. 8. Some facies features of the Lower Istebna Beds in field photographs. **A** — Thick- and very-thick-bedded sandstones in the Sobolów quarry. **B** — Sandstone-mudstone intercalations between thick sandstone beds in the Łęki-klippe section. **C** — Conglomerate beds (cgl) composed of mudstone intraclasts and muddy-sand matrix; Łęki-klippe section. **D** — Sandy mudstone rich plant detritus and very thin sandstone intercalations between thick sandstone beds in the Łęki-klippe section, burrowed with *Ophiomorpha rudis* (*Oph*). **E** — Armoured mudball (the muddy part weathered) in the Łęki-klippe section. **F** — Sideritic mudstone intraclasts in the Sobolów quarry section.

In the studied localities, *Ophiomorpha rudis* is most abundant in the uppermost part of thick beds (Fig. 9H), including the sandy, plant-detritus rich mudstone intercalations (Fig. 8D), which terminate sedimentary rhythms. It is also present in thin-bedded, occasionally discontinuous sandstone intercalations. In such places, it forms more or less horizontal to oblique galleries (called horizontal galleries further in the text) composed of straight, curved or winding, branched,

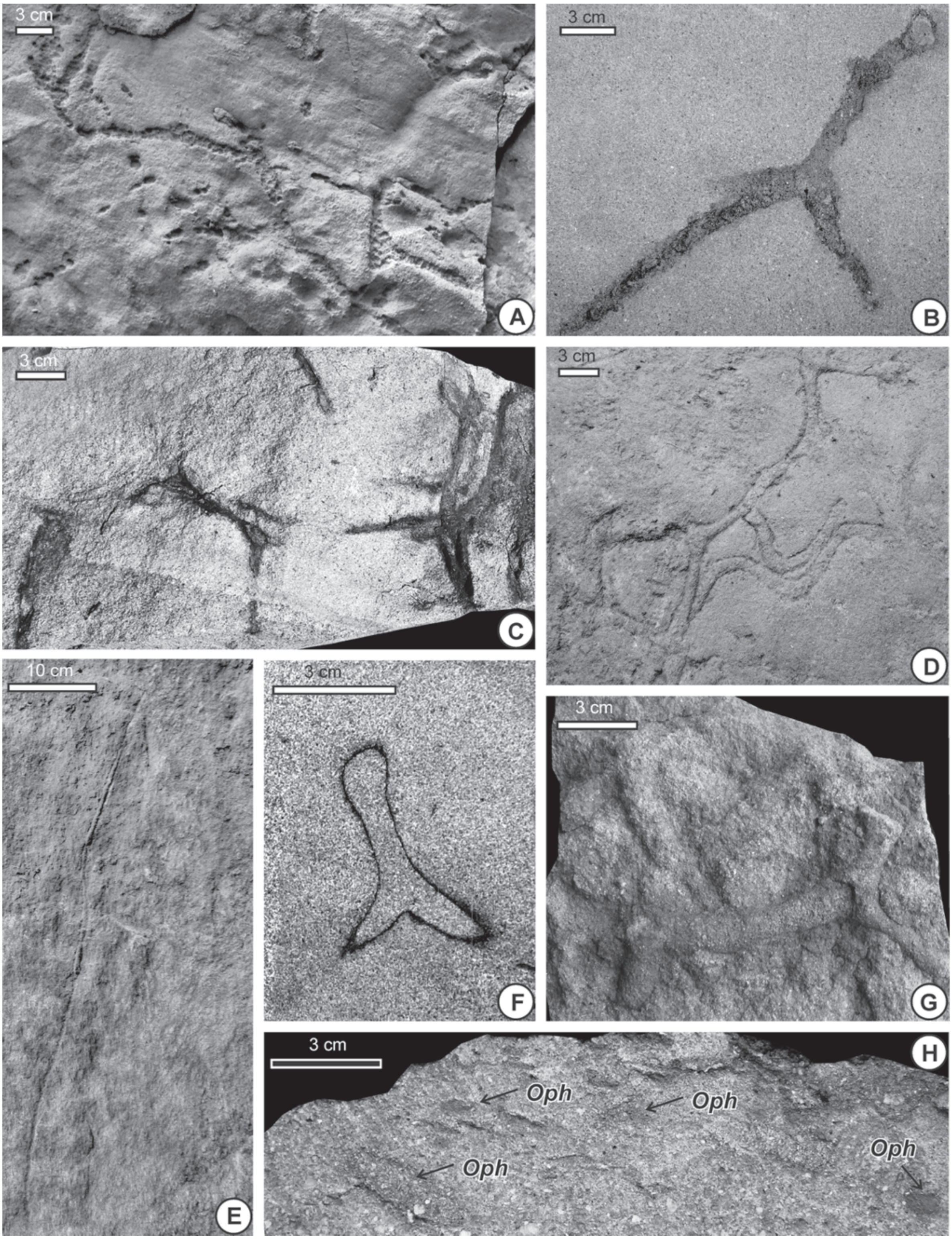

Fig. 9. *Ophiomorpha rudis* in the Lower Istebna Beds of the studies sections. **A** — Weathered tunnels with granulated wall on the lower surface of thick sandstone bed in the Łęki-klippe section. Field photograph. **B** — Sub-horizontal, thinly-lined form, filled with plant detritus-rich sandstone, in medium-bedded sandstone cut slab; Wola Komborska quarry. Stone-cutting factory at Poznachowice Dolne. Field photograph. **C** — Sub-polygonal, horizontal burrow system in the Łęki quarry. Field photograph. **D** — Branched, partly winding burrow system in the Czasław 1 quarry. Field photograph. **E** — Long, sub-vertical burrow in the Leksandrowa quarry. **F** — A branched form with ferruginized wall, probably after oxidization of pyrite. Wola Komborska quarry. Stone-cutting factory at Poznachowice Dolne. Field photograph. **G** — Thinly-lined, branched burrows; Łęki quarry, specimen INGUJ181P8. **H** — Plant detritus-rich sandstone reworked with *Ophiomorpha rudis* (*Oph*); vertical cut surface, Łęki quarry, specimen INGUJ181P12.

