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CONIACIAN–?SANTONIAN PARALIC SEDIMENTATION IN THE RAKOWICE MAŁE AREA OF THE NORTH SUDETIC BASIN, SW POLAND: SEDIMENTARY FACIES, ICHNOLOGICAL RECORD AND PALAEOGEOGRAPHICAL RECONSTRUCTION OF AN EVOLVING MARINE EMBAYMENT

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Abstract: The Coniacian–?Santonian siliciclastic succession outcropped in a sandstone quarry at Rakowice Małe (Żerkowice Member of the Rakowice Wielkie Formation, and the Czerna Formation including the Nowogrodziec Member; North Sudetic Basin, SW Poland) provides an interesting example of paralic deposits. Lithofacies and ichnofossil examination indicate coastal, lacustrine, paludal and lagoonal sedimentation. Valuable new data are supplied by trace fossils, a feature not considered yet in the literature on the Upper Cretaceous of the North Sudetic Basin. Trace fossils are overall abundant in the upper part of the Nowogrodziec Member and overlying part of the Czerna Formation. The following ichnogenera: *Thalassinoides*, *Ophiomorpha*, *Asterosoma*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teredolites*, *Chondrites*, *Cylindrichnus*, *Arenicolites*, *Rosselia*, *Teichichnus*, *Phycodes*, *Phycosiphon*, and *Schaubcylindrichnus* are represented. The trace fossils represent the *Skolithos*, *Teredolites* and *Cruziana* ichnofacies. The *Cruziana* Ichnofacies is typified by the richest trace fossil assemblage characteristic of its archetypal, proximal and stressed expressions.

An upper shoreface to foreshore origin of these sediments is documented using lithofacies and the ichnofossils *Ophiomorpha* and *Thalassinoides* in the exposed part of the Żerkowice Member. Dominance of kaolinite, lack of burrows and upward passage into paludal deposits is interpreted to indicate a lacustrine origin of variegated clayey mudstone at the base of the Nowogrodziec Member. The changes of depositional environments are interpreted as resulting from separation of the area from the open sea by a sand barrier formed due to the termination of the forced regression. Siltstones containing plant roots and fragments of drifted wood showing the trace fossil *Teredolites clavatus*, together with coal-seams containing *Thalassinoides* isp., are assigned to indicate a coastal plain, paludal deposition of the overlying part of the Nowogrodziec Member and incursion of marine waters. The fining upward sequence constituting the top part of the Nowogrodziec Member and showing almost archetypal *Cruziana* Ichnofacies substituted by its expression indicative of highly stressed, brackish conditions are shown to indicate extensive drowning of the area and lagoonal sedimentation. Termination of the drowning, embodied in a maximum flooding surface, is indicated in a bed of coaly mudstone at the top of the Nowogrodziec Member. Sedimentation on a periodically prograded brackish bay shoreface is inferred from lithofacies, ichnofossils and body fossils for the deposits overlying the Nowogrodziec Member and topping the examined succession. The trace fossils indicate *Cruziana* Ichnofacies and *Skolithos* Ichnofacies in the expression of slightly stressed environments. The whole examined part of the Czerna Formation is interpreted as a fifth-order transgressive-regressive cycle.

Key words: shallow-marine, paludal, lagoonal, brackish eninronments, bioturbation, ichnofossils, Cretaceous, Lower Silesia, Poland.

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INTRODUCTION

The Cretaceous of the North Sudetic Basin (SW Poland) constitutes a relatively well recognized sedimentary succession built by siliciclastic and carbonate deposits of epiplatform marine and paralic origin (see Milewicz, 1997). The recognition concerns mainly gross lithofacies, body fossils, stratigraphic architecture and general sediment ori-

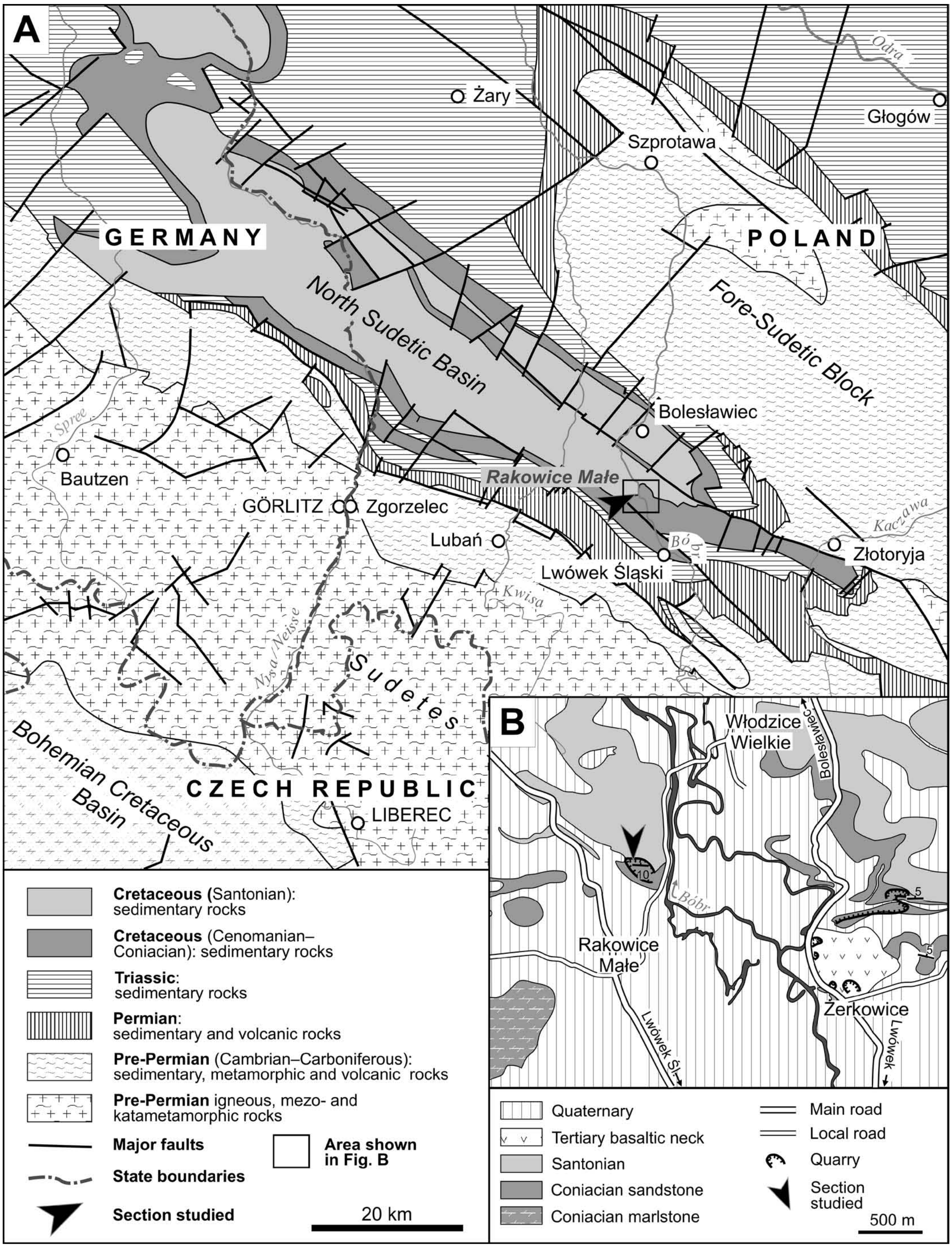

Fig. 1. Geographical and geological location of the studied section. **A** – Location of the studied section relative to the North Sudetic Basin and its surroundings, without Cenozoic formations, compiled after Milewicz (1997) and Pożaryski *et al.* (1984). **B** – Detailed location of the studied section; compiled from Milewicz (1959) and Grocholski (1956)

gin, and ensues from investigations conducted since the end of the eighteen century. Such a long history of investigations is owed to picturesque landforms built by sandstones of this succession and the economic value of some of its parts (building stone, kaolin). Data on body fossils, lithofacies and stratigraphic architecture of the succession formed the basis of previous interpretations of sediment origin and palaeogeography of the area. Recent investigations by the author revealed some new information on sedimentation development of the succession recorded particularly in bioturbation structures. The most interesting data were collected in the active sandstone quarry (Rakowiczki Quarry) located in the village of Rakowice Małe (Fig. 1), mainly in the upper part of the succession fragment cropping out there, which was included by Mazur and Milewicz (1958) in the Santonian (Nowogrodziec Member, Czerna Formation *sensu* Milewicz, 1985). This quarry has been known for a long time for exposing the Upper Cretaceous sediments of

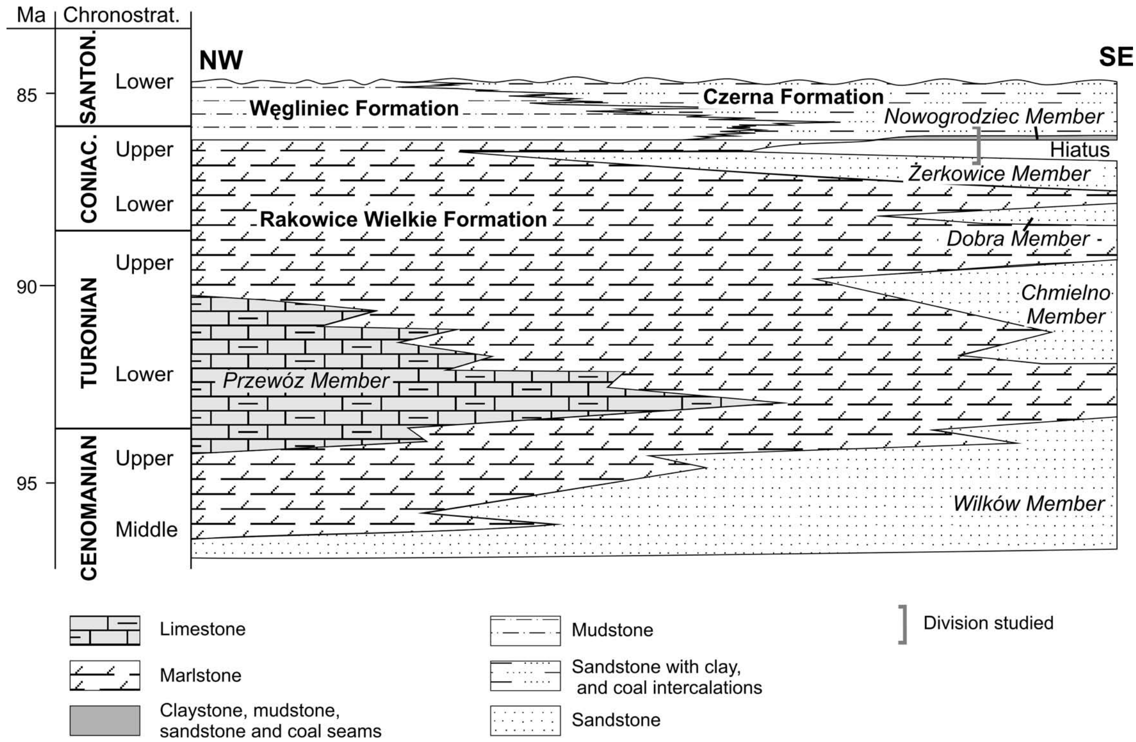

Fig. 2. Stratigraphic scheme of the Cretaceous in the axial crossection of the North Sudetic Basin. Lithostratigraphy after Milewicz (1997), chronostratigraphy after Walaszczyk (2008). According to Milewicz (1997), the lower boundary of the Czerna Formation and Węgliniec Formation is located at the Coniacian/Santonian boundary

marine and non-marine origin (see Drescher, 1863; Scupin, 1912–1913; Milewicz, 1956; Mazur & Milewicz, 1958).

This paper (1) shows features of the Cretaceous sedimentary succession outcropping in the quarry, with particular reference to bioturbation structures, and (2) interprets the depositional environment on the basis of lithofacies and trace fossils. Sea retreat followed by new drowning of the area and consequent environmental changes ranging from lacustrine-paludal to coastal marine are described. The ichnological record of the incursion of marine waters is demonstrated. Some data on lithofacies and trace fossils of the sandstone unit that constitutes the lower part of the investigated succession fragment (Żerkowice Member, Rakowice Wielkie Formation, *sensu* Milewicz, 1985) were collected in the neighbouring quarry located 2 km east, at the village of Żerkowice. This paper provides the first study of these deposits, which broadly considers ichnological features.

LOCATION AND STRATIGRAPHY

The studied section is located in southwestern Poland, north of the Sudetes Mountains, *ca.* 7 km north of the town of Lwówek Śląski, in the southeastern part of the North Sudetic Basin (Fig. 1). The North Sudetic Basin represents one of several basins developed in the mid-Cretaceous times within and around the Bohemian Massif, due to a stress field generated by relative movements of the African and European plates. The basins were formed through reactivation of older, mainly Variscan shear zones dissecting the Bohemian Massif and its peripheries. The North Sudetic Basin forms a southeastern continuation of the East Brandenburg Basin.

The Cretaceous succession forms the youngest part of a discontinuous sedimentary infill of the North Sudetic Basin. The succession comprises Cenomanian through Santonian sandstones, marlstones and mudstones with some admixture of other rock types, primarily limestones (see Milewicz, 1997). The deposits show distinct vertical and lateral variability (Fig. 2) discerned finally through drillings. Stratigraphic architecture of the succession has been variously interpreted (see Milewicz, 1997). The German geologists who investigated these rocks first, termed the sandstone units Quadersandstein (Beyrich, 1849), *i.e.* similarly as equivalent units of other regions. The current lithostratigraphy was proposed by Milewicz (1985), who subdivided the succession into three formations. The lower part of the succession, that embracing the sandstone units together with marlstones separating and coeval with the sandstones, as well as coeval limestones, was distinguished as the Rakowice Wielkie Formation. The sandstone units were classified as separate members. The upper one, forming the base of the section investigated in this paper, was named the Żerkowice Member. The overlying deposits, characterised by noncalcareous fine-grained components, were subdivided into two laterally equivalent formations called respectively the Węgliniec Formation and the Czerna Formation. The former is characterised almost exclusively by mudstones, whereas the latter comprises sandstones with intercalations of clays and thin coal seams. The lowermost part of the Czerna Formation, 2 to 50 m thick, dominated by clays, was distinguished as the Nowogrodziec Member. The Nowogrodziec Member occupies the southeastern part of the North Sudetic Basin, east of the Kwisa river (see Milewicz, 1965). This member, together with several metres of the overlying Czerna Formation, are the main object of this study.

The first newfangled dating of the whole Cretaceous of the North Sudetic Basin was proposed already in the middle of the 19th century by Beyrich (1855). He interpreted the succession as Cenomanian–Senonian. Milewicz (1958) suggested a Santonian age for the upper part of the succession embracing the later distinguished Czerna Formation and Węgliniec Formation. Krutzsch (1966) specified the age of this part of the succession as lower Santonian. Milewicz (1956, 1979) suggested occurrence of a hiatus embracing the upper Emscherian (upper Coniacian according to Milewicz, 1997) in the southeastern part of basin, that is, in the area where the sandstone unit, later called the Żerkowice Member, is overlain by deposits distinguished later as the Nowogrodziec Member. According to the data presented by Milewicz (1956), the site described in this paper also belongs to this area.

Slightly different chronostratigraphy of the succession in question has been recently indicated by Walaszczyk (2008). The boundary between the Rakowice Wielkie Formation and the overlying formations has been located at the middle/upper Coniacian transition. The Coniacian/Santonian boundary has been placed in the middle of the Czerna and Węgliniec Formations. Nevertheless, the distribution of the Santonian has been shown according to Milewicz (1997) with one unclear exception of a small area along the Bóbr river. The hiatus has been shown to be entirely middle Coniacian. Unfortunately, the changes have not been commented in the paper, and therefore, in this paper, chronostratigraphy proposed by Milewicz (1985) is used but is annexed with question marks. One has to note that in the stratigraphic scheme indicated by Walaszczyk (2008), marlstones extend over the whole Żerkowice Member, whereas Milewicz (1997) has shown that in the southeastern part of the North Sudetic Basin, the Żerkowice Member is overlain with a hiatus by noncalcareous fine-grained deposits of the Nowogrodziec Member. The paper will demonstrate that it is Milewicz's opinion which is here correct.

The whole Cretaceous succession of the North Sudetic Basin is as much as 1300 m thick (Milewicz, 1991). Its greatest thickness is recorded in the central part of the basin. The deposits rest transgressively on Triassic deposits, mainly on the Buntsandstein. Only in the Wleń Graben (southeast of Lwówek Śląski), the Cretaceous strata overlie Rotliegendes and older Palaeozoic rocks (see Milewicz, 1997). The section studied in this paper is located at the southern border of the area occupied by deposits interpreted by Milewicz (1958) as Santonian in age.

DEPOSITIONAL SETTING AND PALAEOGEOGRAPHY: PREVIOUS INTERPRETATIONS

The Cretaceous of the North Sudetic Basin has been known since the 19th century as of marine and paralic origin. The interpretations were based mainly on lithofacies and body fossils. A marine origin was indicated for the deposits of the recently named Rakowice Wielkie Formation and the Węgliniec Formation (see Milewicz, 1997). Later on, the sandstone units of the Rakowice Wielkie Formation were interpreted as laid down in shoreface to foreshore environments whereas an offshore setting was indicated for the units dominated by marlstones, limestones and mudstones. Lacustrine and swamp sediments were recognised in the Nowogrodziec Member, and a deltaic to alluvial milieu was suggested for the overlying part of the Czerna Formation (see Milewicz, 1997).

Data on stratigraphy, gathered throughout the long period of investigation, show that sedimentation of the North Sudetic Cretaceous began during the worldwide Cenomanian transgression and continued at least until the middle Santonian (see Milewicz, 1997; Walaszczyk, 2008). The stratigraphic architecture of the deposits has been interpreted since the beginning of the 20th century as reflecting palaeogeographic changes of the region. Partsch (1896) suggested connection of the North Sudetic Basin with the Bohemian Basin during the Late Cretaceous. Scupin (1910) argued that deposition of the Cretaceous deposits of the North Sudetic Basin took place in a southeast-northwest trending basin (North Sudetic Basin) bordered by elevated areas forming islands to the northeast and southwest. The elevated areas were called by him, respectively, Ostsudetische Landmasse and Riesengebirgsinsel. He also advocated connection of the North Sudetic Basin with the Central Sudetic Basin (Intrasudetic Basin) since the late Cenomanian. Later on, Scupin (1912–1913) recognized passage of sandy deposits into marlstones to the northwest of the basin, and consequently indicated the direction of basin deepening. Andert (1934) also pointed out two land masses in the Sudetes during the sedimentation of the Sudetic Cretaceous deposits. However, the land mass indicated as bordering the North Sudetic basin on southwest was suggested to consist of two islands, called by him respectively Lausitz Insel and Riesengebirges Insel. The other one was indicated as a small island located southeast of the North Sudetic Basin and embracing a small part of the area inferred by Scupin (1910) to constitute the Ostsudetische Landmasse. This island was called by the author the Eulengebirges Insel. In the same paper, Andert also indicated complete drowning of the islands periodically.

Actually, the framework of palaeogeography suggested by Scupin (1910) remains still valid. Subsequent changes resulted from some alterations of stratigraphy and new data on facies distribution in the succession. Indication of a hiatus embracing the upper Coniacian in the southeastern part of the basin (Milewicz, 1956), as well as new data on stratigraphy and facies distribution gained from the northwestern part of the basin (Milewicz, 1965, 1966, 1973; Milewicz *et al.*, 1968) were of particular significance. Milewicz (1997) suggested a northwestward retreat of the sea, almost from the whole basin, during final stages of sedimentation of the Żerkowice Member. The emerged area was claimed to be eroded during the late Coniacian. The overlying deposits of the Czerna Formation were interpreted by Milewicz (1958) as deposited since beginning of the Santonian. According to Walaszczyk (2008), the hiatus embraced only part of the middle Coniacian. The new sedimentation episode started with deposits interpreted earlier as lacustrine (Milewicz, 1956, 1965, 1970, 1997), and then as paludal (Milewicz, 2006). This type of sedimentation was followed by brackish marine and deltaic deposits accumulated at least until the middle Santonian (Milewicz, 1956, 1965, 1970, 1997, 2006). The Ostsudetische Landmasse is now called East Sudetic Island, whereas the Riesengebirgsinsel is called West Sudetic Island. Musstow (1968) pointed out the connection of the North Sudetic Basin with the East Brandenburg Basin for the whole duration of the north Sudetic Cretaceous sedimentation. In general, the previous papers show that the stratigraphic architecture of the North Sudetic Cretaceous reflects an interplay between sediment supply, accommodation space and eustasy. According to Milewicz (1997), the Coniacian–Santonian deposits of the North Sudetic Basin represent the top part of a regressive phase of a transgressive-regressive cycle (T-R cycle) and basal part of a transgressive phase of a next T-R cycle. Walaszczyk (2008) suggested that the Cretaceous of the North Sudetic Basin represents one major T-R cycle consisting of several minor, not yet defined cycles. The Czerna Formation and Węgliniec Formation were considered in that paper to represent the final, complex regressive phase of the minor transgressive-regressive cycles.

METHODS

The succession was analysed macroscopically for rock features in the whole quarry and logged in detail in several sections. Depending on character, the rock features were measured, described and photographed. The description included bioturbation style and intensity, trace fossil assemblage, interrelations and relations to sediment. Trace fossils as well as ichnofabric were examined on rock surfaces, both bedding-parallel and oblique, leveled with knife and spatula. Highly bioturbated soft, coaly mudstone (rash) grading to sandstone, located at the passage from the Nowogrodziec Member to the overlying part of the Czerna Formation was investigated for ichnofabric and trace fossil features through gradual removing of sediment from a surface of ca. 80 cm^2 in a 35 cm thick division. Trace fossils were determined mainly at the ichnogenus level as most of them were recorded in cross-sections only. Ichnotaxa determined at the ichnogenus level are mentioned in the text as for example, *Thalassinoides* isp. indet. Field work was carried out in the years 2007–2009.

Clayey mudstone from the lowermost bed of the Nowogrodziec Member was investigated for mineral composition using the XRD method, in three samples, at the Institute of Geological Sciences, Jagiellonian University. Mudstone at the top of Nowogrodziec Member as well as mudstone from the overlying part of the Czerna Formation were investigated in 5 samples for microfossils. The investigations were performed in samples disintegrated through immersion in water solution of Glauber's salt and repeated crystallisation and solution of salt and then washed with tap water on a 0.09 mm sieve.

RESULTS

General characteristics of the sedimentary succession

The Cretaceous deposits outcropping in the quarry at Rakowice Małe include a sedimentary succession some 25 m thick (Figs 3A, 4). Its lower half is composed of massive sandstone that constitutes the proper goal of local mining and represents the Żerkowice Member. The sandstone shows vertical jointing with small dislocations and open fractures. The overlying half of the succession, being the main object of this study, occurs exclusively in the northern wall of the quarry. It is composed of claystones, mudstones, siltstones and sandstones, and three thin coal seams. The deposits show small lateral facies changes. They represent the Czerna Formation. Their lower part, 5.5 m thick, reaching up to the top of a 1 m thick mudstone bed, represents the Nowogrodziec Member. The entire succession dips gently (10°) to the north. It is exposed here nearly along strike, for a distance of about 200 m. However, the western part of the quarry became a waste rock damp and the lower part of the succession becomes gradually buried. The succession is undeformed, except for a duplex structure in the lower half of the Nowogrodziec Member (Fig. 3A, B). Moreover, two closely spaced thrust faults embracing the upper half of the Nowogrodziec Member occur in the western sector of the quarry (Fig. 3C). Fault planes, both in the duplex and the thrust faults are inclined to the northwest, that is, along the strike. The duplex was described by Milewicz (1956) as a fossil slump resulting from synsedimentary westward tilting of the area.

Detailed sedimentological and ichnological description

The Żerkowice Member

The sandstone of the Żerkowice Member (unit 1 in Fig. 4) is fine to medium-grained, subordinately coarse-grained, light grey to light orange, quartzose, weakly cemented arenite. It is massive to faintly parallel-stratified and large-scale cross-stratified (Fig. 5). Stratification is apparent almost exclusively on weathered surfaces located ca. 1 m below the top of the member. Cross-stratification occurs in sets 20 to 30 cm thick, which reveal high-angle to low-angle, trough and tabular varieties (Fig. 5C, D). Stratification is marked by minor change in grain size. Foresets dip mainly to the south and southeast. Careful inspection of rock walls allows one to recognize the occurrence of various-scale erosional surfaces randomly distributed in the succession.