sand-filled tunnels (Fig. 8D), which are partly arranged in an irregular polygonal pattern (Fig. 9C,G). The hexagons are mostly 150–200 mm wide. The tunnels are 4–14 mm (most often 7–11 mm) wide. The branches are mostly Y-shaped, with only slight enlargement in the branching point. Vertical or oblique shafts, which display the same morphology and size as the horizontal galleries, cross thick sandstone beds (Fig. 8E). They are up to at least 110 cm long, rarely branched, and much less common than the horizontal galleries. In some cases, the shaft crosses more than one bed. Probably, such cases and the length of the shaft are underestimated, because exposure surfaces usually follow only a fragment of a burrow system. Judging from thickness of some beds, which contain *O. rudis* in their lower part, the total length of shafts can exceed 200 cm. The shafts join the horizontal galleries on the lower surface of the thick beds, or below in the sandy mudstones, where many branches run out, sometimes in a rosette pattern. Some shafts enter larger intraclasts and mudballs, where they can branch pointing to reworking of their sediment. In the Czasław 1 quarry, *O. rudis* crosses dish structures and up to 8 cm-thick sand veins, pointing to their early origin.

The shafts and galleries are smooth, showing sharp margins, or are lined with ashy muddy sand, or are bounded by a more distinct, locally granulated wall composed of ashy muddy sand (Fig. 9A). The granules are irregularly ovate, 1–2 mm wide. Rarely, the lining is ferruginous (Czasław 1 and Wola Komborska quarries; Fig. 9F), probably after oxidized pyrite. The shafts and galleries are filled mostly by sandstone, which is the same as in the thick beds, or different in grain size, rarely enriched in plant detritus (Fig. 9B).

Zoophycos isp. (Fig. 10I) occurs only in the Łęki quarry, 5 cm below the top of a 50 cm-thick bed. It is a spreite planar lobe, at least up to 250 mm long and at least up to 175 mm wide. *Zoophycos* was produced by an unknown organism, which collected sediment from the surface and placed it deeply in the sediment (see Bromley & Hanken 2003; Löwemark et al. 2007; and references therein for discussion). For alternative interpretations see Olivero & Gaillard 2007).

Chondrites isp. (Fig. 10A) is present at the top of the bed with *Zoophycos* isp. in the Łęki quarry and in three beds in the Wola Komborska quarry. It is seen as horizontal to oblique, branched, mud-filled, 1–2 mm wide tunnels. *Chondrites* isp. is produced by deeply-penetrating, probably chemosymbiotic organisms (see Fu 1991; Uchman 1999, and references therein).

Trace fossils in thin- and medium-bedded flysch of the Lower Istebna Beds

In the "Inoceramian-type flysch" (see geological setting) in the Łęki-river section, *Planolites* isp., *Chondrites* isp., *Phycosiphon incertum*, *Arthrophycus strictus*, *Thalassinoides* isp., *Ophiomorpha annulata*, *O. rudis* and *Scolicia strozzii* have been found. *Planolites* isp. is common, other trace fossils are rare. *Planolites* isp. also occurs in a very thin intercalation of greenish mudstone in the Czasław 1 quarry and in greenish grey and greenish mudstones or on soles of overlying sandstone beds in the lower part of the Czasław 2 quarry section.

In the non-calcareous thin-bedded package in the higher part of the Wola Komborska section, in loose slabs of thin-bedded sandstones, *Helminthorhaphe flexuosa* was found. Moreover, *Chondrites* isp. occurs here.

Arthrophycus strictus Książkiewicz, 1977 (Fig. 10D) is a tubular, dichotomously branched, hypichnial burrow, 3–3.5 mm wide, locally covered with thin, perpendicular striae. The branches are up to 30 mm long. For discussion of this trace fossil see Uchman (1998).

Helminthorhaphe flexuosa Uchman, 1995 (Fig. 10B) is a hypichnial, 1 mm wide, meandering string. The meanders are at least 40 mm deep, and 3.5–5 mm wide, and show gentle, second-order undulations. For discussion of *Helminthorhaphe* see Uchman (1995).

Phycosiphon incertum Fischer-Ooster, 1858 (Fig. 10E,G) is manifested as thin, curved tunnels, 0.8–1 mm wide, which form 3–4 mm wide and up to12 mm long lobes. For discussion of *Phycosiphon* see Wetzel & Bromley (1994).

Planolites isp. (Fig. 10F–H) is a tubular, unlined, variably oriented burrow, 1.5–2 mm, rarely up to 4 mm in diameter. It is observed as hypichnial semi-reliefs (Fig. 10F) in sandstone beds above shales, or as endichnial full reliefs (Fig. 10G–H) in greenish-grey and greenish mudstones, where it gives spotty fabric (darker oval spots on lighter background) in cross section. For discussion, see Pemberton & Frey (1982) and Keighley & Pickerill (1995).

Thalassinoides isp. (Fig. 10F) occurs as hypichnial branched ridges, 8–15 mm wide, which are preserved in semi-relief. For discussion of *Thalassinoides* see Frey et al. (1984).

Ophiomorpha annulata (Książkiewicz, 1977) (Fig. 10C) is a horizontal, 2–4 mm thick, branched, sand-filled tunnel, which was found at the base of a 12 cm thick sandstone bed. For more data on this ichnospecies see Uchman (1995).