Bedding surfaces covered with bioturbation structures were recorded in four loose sandstone blocks. These were exclusively dispersed horizontal burrows. In three blocks, these were burrows determined as *Thalassinoides* isp. (Fig. 6A). They were 8–10 mm wide and displayed Y-shaped and T-shaped branching. In some places, the burrow wall showed knobby protrusions. In one block, structures in a form of irregularly outlined, convex upward lumps, 1 to 5 cm in cross section were recorded (Fig. 6B). Moreover, one vertical *Ophiomorpha nodosa* Lundgren, 1891 was recorded in the sandstone *in situ*. In the neighbouring quarry

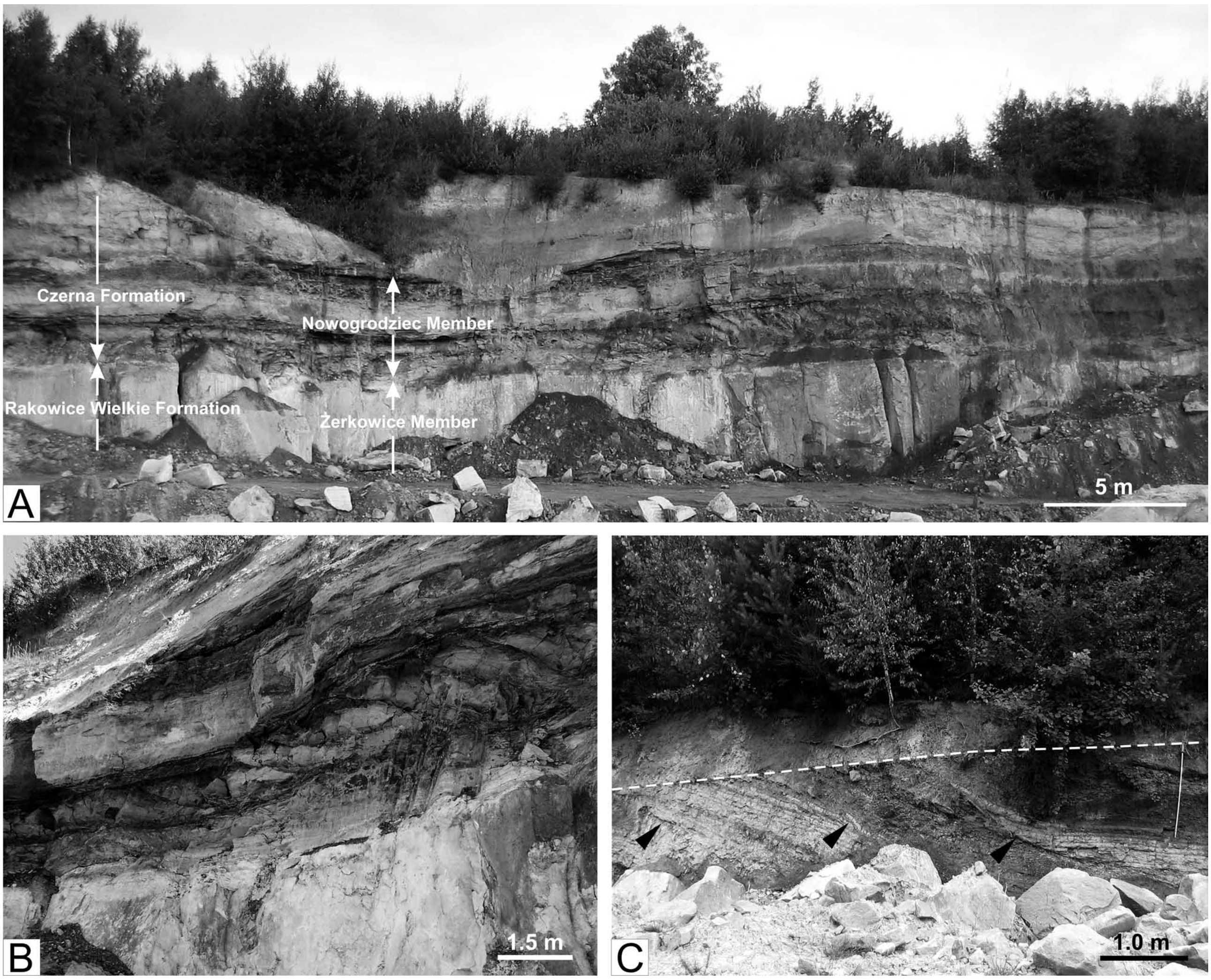

Fig. 3. Cretaceous succession in central fragment of northern wall of quarry. **A** – General view; state in May, 2007. The wall is as much as 15 m high. Note duplex structure on right side of photo, in the lower part of Nowogrodziec Member. **B** – Close-up view of duplex. **C** – Close-up view of three small thrusts (black arrows) in top part of Nowogrodziec Member. Member's top indicated by long dashed line. Walking stick (white encircled) 1.1 m long, as a scale. Western part of southern wall of quarry in July, 2007

at Żerkowice, the sandstone is richer in trace fossils and their variability is higher there. Most distinct are there horizontal burrow systems of *Thalassinoides* isp. and *Ophiomorpha nodosa*. In total, the trace fossil assemblage recorded in the examined deposits represents the *Skolithos* Ichnofacies in its expression indicative of stressed environments. The assemblage dominated by horizontal burrows including the ichnogenera *Ophiomorpha* and *Thalassinoides* infer the *Skolithos* Ichnofacies in its distal expression (see MacEachern *et al.*, 2007a).

The top of the Żerkowice Sandstone Member is sharp, generally flat and covered with orange-brown ironstone (limonite) crust, as much as 3 cm thick. This crust passes downward into an irregular zone of orange to yellow stained sandstone, up to 15 cm thick (Fig. 7). In one place, a 40 cm thick, top part of the sandstone appeared to display faint cross-stratification. In other places, the top part of the sandstone appeared to show slightly more irregular texture than that of the lower-lying part.

The Nowogrodziec Member

The ironstone crust is overlain by clayey mudstone commencing the Nowogrodziec Member of the Czerna Formation (unit 2 in Fig. 4). The mudstone forms a 0.65 m thick bed showing white, light-grey, cherry-red and rusty banding, streaking and mottling that extends generally parallel to bedding. White mudstone, 13–15 cm thick, rests immediately on the ironstone crust and is merged with it by a 1 cm thick transition zone. The white mudstone is overlain by a several centimetres thick purple-red band. The purple-red mudstone within a small flexure displays vertically elongated, root-like structures marked with white colouration. X-ray diffraction analysis of three samples revealed that this is a kaolinite dominated deposit (kaolinite content: 51.48, 54.7, 55.48 wt %). The clayey mudstone passes upward into a 70 cm thick bed of mottled, brown mudstone containing a 15–20 cm thick layer of mottled siltstone to fine-grained sandstone in its lower part (unit 3 in Fig. 4). The deposits show dispersed fragments of coalified plants of different

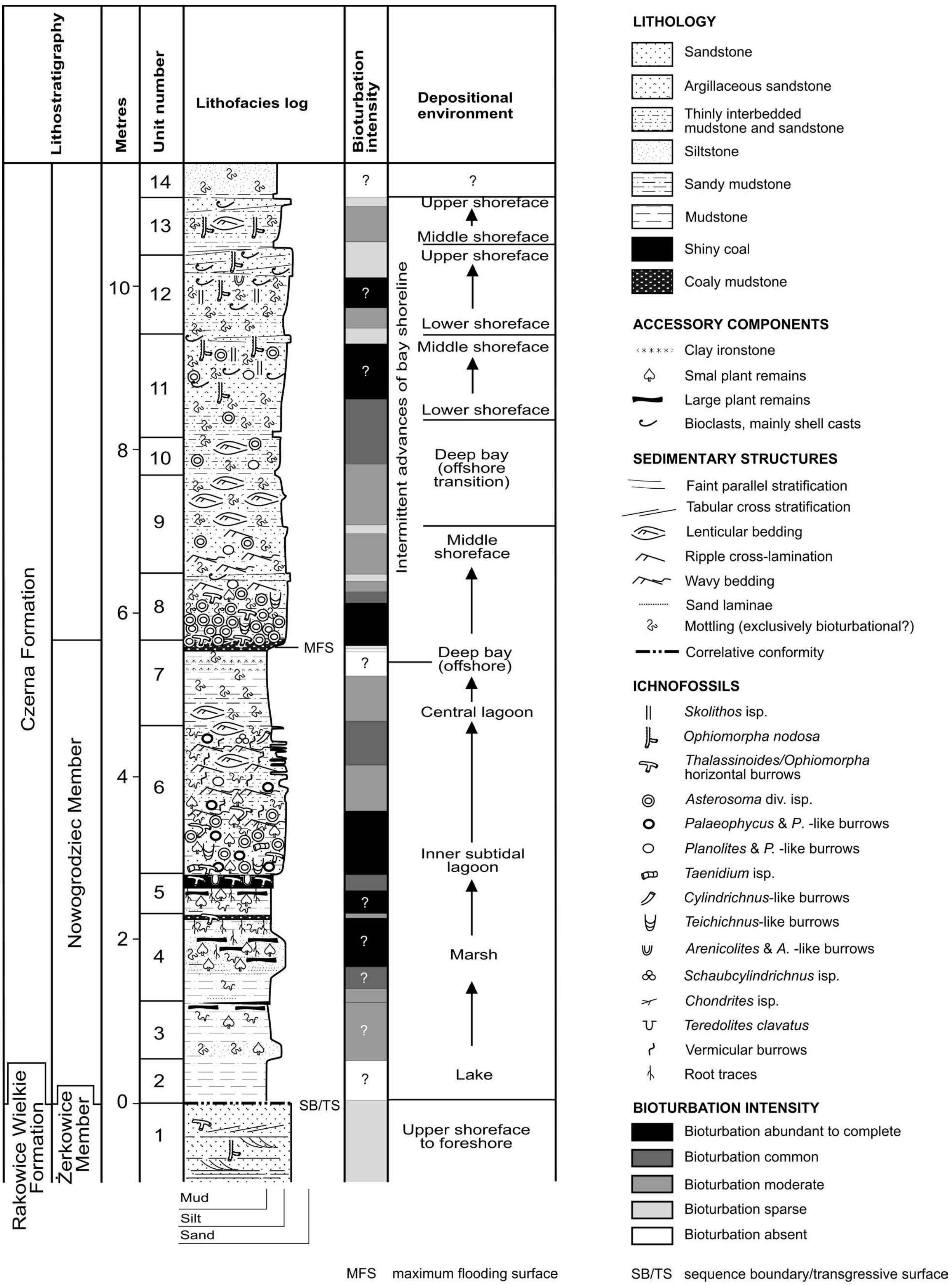

Fig. 4. Sedimentary log, trace fossil data, stratigraphy and depositional history of the studied section

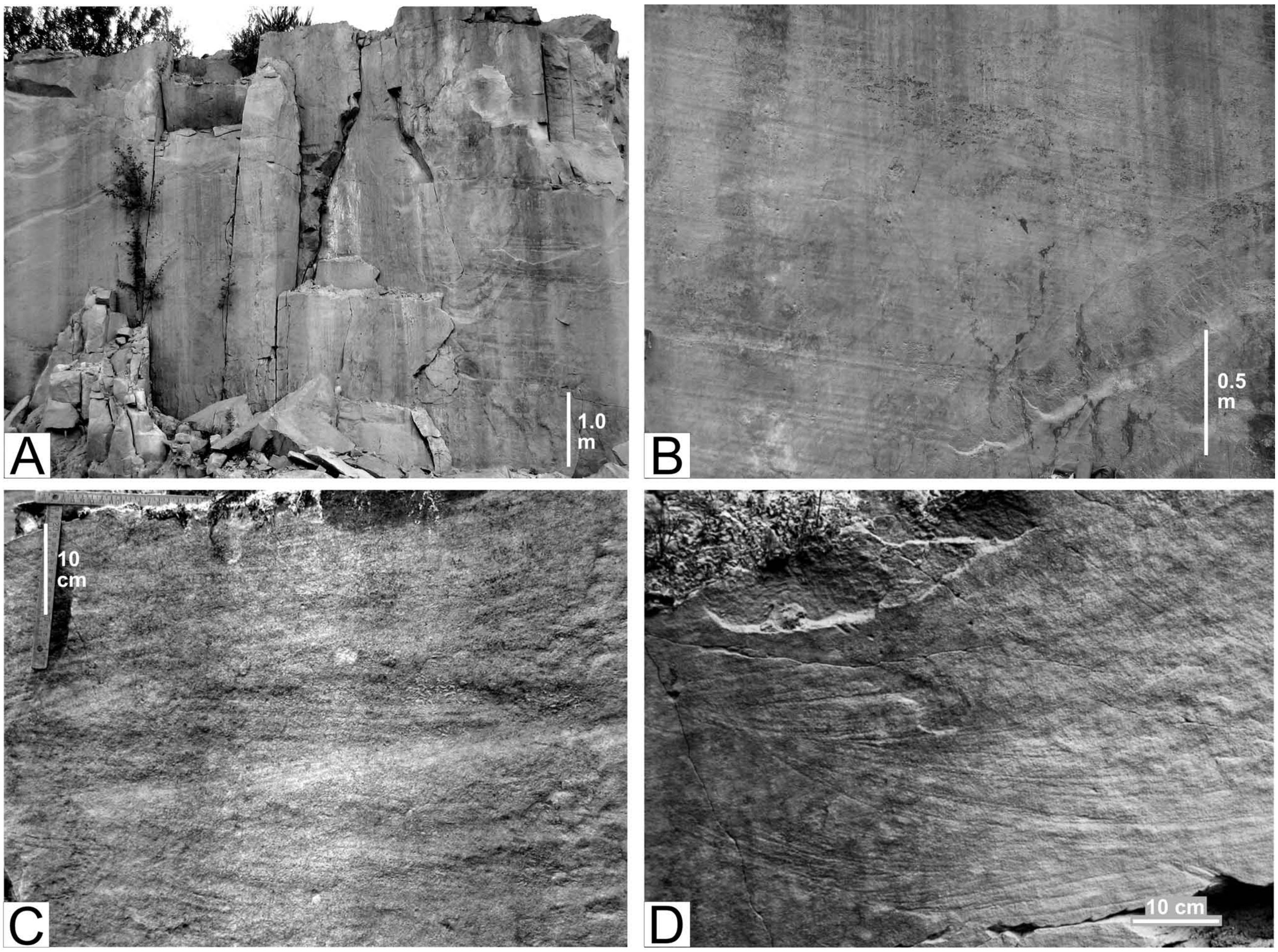

Fig. 5. Sandstone of the Żerkowice Member. **A** – General view of the sandstone in the southern wall of the quarry. Faint parallel stratification on right side of photo indicates foreshore origin. **B** – Close-up view of faintly parallel-stratified and massive sandstone. **C** – Sandstone showing interbedded faint tabular cross-stratification and parallel stratification; welded beach face and coastal sand bar deposits. **D** – Sandstone showing trough cross-stratification and non stratified. Sediment origin as in Fig. C