Scolicia strozzii (Savi & Meneghini, 1850) (Fig. 10F) is winding, smooth, bilobate hypichnial ridge, about 25–27 mm wide, divided by a semicircular axial furrow that occupies most of the ridge width. The structure is preserved in semi-relief in fine-grained sandstone turbidites. This ichnospecies was described as *Taphrhelminthopsis* Sacco or *Taphrhelminthoida* Książkiewicz in the earlier literature, but is considered to be a casted washed-out shallow *Scolicia*, a burrow attributed to irregular echinoids (Uchman 1995).

Ophiomorpha rudis (Książkiewicz, 1977) and *Chondrites* isp. display the same features as in the thick-bedded sediments (see the previous chapter).

Discussion

The presented data and the data from the literature (Table 1) show that the trace fossil assemblage from the Lower Istebna Beds is low in diversity, and most ichnotaxa occur rarely. The total of 17 ichnogenera occurring in the Campanian–Maastrichtian Lower Istebna Beds is only half the number for the maximum diversity in flysch sediments at that time (Uchman 2007).

The trace fossil assemblage in the thick-bedded sandstone is dominated by *Ophiomorpha rudis*. However, it is absent in

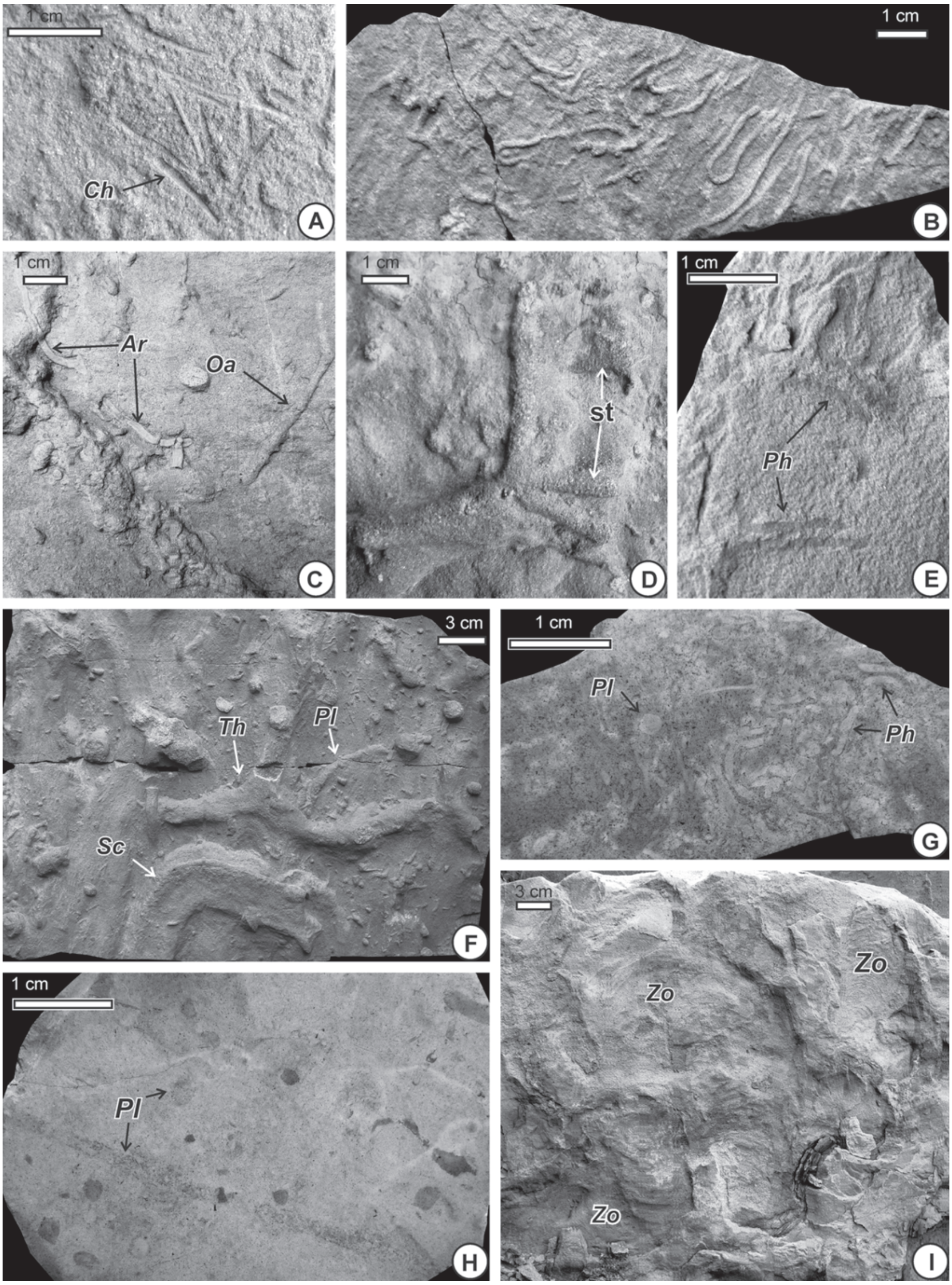

Fig. 10. Trace fossils of the Lower Istebna Beds of the studied sections. **A** — *Chondrites* isp. (*Ch*), bedding surface, Łęki quarry, specimen INGUJ181P4. **B** — *Helminthorhaphe flexuosa*, lower bedding surface, Wola Komborska quarry, specimen INGUJ181P49. **C** — *Ophiomorpha annulata* (*Oa*) and the large protest *Arthrodendron maguricum* (*Ar*) on the lower bedding surface, the "Inoceramian-type flysch" beds, Łęki-river section, field photograph. **D** — *Arthrophycus strictus* showing perpendicular striae (st), hypichnion, the "Inoceramian-type flysch" beds, Łęki-river section, specimen INGUJ181P24. **E** — *Phycosiphon incertum* (*Ph*), endichnion on parting surfaces, the "Inoceramian-type flysch" beds, Łęki-river section, specimen INGUJ181P47. **F** — *Thalassinoides* isp. (*Th*), *Scolicia strozzii* (*Sc*) and *Planolites* isp. (*Pl*) on the lower bedding surface, the "Inoceramian-type flysch" beds, Łęki-river section, loose slab, specimen INGUJ181P25. **G** — *Phycosiphon incertum* (*Ph*) and *Planolites* isp. (*Pl*) in mudstone, horizontal polished and oiled surface, Sobolów quarry, specimen INGUJ181P57. **H** — *Planolites* isp. (*Pl*) in totally bioturbated mudstone, horizontal polished and oiled surface, Sobolów quarry, specimen INGUJ181P56. **I** — *Zoophycos* isp. (*Zo*) in the upper part of sandstone bed; Łęki quarry, field photograph.