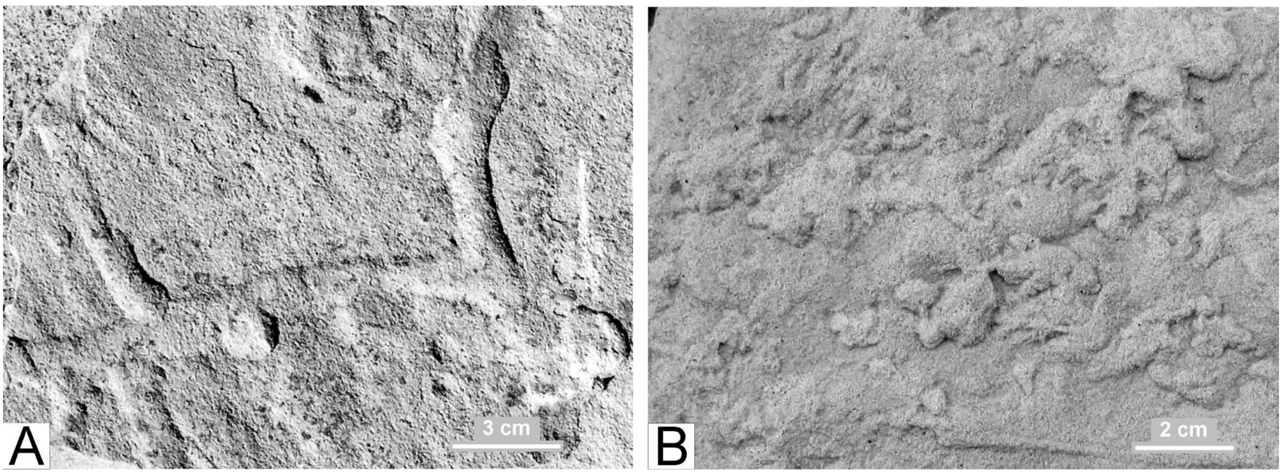

Fig. 6. Trace fossils recorded in sandstone of the Żerkowice Member. **A** – *Thalassinoides* isp., convex epirelief in sandstone. **B** – ?Fodinichnia, convex hyporelief in sandstone

size, usually thinner than 0.5 cm. Thin, discontinuous, bedding-parallel sand laminae occur in the siltstone layer. The top of the mudstone bed is marked with a level rich in coalified plant fragments forming locally a shiny coal layer as much as 2 cm thick.

The overlying part of the succession is a 37 cm thick bed of grey-brown, mottled to subtly parallel laminated mudstone (Fig. 8). Lamination occurs locally in the lower part of the bed. The mudstone grades upward into siltstone and subsequently to an argillaceous sandstone as much as 30 cm thick. The latter grades upward into a 22 cm thick layer of dark-brown mudstone capped by a 5–10 cm thick coal seam. All these deposits constitute unit 4 in Fig. 4. The sandstone is rich in large coalified plant debris and is cut by plant roots. It is this unit in which the aforementioned duplex structure occurs. The coal seam bifurcates locally into two thin layers separated by thin sandstone. The coal seam locally contains sand bodies showing lenticular cross-section and ropelike to lumpy shape in plan view. The sand bodies are 1.5 to 2.0 cm in cross section and show non-laminated to obliquely laminated structure in vertical cross-section. Bodies of analogous size and shape in bed cross-section, occurring in coal of Upper Cretaceous of east-central Utah (USA) were shown by Kamola (1984) to represent the trace fossils *Thalassinoides suevicus*, *T. paradoxicus* and *T.* isp., whereas MacEachern *et al.* (2007a, b) have shown such structures as *Thalassinoides* isp. In the deposit in question, the majority of the sand bodies also seems to represent trace fossils, however, their taxonomic affiliation is not clear. The doubts result from the rarity of the bodies and poor accessibility for examination on bedding parallel surfaces. It cannot be excluded that they actually include burrows of the ichnogenus *Thalassinoides*. In this case, the poor trace fossil assemblage would represent the *Teredolites* Ichnofacies of a stressed environment, lacking the namesake ichnotaxon (see MacEachern *et al.*, 2007c). The archetypal expression of this ichnofacies embraces burrows and borings excavated in marine or marginal woody or coaly substrates (Bromley *et al.*, 1984; Savrda, 1991).

Except for a small area located over the duplex structure, the coal seam is overlain by a brown mudstone, 33–45 cm thick, showing mottled structure, and locally penetrated by plant roots (Fig. 9). The latter show abrupt termination at the bed top. This mudstone is overlain by a bed of a dirty coal, as much as 20 cm thick (which together with the underlying mudstone forms unit 5 in Fig. 4). In a small area located over the duplex structure, this coal seam occurs joined in one bed with the lower lying coal seam. The deposit of the upper coal seam is brittle, generally overfilled with sand bodies showing a vertical section similar to those recorded in the lower lying coal bed (Fig. 10A). Moreover, it additionally contains sand bodies showing complex, tortuous shapes and some dish shaped lamellation in cross-section, bodies appearing to consist of bundles of sand lenses, and some forming highly elongated lenses. In bed cross-sections, most of the sand bodies resemble structures shown by Kamola (1984) as different ichnospecies of *Thalassinoides*. These showing tortuous shape and lamellation in cross-section are reminiscent of structures shown by Seilacher (1955) as cf. *Phycodes palmatum* Hall (1852), and to some extent

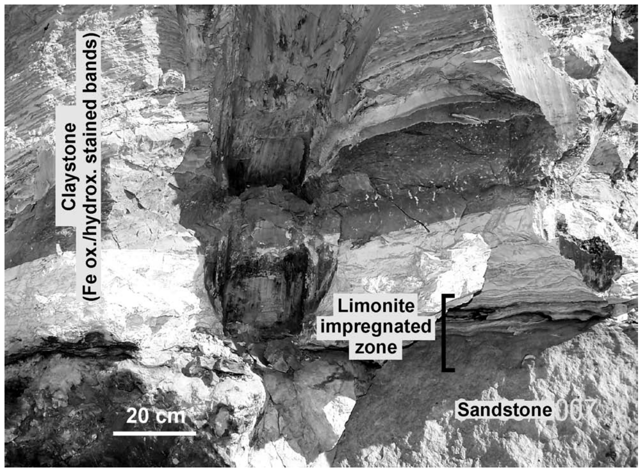

Fig. 7. Contact of Żerkowice Member (sandstone) with Nowogrodziec Member (claystone), interpreted as paraconformity. Note claystone layering due to staining with iron oxides and hydroxides. Dark coloured bed in the lower part of claystone (actually dark pink) shows white, vertically elongated spots resembling plant roots

Fig. 8. Brown mudstone, massive to faintly parallel stratified and two layers of shiny coal in its lower part (shown with arrows)

Fig. 9. Muddy sandstone passing upward into mudstone showing plant roots (arrows) and capped with muddy to shiny coal

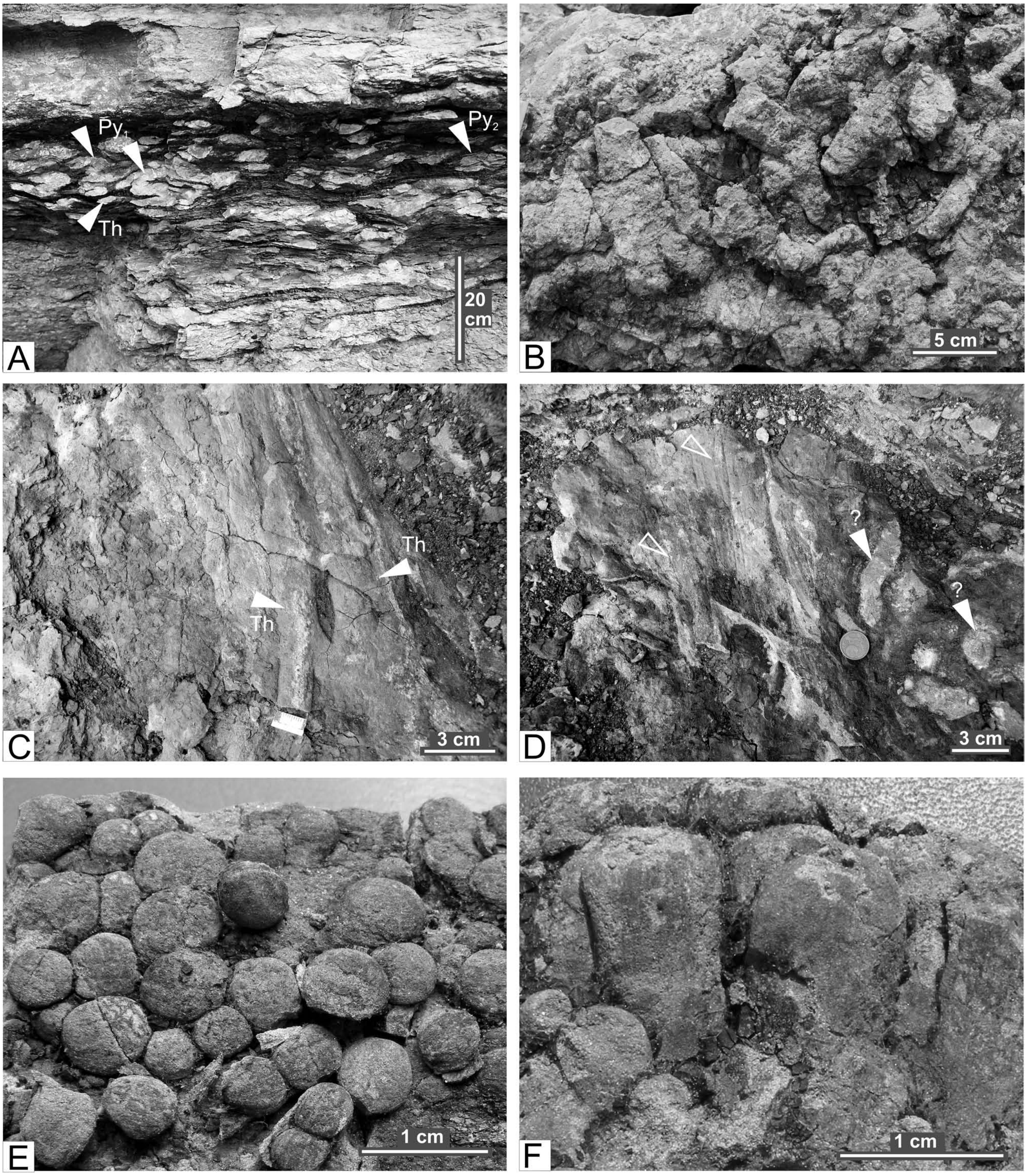

Fig. 10. Features of a coal seam. **A** – Dense packing of coal with sand bodies showing different size, shape and internal structure; vertical cross-section view. The bodies appear to represent mainly sand-filled burrows *Thalassinoides* isp. (Th), cf. *Phycodes palmatum* (Py_1), ?*Phycodes* isp. (Py_2); **B–D** – Appearance of sand bodies (light colours) on surfaces parallel to bedding. The bodies in **B** (view from below) are superimposed burrows of several ichnotaxa. **C** and **D** show trace fossils of ichnogenus *Thalassinoides* (Th), taxonomically undetermined trace fossils (?) and sand bodies of unclear origin (white outlined arrows), (view from above); **E**, **F** – *Teredolites clavatus* (knobs) at top of coal seam; full relief, plan view from below. Examples differing in compression style

Teichichnus zigzag Frey and Bromley, 1985. Their tortuosity may in part result from compaction. The sand bodies appearing to consist of bundles of sand lenses may also represent ichnogenus *Phycodes*. Unfortunately, their horizontal pattern has not been recognised. Rope-like shapes, variable size and lack of clear branching were visible on one bedding-parallel surface of a size of 800 cm^2 (Fig. 10B). Sand bodies of similar shapes and sizes, some branched, rather straight and highly curved, and, additionally, bodies of lobate and sheet-like shapes, showing a striated surface and an obliquely laminated interior in cross section were recorded in plan view in an adjacent place (Fig. 10C, D). Striations recorded on the surface of lobate specimens are reminiscent of a thick spreite and widely spread, low angle, backfill lamellae (menisci). These bodies may represent ichnogenus *Teichichnus*. The branched, rope sized burrows (1.5–2.0 cm wide) appear to represent two *Thalassinoides* ispp. One ichnospecies shows rather straight burrows, the other is highly curved and more flat in cross- section. The first-mentioned ichnospecies cuts the former one. Rope-sized but slightly thinner (0.6–1.0 cm wide), curved, bedding-parallel bodies of massive sand showing an irregular outline and irregular (?peletted) mud lining appear to represent *Ophiomorpha* isp. indet. Some sand bodies, particularly the sheet-like structure in plan view, may be of abiotic, sedimentary origin. Another characteristic feature of the coal seam is the occurrence at its top of fragments of tree trunks containing casts of wood borings *Teredolites clavatus* Leymerie, 1842 (Fig. 10E, F). These trace fossils commonly show significant compaction perpendicular to their elongation. In total, burrows enclosed in this coal seam represent the archetypal *Teredolites* Ichnofacies. Actually, according to composition, this bed fully corresponds to Savrda *et al.'s* (1993) "log-ground", that is a ground consisting of a high concentration of allochthonous wood strewn across a depositional surface.