many beds. Other trace fossils are very rare. This is probably caused by the dominant sandy substrate, which was successfully colonized only by the *Ophiomorpha* tracemaker, probably a decapod crustacean (Uchman 2009). Most flysch trace makers lived in mud (Kern 1980; Uchman 1998). The crustacean trace maker of *Ophiomorpha rudis* burrowed deeply to reach buried muddy sands and sandy mudstones, including these rich in plant detritus. It is supposed that the trace maker fed on the plant detritus with microbially decomposed cellulose below the redox boundary (Uchman 2009). Probably, the decomposed plant detritus was not the exclusive diet of the crustaceans. Nevertheless, *O. rudis* can be considered as a domichnial-fodinichnial burrow system. The discussed assemblage can be ascribed to the Ophiomorpha rudis ichnosubfacies of the Nereites ichnofacies, which is typical of channel facies and proximal depositional lobes in the deep-sea fan models (Uchman 2001, 2009). However, more than half of the studied sections do not show the characteristic thickening/coarsening up packages typical of prograding depositional lobes or the typical thinning/fining up packages typical of channel fills (see Mutti & Ricci Lucchi 1972; Walker 1978). The sections (Figs. 4–7) show rather an aggradation pattern (Czasław 1 quarry, Sobolów quarry, lower-middle part of the Łęki-klippe sections), with only occasional thin channel-type packages (lower part of the Łęki quarry, upper part of the Wola Komborska quarry sections), or with thin prograding depositional lobes (uppermost part of the Łęki-klippe and Czasław 2 quarry sections). However, the thickening-up packages can also be interpreted as the crevasse splay sediments of meandering channels in the sense of deep-water sedimentation (e.g. Posamentier & Walker 2006). The aggradation-type arrangement of beds fits well into the model of a siliciclastic ramp or apron (Stow et al. 1996 and references therein) that formed in proximity to its clastic material source, as proposed for the Lower Istebna Beds in the western part of the Polish Flysch Carpathians (Strzeboński 2003). Such deposits are formed from non-turbulent gravitational flows, sandy-debris or turbiditic flows, or cohesive debrites in the case of the pebble mudstones (Strzeboński 2005). Thus, sand rich ramps and slope aprons, or crevasse splays can be added as new places for the Ophiomorpha rudis ichnosubfacies occurrence.

The medium- and thin-bedded flysch packages in the Lower Istebna Beds display the impoverished Nereites ichnofacies. Several beds do not contain any trace fossils. The presence of the graphoglyptid trace fossil *Helminthorhaphe* in the Wola Komborska quarry, *Helminthorhaphe* and *Paleodictyon* in the "Inoceramian-type facies" at Czchów (20 km SE of the area C in Fig. 1; Table 1) suggest the Paleodictyon ichnosubfacies of the Nereites ichnofacies, which is typical of the overchannel, distal depositional lobe and inter-lobe facies (Uchman 2004; Uchman & Wetzel 2011). However, relatively low diversity (not more than three ichnotaxa in one bed) and scarcity of graphoglyptids suggest the impoverished Paleodictyon ichnosubfacies. The impoverishment can be caused by lowered oxygenation, high sedimentation rate causing frequent disturbances of the sea floor, and probably by limited areas of muddy sea floor. The lowered oxygenation can be important for some beds, in which shales display dark colour and low degree of bioturbation (Łęki-river section). Książkiewicz (1977) mentioned that beside coarse sediments, black shales (implying low oxygenation) are the most important factors limiting diversity of trace fossils in the Lower Istebna Beds. However, more detailed studies on oxygenation changes in the Lower Istebna Beds have not been done so far. Frequent disturbances of the sea floor, for example by scouring, can limit re-establishment of ichnofauna. Most of flysch ichnofauna live in mud (Kern 1980). Therefore, limited areas of muddy sea floor between sandy areas, provided little space for their development.

Conclusions

1. Thick- and very thick-bedded sandstones of the Lower Istebna Beds contain mainly *Ophiomorpha rudis*, rarely *Zoophycos* isp. and *Chondrites* isp. This assemblage is typical of the Ophiomorpha rudis ichnosubfacies of the Nereites ichnofacies. The Ophiomorpha rudis ichnosubfacies range can be extended to deep-sea clastic ramps and aprons, which are interpreted as paleoenvironment in a part of the Lower Istebna Beds.
2. The medium- and thin-bedded packages of flysch sandwiched between the thick-bedded sandstones contain *Chondrites* isp., *Phycosiphon incertum*, *Planolites* isp., *Arthrophycus strictus*, *Thalassinoides* isp., *Ophiomorpha annulata*, *O. rudis*, *Scolicia strozzii*, and *Helminthorhaphe flexuosa*. This assemblage, together with the published data, is interpreted as the impoverished Paleodictyon ichnosubfacies of the Nereites ichnofacies. The impoverishment is influenced by limited areas of muddy substrate and partly influenced by lowered oxygenation.

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