The overlying unit (unit 6 in Fig. 4) comprises highly to completely bioturbated argillaceous sandstone passing upward into a sandstone–mudstone heterolith showing variable bioturbation intensity. The whole unit is 165 cm thick (Fig. 11A). The argillaceous sandstone constitutes the lower, 1 m thick part of the unit. It tends to show some coarsening upward displayed in a decreasing content of organic material. It is fine-grained, variegated in colour, dark-brown to drab. The variegated appearance ensues from the irregular distribution of plant debris. The sediment shows mottled structure, remnants of flaser bedding and wavy bedding. Differentiation between bioturbation structures and sedimentry structures is here problematic in many instances (Fig. 11B). This is in part due to a high content of organic debris that stresses the mottled appearance of the deposit. Additionally, precise taxonomy is rarely possible because trace fossils are visible almost exclusively in sections mainly roughly perpendicular to bedding.

Trace fossils of the ichnogenera *Asterosoma*, *Palaeophycus*, *Ophiomorpha*, *Thalassinoides*, *Planolites* and *Taenidium* appear to be the dominant distinct ichnotaxa, particularly in the lower part of the muddy-sandstone unit. *Asterosoma* seems to dominate in the lower part of the unit and appears to be the main constituent of its fabric (Fig. 11B). Structures reminiscent of the ichnogenus *Cylindrichnus* are recorded locally associated with *Asterosoma* isp. indet. (Fig. 11C, D). In some places, the sediment fabric is composed of *Asterosoma* and inferred *Cylindrichnus* overprinted by *Thalassinoides* isp., thickly mud-lined burrow tentatively called *Palaeophycu*s isp., *P.* cf. *tubularis* Hall, 1847, and *Planolites* isp. indet. (Fig. 11C–E). Elsewhere, in the lower part of the unit, the ichnofabric is dominated by roughly horizontally winding burrows showing irregular, pelleted mud lining characteristic of the ichnogenus *Ophiomorpha* and smooth-walled, mud-lined burrows of the ichnogenus *Palaeophycus* (Fig. 12B). Most burrows in the lower part of the argillaceous sandstone show irregular, pelleted mud lining resembling that in *Ophiomorpha irregulaire* Frey, Howard and Pryor, 1978 (see Fig. 12A, C, D). They are accompanied by rare burrows appearing to show annulations of the pelleted mud lining as in *O. annulata* (Książkiewicz, 1977) (Fig. 12A, B). Bedding-parallel to oblique burrows showing a meniscate fill, resembling ichnogenus *Taenidium*, occur locally in the argillaceous sandstone (Fig. 11D). Specimens of *Taenidium baretti* (Bradshaw, 1981) (Fig. 12C, D) and *Taenidium serpentinum* Heer, 1877 (Fig. 12B) were recorded in the *Ophiomorpha*-dominated division. Moreover, one specimen suggestive of ichnogenus *Rosselia* has been found in the upper part of the argillaceous sandstone (Fig. 11F). In total, the trace fossil assemblage appears to represent the *Cruziana* Ichnofacies in the proximal expression of a stressed environment. The latter is suggested by the lack of some ichnotaxa characteristic of this ichnofacies (*e.g.*, *Rhizocorallium*), and the rich content of plant detritus in the sediments.

The overlying heterolith (unit B in Fig. 11A) comprises interbedded drab to pale-coloured argillaceous sandstone, arenitic sandstone and grey to dark-brown sandy mudstone and mudstone. The deposits show variable intensity and style of bioturbation. Proportion of sandstone relative to mudstone decreases upward. The mudstone becomes more clayey upward. The less bioturbated divisions show wavy to lenticular bedding (Fig. 13A, B). Lamination of current ripples showing opposite directions, combined-flow ripples and wave ripples are recognizable in the poorly bioturbated sand lenses and layers. The ichnofabric is constituted primarily by irregular mottles of tan to drab coloured sediment. Distinct trace fossils are represented by several ichnotaxa dominated by 1 mm thick, bedding-parallel to vertical mud-lined and sand-filled burrows and similarly thick, unlined, mud-filled burrows (Fig. 13A–D). Some thin, mud-lined burrows are U-shaped and Y-shaped and resemble *Arenicolites* and *Psilonichnus*, however the size of the U-shaped structures is 5x10 mm only (Fig. 13E). Numerous pairs of such tiny, vertical burrows recorded on bedding-parallel surfaces in some sandstone beds suggest that such trace fossils may be locally abundant. They are analogous with burrows of a polychaete, *Capitella* cf. *capitula*, described from the upper offshore of Georgia, U.S.A. (Hertweck *et al.*, 2007). The mud-lined burrows showing different orientation to bedding appear to correspond to the trace fossil *Bornichnus tortuosus* Bromley and Uchman (2003) described from the Lower–Middle Jurassic tidal flat deposits of Bornholm (Denmark). Other ichnotaxa include *Schaubcylindrichnus* isp. indet., ?*Phycosiphon* isp. indet., *Planolites* isp. indet. (Fig. 13B, C) and other taxonomically undetermined forms (Fig. 13F). Some specimens of *Schaubcylindrichnus* resemble ichnospecies S. *coronus* Frey and Howard, 1981. They tend to occur in bundles of congruent, sand-lined tubes. Some rock parts contain aggregations of taxonomically undetermined sand-filled burrows resembling diminutive *Planolites* in cross-section and small burrows showing

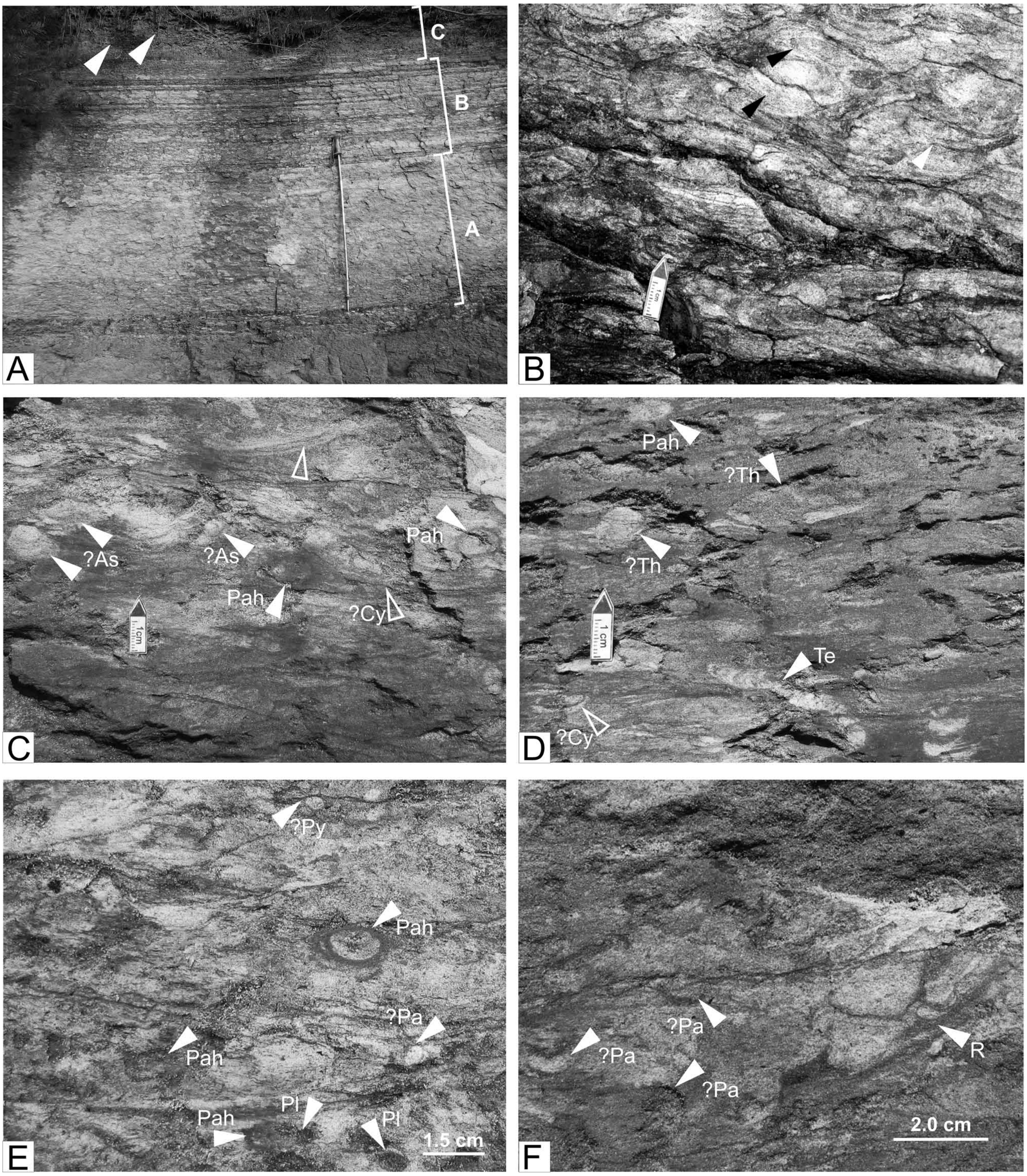

Fig. 11. Features of the upper part of the Nowogrodziec Member. **A** – General view. Note up-bed passage from muddy sandstone (A) to sandstone and mudstone heterolith (B) and finally to mudstone including two clay ironstone (siderite) beds (white arrows) (C). Walking stick (1.1 m long) stands on coal seam. **B** – Completely bioturbated muddy sandstone dominated by *Asterosoma* isp. (examples indicated with black arrows) (*Asterosoma* ichnofabric), vertical cross-section view (vcsv). Some structures resemble *Cylindrichnus* isp. (white arrows). **C** – Highly bioturbated muddy sandstone showing ?*Asterosoma* isp. (?As), *Palaeophycus* isp. (Pah). White outlined arrows indicate longitudinal cross-sections of burrows showing laminated filling resembling ?*Cylindrichnus* isp. (?Cy); vcsv. **D** – Muddy sandstone rich in organic material showing thickly mud-lined burrow resembling *Palaeophycus* isp. (Pah), ?*Thalassinoides* isp. (?Th), *Taenidium* isp. (Te), and cross-section of burrow showing laminated filling resembling ?*Cylindrichnus* isp. (?Cy); vcsv. **E** – Completely bioturbated muddy sandstone showing thinly lined burrows of different size, corresponding *Palaeophycus tubularis* (?Pa), thickly mud-lined burrow resembling *Palaeophycus* isp. (Pah), *Planolites* isp. (Pl) and cluster of mud lined burrows resembling the ichnogenus *Phycodes* (?Py); vcsv. **F** – Completely bioturbated muddy sandstone showing mud lined burrows of different size, corresponding to ichnogenus *Palaeophycus* (?Pa), and concentrically laminated, inclined burrow resembling *Rosselia* isp. (R); vcsv

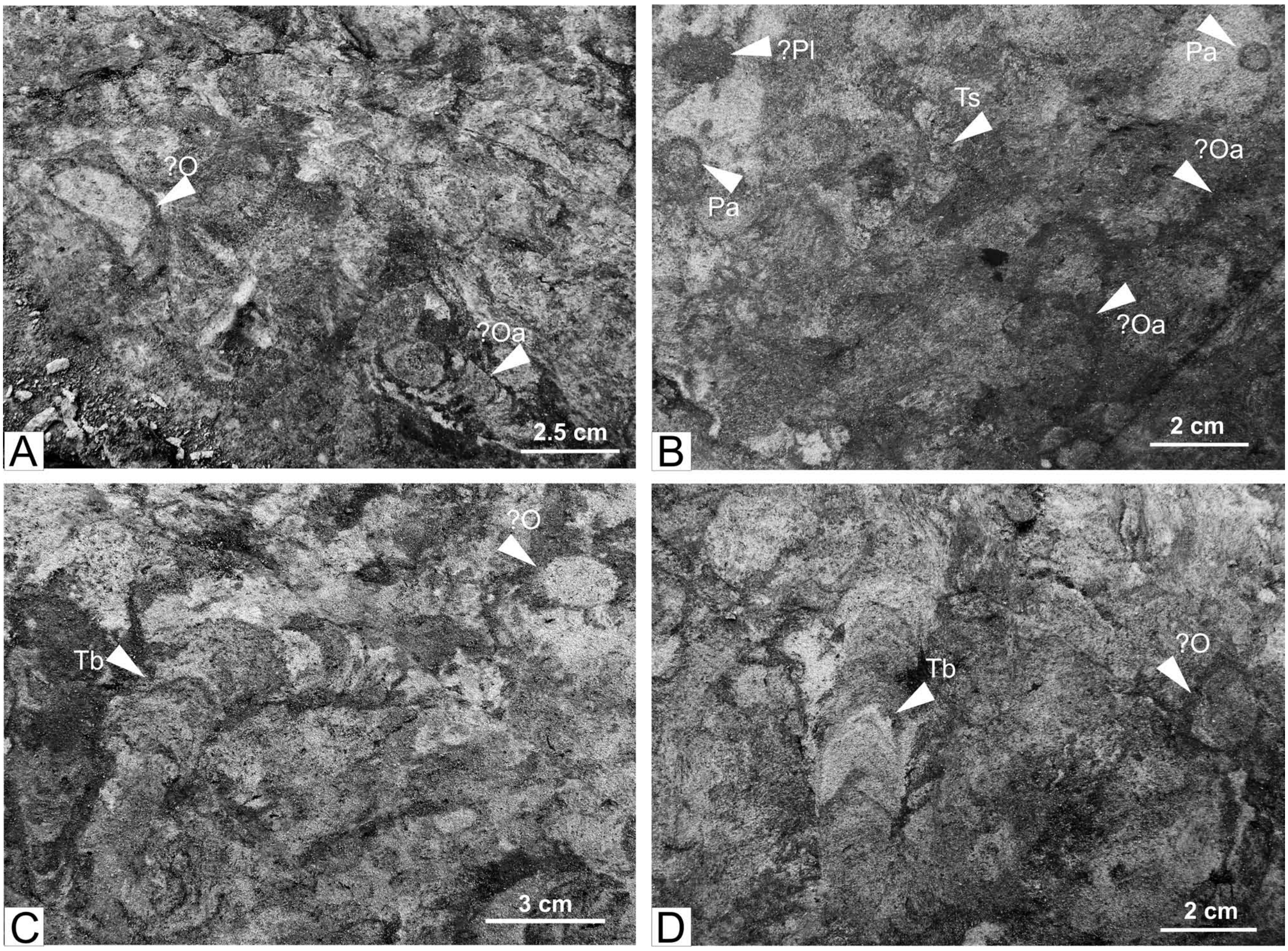

Fig. 12. Features of the lower, muddy sandstone division, upper part of Nowogrodziec Member. Bedding-parallel surfaces, view from below. **A**, **B** – *Ophiomorpha–Palaeophycus* ichnofabric in a less muddy part of the division. Ichnospecific affiliation of specimens is in most cases not possible. ?*Ophiomorpha* isp. indet. (?O) seem to prevail. ?*Ophiomorpha annulata* (?Oa) is recorded sparsely. Less common are burrows of the ichnogenus *Palaeophycus* (Pa). Accessory burrows include specimens resembling ichnogenus *Planolites* (?Pl) and *Taenidium*, with *T. serpentinum* (Ts). **C**, **D** – *Ophiomorpha* isp. indet. (?O) and *Taenidium baretti* (Tb)

concentric structure in cross-section (Fig. 13D, E). The trace fossil assemblage would seem to represent a single ecological suite. The forms of structures, the inferred ichnotaxa as well as the sedimentological and ichnological context of these deposits together indicate that they represent the *Cruziana* Ichnofacies of a highly stressed environment.

The heterolith passes gradually upward into a 1 m thick bed composed of grey to greenish-grey and green clayey mudstone enclosing several thin clay ironstone (siderite) beds and topped by a coaly mudstone layer several centimetres thick (unit 7 in Fig. 4, unit C in Fig. 11A; Fig. 14A, B). The latter is the highest unit in the sedimentary succession of the Nowogrodziec Member. The grey to greenish-grey and green mudstone shows some colour mottling resulting probably from bioturbation. Distinct bioturbation structures, however, have not been found in this deposit. Investigations of three samples taken from the lower, middle and upper part of bed revealed an absence of foraminifera and other microfossils. This is in distinct contrast to other areas where foraminifera were recorded in the lower part of the Czerna Formation (see Alexandrowicz, 1976; Gawor-Biedowa, 1991). Facies of these deposits suggest that their bioturbation structures may be related to *Zoophycos* Ichnofacies of a highly stressed environment.

The overlying coaly mudstone becomes highly burrowed in its upper part. Bioturbation obscures the upper boundary of this unit and adds to gradual passage of the coaly mudstone into the overlying sandstone, which initiates the higher part of the Czerna Formation (unit 8 in Fig. 4; Fig. 14C). Bioturbation of the boundary division is conspicuous, dominated by the densely packed sand-filled burrows *Asterosoma ludwigae* Schlirf, 2000 (Fig. 14D–F), accompanied by *Thalassinoides* isp. indet. (Fig. 14D–F), *Chondrites* isp. indet. (Fig. 14F) and some other taxonomically undetermined ichnotaxa. *Asterosoma* occurs as the dominating ichnotaxon in the whole division. *Thalassinoides* is most densely distributed from 10 to 20 cm above the lower boundary of the coaly mudstone bed. *Chondrites* is recorded from 5 to 9 cm above this boundary only (Fig. 14C). *Asterosoma* shows intersection by *Thalassinoides* isp. Both ichnotaxa cross cut *Chondrites* isp. Burrowing becomes less distinct upward, in the drab coloured argilla-

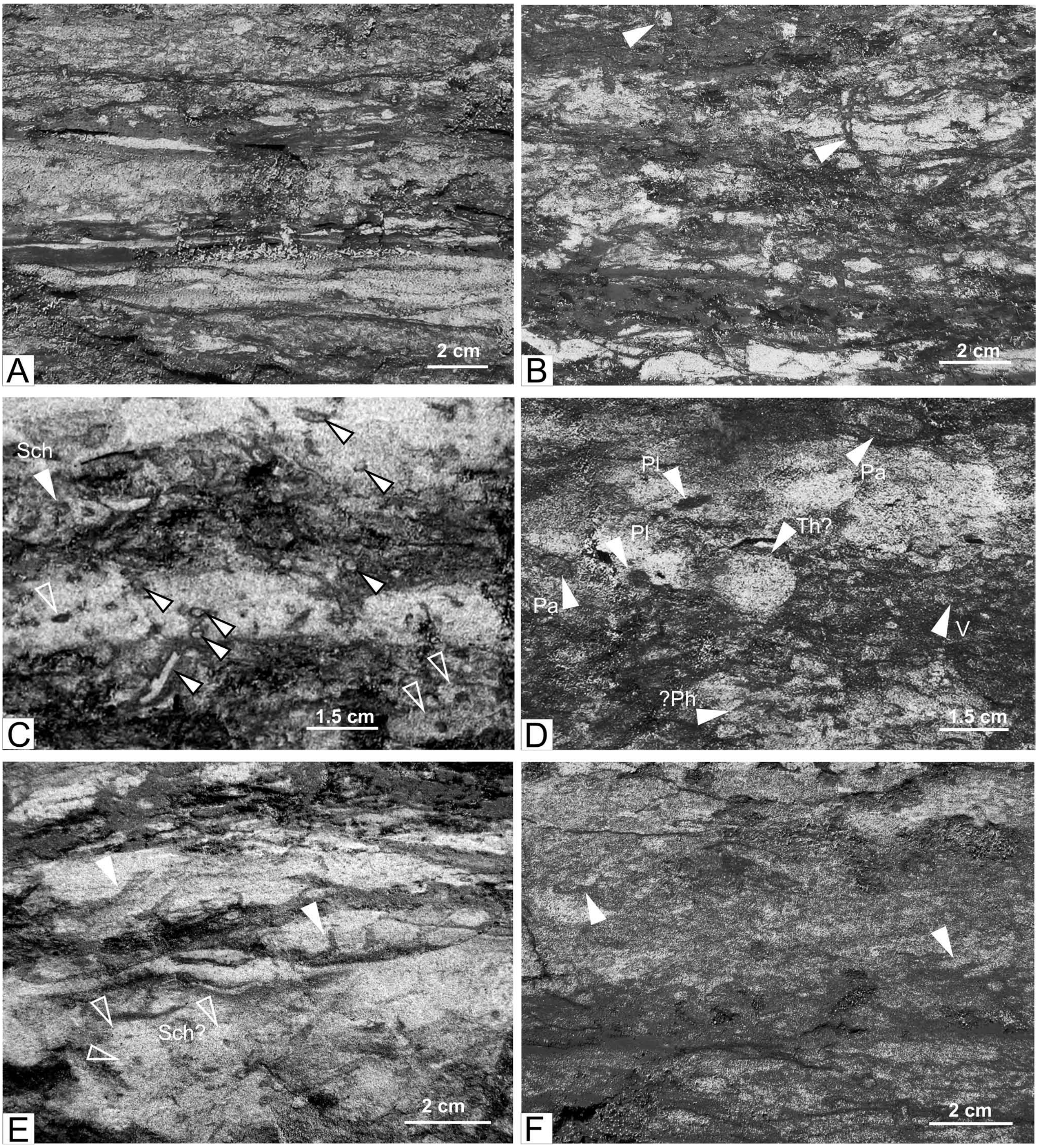

Fig. 13. Features of the heterolithic division of the upper part of the Nowogrodziec Member (unit B in Fig. 11A). **A** – Wavy and lenticularly bedded heterolith showing variable bioturbation intensity. Highly to completely bioturbated horizons interchange with poorly bioturbated to unbioturbated ones. **B** – Wavy and lenticularly bedded heterolith differently modified by bioturbation structures. Note numerous, bedding oblique to vertical and horizontal burrows (two burrows shown with arrows); vcsv. **C** – Highly bioturbated heterolith showing numerous thin (1.6 mm diameter), cylindrical, mud-lined, sand-filled burrows resembling ichnogenus *Palaeophycus* (small black outlined arrow), thin, mud-filled burrows (small, white outlined arrow), *Schaubcylindrichnus* isp. cluster (Sch); vcsv. **D** – Highly to completely bioturbated heterolith showing some distinct trace fossils. Most numerous are taxonomically undetermined, thin, mud-lined burrows occurring in clusters suggesting a vermicular course (V). Less numerous forms include *Palaeophycus* ?*tubularis* (Pa), ?pale mantled burrows reminding *Phycosiphon* (?Ph), black filled burrow resembling *Planolites* isp. (Pl). Single large, and cylindrical burrows reminding *Thalassinoides* isp. (Th?) occur in some places; vcsv. **E** – Sandstone showing two types of thin, unlined, mud-filled, U-shaped trace fossils (white arrow) and clusters of burrows resembling ichnogenus *Schaubcylindrichnus* (Sch?); vcsv. **F** – Completely burrowed sandy mudstone showing taxonomically undetermined, small, sand-filled burrows of two sorts (arrows); vcsv

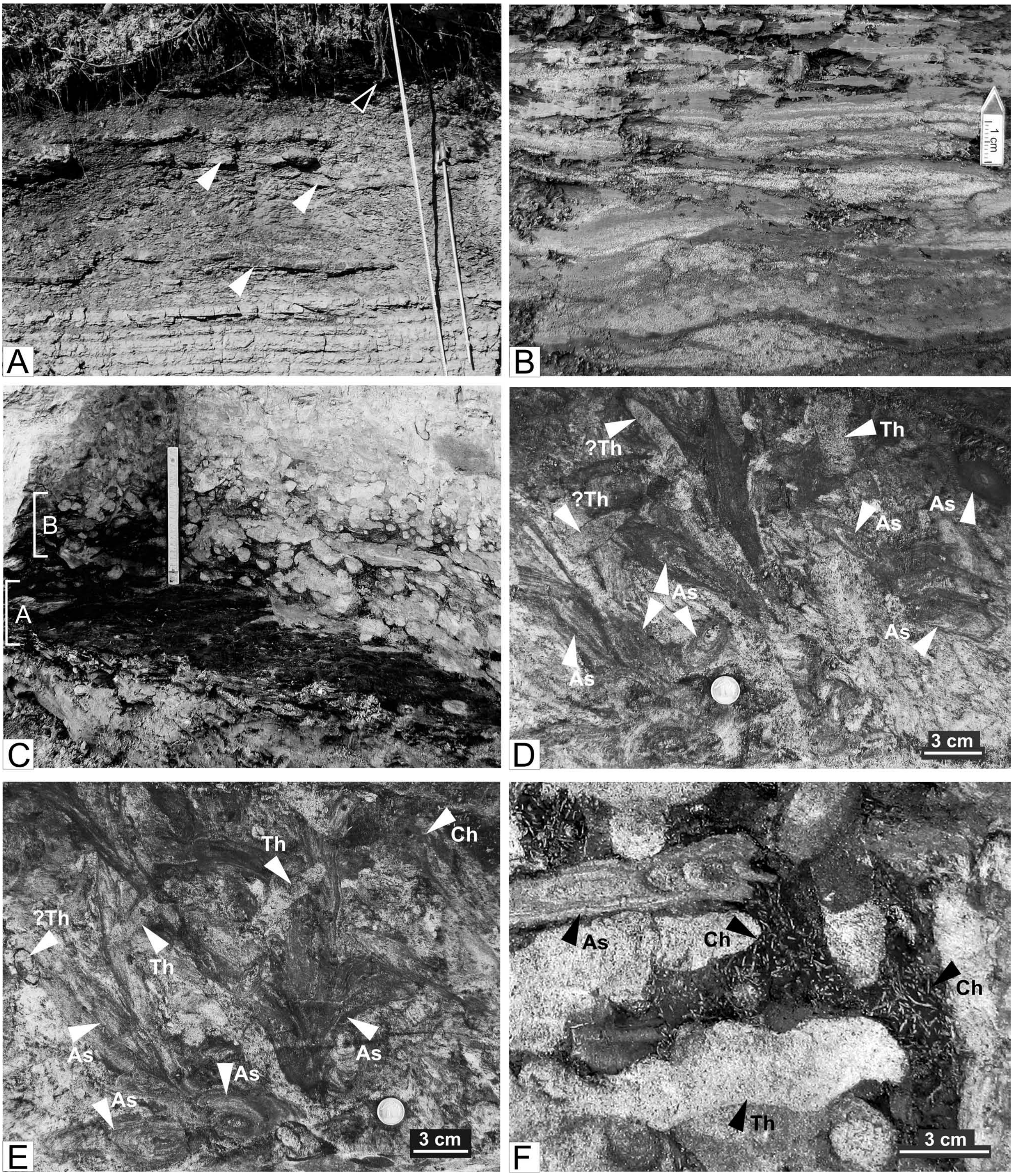

Fig. 14. Features of the top part of Nowogrodziec Member. **A** – Dark-grey to green mudstone divided by several thin, clay ironstone (siderite) beds (white arrows) developing from the underlying heterolith and capped by thin coaly mudstone (white outlined black arrow). Walking stick (1.1 m long) as a scale. **B** – Wavy and lenticularly bedded heterolith passing upward into dark-grey mudstone. **C** – Green mudstone overlain by coaly mudstone that grades upward into muddy sandstone. Upper part of the coaly mudstone and the overlying deposit are highly to completely bioturbated. *Asterosoma ludvigae* is the dominating burrow in the whole bioturbated unit. *Thalassinoides* isp. indet. is most densely distributed in the middle part of the unit (division B) and *Chondrites* isp. indet. is recorded in the lower part of the unit only (division A). **D** – *Asterosoma ludwigae* (As) showing diverse cross-section of bulbs cross-cut by *Thalassinoides* isp. indet. (Th). Note occurrence of black lining in some *Thalassinoides*-looking burrows. **E** – *Asterosoma ludwigae* (As) seen in variably cross-sectioned bulbs cut by *Thalassinoides* isp. indet. (Th) and a mud-lined burrow (Th?). **F** – *Asterosoma* (As), *Thalassinoides* (Th) and *Chondrites* (Ch). Note that *Chondrites* is cross-cut both by *Asterosoma* and *Thalassinoides*. The latter ichnotaxon also cross-cuts *Asterosoma*. Sand bodies on the right side of the photograph represent undifferentiated *Asterosoma* and *Thalassinoides*

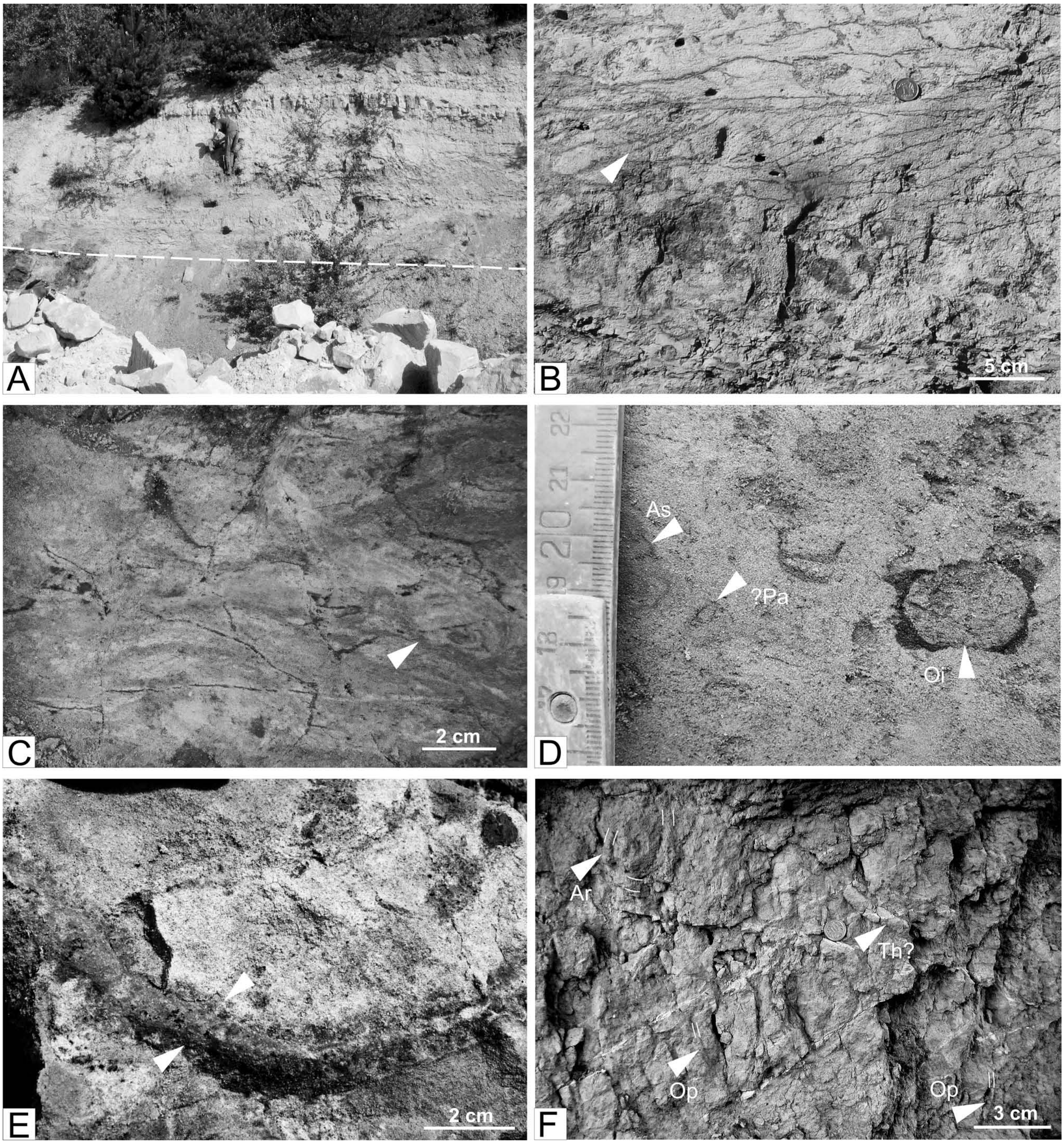

Fig. 15. Features of Czerna Formation above Nowogrodziec Member. **A** – The general appearance of the Czerna Formation above the Nowogrodziec Member in the Rakowice quarry. Dashed line indicates the upper boundary of the Nowogrodziec Member. Bodies of clean sandstone usually less bioturbated than the adjacent sandstone are protruding from the quarry wall. Note the lateral pinching out of the upper sandstone body. **B** – Appearance of the weathered sandstone in the sandstone part of a lower coarsening-upward unit. Note the cross-lamination (arrow). **C** – Completely bioturbated muddy-sandstone showing *Asterosoma* isp. indet. (arrow). **D** – Muddy-sandstone showing *Ophiomorpha* cf. *irregulaire* (Oi), faint *Asterosoma* isp. indet. (As), and thinly lined *Paleophycus* cf. *tubularis* (Pa). **E** – Sandstone containing *Ophiomorpha* cf. *irregulaire* (arrows). **F** – Highly bioturbated sandstone showing ?*Arenicolites* isp. indet. (Ar), ?*Thalassinoides* isp. indet. (Th?), and poorly marked *Ophiomorpha* cf. *nodosa* (Op)

ceous sandstone; however, the mottled appearance of its splitting surfaces suggests profound bioturbation. The ichnofossils are typical of taxonomically impoverished archetypal *Cruziana* Ichnofacies (see MacEachern *et al.*, 2007a).

The Czerna Formation over the Nowogrodziec Member

The overlying part of the succession consists of two coarsening-upward to fining-upward divisions comprising seven coarsening-upward units (units 8–14 in Fig. 4; Fig. 15A). The top part of the higher order unit (unit 14 in Fig. 4)

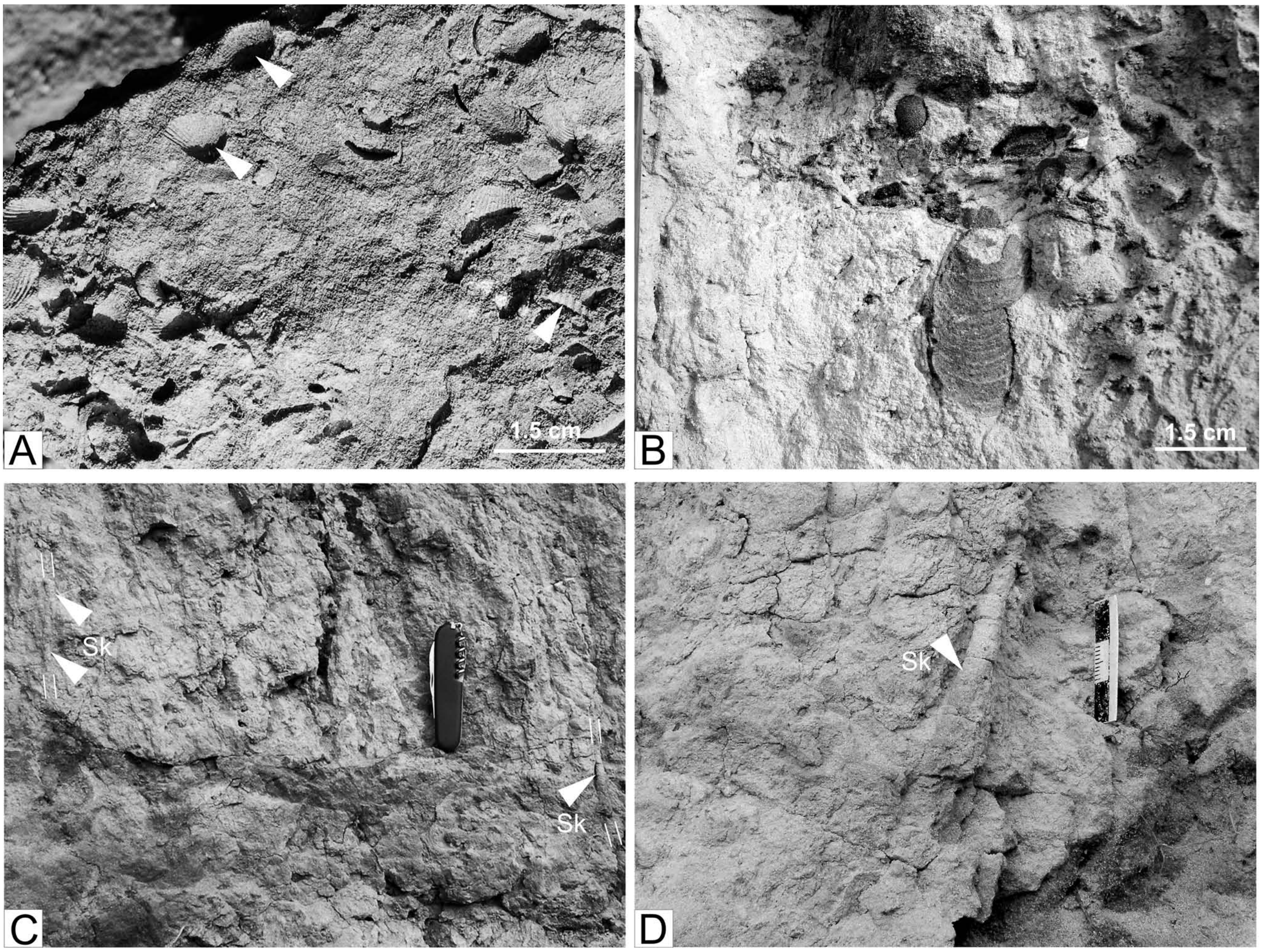

Fig. 16. Features of highest part of the section (Czerna Formation above the Nowogrodziec Member). **A** – Sandstone rich in casts of bivalve shells. Coin diameter 16 mm. **B** – Bivalve in life position, in sandstone. **C** – Completely bioturbated sandstone showing *Skolithos linearis* (Sk). Pocket knife 9 cm long. **D** – *Skolithos linearis* oriented oblique to bedding

is strongly reworked by Quaternary surficial processes. Actually, this whole succession is relatively poorly preserved, being strongly jointed, irregularly impregnated with iron oxides, and commonly penetrated with recent plant roots. These properties mask the subtle features of the original structure of the deposits, and, consequently, hinder recognition of their mode of origin.

Each coarsening-upward unit starts with a mud-dominated heterolith. Massive or cross-stratified sandstone or a sand-dominated heterolith occurs at the top of the units. The heterolithic divisions comprise drab to pale coloured mudstone to siltstone and drab to pale-coloured fine-grained sandstone streaks, layers and lenses. The deposits display wavy to lenticular bedding and a chaotic structure. The latter occurs in some highly bioturbated heterolith divisions and in soft-sediment deformed intervals. Lamination of current ripples, combined-flow ripples and wave ripples is visible in some sand lenses and some sandstone layers. The sandstone of sandstone divisions is pale to orange and yellowish in colour and shows a generally massive structure. Some its parts appear to display ripple lamination and medium-scale cross-stratification (Fig. 15B). It shows sparse to abundant bioturbation. The latter is inferred for argillaceous sandstone showing irregular, lumpy weathering. Bioturbation structures are mainly obscure, being poorly visible in the whole unit. Thorough examination revealed the occurrence of *Asterosoma* isp. indet. (Fig. 15C, D), *Paleophycus* cf. *tubularis*, *Ophiomorpha* cf. *irregulaire* (Fig. 15D, E), *O.* cf. *nodosa* and *Planolites* isp. Burrows included to *O.* cf. *irregulaire* show sparse, irregular, pelleted mud lining with ovoid to elongate pellets (cf. Pedersen & Bromley, 2006; Bromley & Pedersen, 2008). Unfortunately, only small fragments of this trace fossil were observed and therefore its precise determination is not possible. *O.* cf. *nodosa* is thinner than *O.* cf. *irregulaire*, shows a more regular lining and mainly a vertical course. It occurs in the sandstone part of the two upper coarsening-upward units. Argillaceous sandstone of these units shows rich casts of various mollusc shells, mainly bivalves (see Milewicz, 1970). In part, they occur concentrated at bedding-parallel stratification surfaces (Fig. 16A). Sandstone of the lower part of the thickest coarsening-upward unit shows bivalve shells in life position (Fig. 16B), fragments of vertical to nearly vertical, cylindrical, smooth-walled burrows resembling *Skolithos linearis* Haldeman, 1840 (Fig. 16C, D) and *Arenicolites*-like trace fossils (Fig. 15F).

The trace fossils of mud-dominated heteroliths probably represent *Cruziana* Ichnofacies in a distal expresion, however, quality of exposure and applied examination methods precluded its unequivocal documentation. Trace fossils recorded in sand-dominated heteroliths and intensely bioturbated sandstones indicate taxonomically impoverished *Cruziana* Ichnofacies in the proximal expression of a stressed environment, whereas the assemblage recorded in massive, poorly bioturbated sandstones seems to represent *Skolithos* Ichnofacies.

DISCUSSION

The above described features indicate the complex origination of the succession both with respect to depositional processes and depositional setting. Previous interpretations are generally confirmed, still, several new opinions are added. The new opinions particularly concern deposits of the Nowogrodziec Member and result in part from the ichnological investigations.

Depositional environment

The almost homogeneous lithology of the Żerkowice Member, consisting basically of fine-grained to medium-grained sandstone showing planar stratification and large-scale cross-stratification, provide evidence for sedimentation in upper shoreface and foreshore environments. Such an origin is also supported by the rare vertical burrows, *Ophiomorpha nodosa*, characteristic of *Skolithos* Ichnofacies, typical of sandy shores. The horizontal burrows, including *Ophiomorpha* and *Thalassinoides*, recorded at bedding surfaces, together with remnants of muddy drapes, record short periods of lowered water energy and the arrival of conditions characteristic of the middle shoreface. Large-scale cross-stratification point to deposition in a hydrodynamically energetic environment, through gradual filling of chutes and accretion on wave-formed bars. Opposite directions of cross-stratification recorded in some places indicate significant variation of water energy and occasional strong agitation of water, as is characteristic of storms. Onshore-directed, large-scale, high-angle stratification is produced during fair-weather conditions whereas the opposite is formed during storms, particularly by rip currents (see Dumas & Arnott, 2009). Dominance of stratification inclined to the south, southeast, that is toward the shore of this basin (see Milewicz, 1997) indicates prevalence of onshore sediment transport. This state is consistent with the findings of studies of modern shoreface settings. Opposite directions of cross-stratification are also characteristic of coasts influenced by high tidal flows. The tidally produced cross-stratification displays, however, specific rhythmicity and mud draping (see Boer *et al.*, 1988, 1989), which were not recognized here. The massive sandstone may owe its structure to remodeling by sediment fluidization and redeposition by mass sand-flows. The occurrence of large-scale fluidization is distinctively recorded in the Żerkowice Sandstone Member in the quarry at Żerkowice. However, sediment mixing by thorough bioturbation of *Macaronichnus segregatis* (*e.g.*, Gerard & Bromley, 2008, p. 79, IF2) cannot be excluded as well. This trace fossil is typical of upper shoreface sandstone and is rarely clearly visible (cf. Gerard & Bromley, 2008). This particularly concerns clean sandstones lacking adequate admixture of organic matter, mud or minerals differing clearly in colour from the main rock component. These features fully correspond to those of the sandstone in question.

The rarity of trace fossils in the Żerkowice Member may result from low stability of the sandy substrate caused by high water energy and deficiency of food in the depositional environment. Such environmental conditions are indicated by good sediment sorting and type of its stratification. These circumstances must have significantly limited colonisation of these sediments by animals and their burrowing activity.

The kaolinitic clayey mudstone resting on the Żerkowice Sandstone Member shows mineral composition (dominance of kaolinite among clay minerals) and colours similar to a saprolite, which is the *in-situ* product of subaerial weathering. However, the mudstone differs from a true saprolite in showing a sharp, flat surface covered with ironstone crust, against the underlying sandstone, a very homogeneous texture in the lower part of the bed and the occurrence of parallel lamination marked with silty material in its upper part. The sharp boundary to the underlying sandstone, being parallel to the sandstone stratification, together with the parallel silty laminae in the upper part of the bed suggest transportational origin of the clayey mudstone rather than being due to production by weathering processes in place, as is the case in a true saprolite (see Aleva, 1983). It seems rather that the mudstone consists of material flushed from a saprolite occurring in adjacent areas. Its location in the succession, together with the above mentioned features, suggest an offshore lacustrine depositional setting. Lack of organic matter and bioturbation imply deposition in a highly oligotrophic lake. A considerable oligotrophy of this lake can be inferred from its development over the area covered by clean sand. The vertically elongated, rootlike mottles recorded in the red band within a small flexure are apparently of tectonically induced diagenetic origin and mark zones of sediment tearing.

The colour mottling and banding of the clayey mudstone, as well as the occurrence of ironstone crust at the contact with the underlying sandstone seem to be formed due to the passing of these deposits through an episode of a fluctuating redox front. Such circumstances normally take place in a zone affected by fluctuating groundwater. The white coloured bands represent bleached zones deprived of iron due to the occurence of reducing conditions. Iron liberated from these zones was transferred to oxidation zones where it reprecipitated in oxides and hydroxides giving the orange, brown and cherry-red colours to the deposit. The contact surface of the Żerkowice Member sandstone and the Nowogrodziec Member clayey mudstone formed a baffle to the movement of pore fluids enclosed within the highly permeable sandstone. This surface behaved similarly to the wall of a water pipe.

Deposits overlying the clayey mudstone up to the top of the upper coal seam (units 3–5 in Fig. 4) show features indicative of sedimentation in a shallowing lake, in an area undergoing gradual transformation into a marsh. Sedimentation became dominated here with silt and fine sand. Some parts of the area were occasionally overgrown with smaller marsh plants and aquatic plants, as is indicated by the small size of roots and the intensely soft-sediment deformed muddy substrate together with its lateral passage into finer-grained sediment, lacking plant roots. The area was fed with local and drifted plant material forming locally thin peat layers (now coal seams), containing dispersed large fragments of wood. The appearance of *Teredolites clavatus* in large wood fragments contained in unit 5, and particularly the extensive occurrence of this trace fossil at the top of the upper coal seam, together with other trace fossils contained in this bed, indicate incursion of marine waters in the area. Noteworthy are the rare, sand-built structures reminding of *Thalassinoides*, recorded in the coal seam of unit 4. These are actually the first indicators of the initiation of marine influences in the area. Both of these two ichnotaxa recorded in coaly substrate represent the *Teredolites* Ichnofacies, considered as being confined to marine and marginal marine (brackish-water) settings (*e.g.*, MacEachern, *et al.*, 2007a). In this case, they suggest that the area could transform into a shallow subtidal zone of a lagoon. Consequently, the trace fossils show that marine incursion in this area occurred much earlier than it was suggested by Milewicz (1956, 1965, 1970).

Continuation of the trace fossils contained in the coal seam of unit 5 in the overlying sediment, together with the high organic matter content characteristic of the coal precursor, suggest rather postdepositional colonisation of the flooded peat bog. Moreover, crosscutting relationships of the trace fossils contained in the coal bed indicate a gradual biocoenosis change. The producers of *Teredolites clavatus* were probably the first macroanimals that penetrated this bed.

The different outline of the two *Thalassinoides* ichnospecies recorded in the coal seam of unit 5 seems to result from their distinct compaction. Crosscutting relationships indicate that the more flattened ichnotaxon was produced earlier and therefore underwent higher compaction than that showing the more rounded outline in vertical cross-section.

Units 6 and 7 show features indicative of deposition in a period of gradual decrease of sand supply and decreasing bottom-water energy. Such conditions could have resulted from gradual deepening of the area. Unit 6 shows features characteristic of deposition on a gradually deepened micro-tidal margin of a lagoon. Lagoonal origin, in a subtidal zone, is inferred from the relatively fine sediments, intense bioturbation, trace fossils of *Cruziana* Ichnofacies lacking some fossils characteristic of open marine setting, and the absence of a shelly fauna and lack of tempestites. The vertical distribution of trace fossils in unit 6 showing the upward disappearance of large, bedding-parallel and oblique burrows, namely the thickly mud-lined *Palaeophycus* isp., *Thalassinoides*, *Asterosoma* and *Teichichnus*, and the expansion of diminutive, vermiform burrows suggest development of environmental stress due to salinity reduction and reduced oxygenation during sedimentation of these deposits (see MacEachern *et al.*, 2007c; Hauck *et al.*, 2009). Their lower part shows features indicating deposition in slightly brackish water, whereas the upper part implies deposition in highly brackish, poorly oxygenated benthic water. Poor oxygenation is particularly suggested by the diminutive, vermiform burrows. They fully resemble burrows of recent polychaete *Capitella* cf. *aciculata* (Hartman) that is most abundant in areas composed of heterolithic sediments of anoxic, organic-rich sedimentary environments (Hertweck, 1972, *vide* Hertweck *et al.*, 2007).

Unit 7, comprising mudstone containing several clay ironstone (siderite) beds, and lacking distinctive trace fossils and body fossils, implies deposition in a stressed environment of low water energy, reduced salinity and possibly increased turbidity (see MacEachern & Pemberton, 1994; MacEachern *et al.*, 1999). This presumably was an off-margin part of a brackish lagoon. Very uniform, mudstone development over the whole quarry, suggests that the unit records the time of maximum transgression for the part of the Czerna Formation described in this paper. The maximum flooding surface is located in the coaly mudstone at the unit top. High organic matter content together with restriction of burrows to the upper part of the coaly mudstone bed and occurrence of *Chondrites* as the first-produced trace fossil, suggest that this mudstone represents time of minimum oxygenation of benthic water. Moreover, the appearance of *Chondrites* suggests some increase of water salinity, and, consequently, an increase in connection of this area with the open sea.

The deposits that overlie the Nowogrodziec Member in the investigated part of the Czerna Formation display features indicative of sedimentation in a shallow-marine, brackish environment, on an intermittently prograding shoreface. A brackish environment is indicated by the macrofauna recorded in these deposits (see Milewicz, 1965, 1970) and the foraminifera described from the lower part of the Czerna Formation (see Alexandrowicz, 1976; Gawor-Biedowa, 1991). Sedimentation on the intermittently prograding shoreface is pointed out by the pattern of succession, consisting of stacked, coarsening-upward units, and its bioturbation structures representing the *Cruziana* and *Skolithos* ichnofacies. Relatively high bioturbation intensity and rich brackish fauna, including shells in life position, indicate deposition in a rather small, semiconfined basin of low hydraulic energy, richly fed with fresh water. Rich, fine-grained plant detritus contained in heteroliths, together with brackish fauna, suggest deposition influenced by deltaic distributary, perhaps in a sheltered, quiescent cove of a lower delta plain. Distribution of these and coeval deposits in the region indicate deposition in a bay. The small thickness of the coarsening upward units showing features indicative of deposition from a lower shoreface to upper shoreface setting implies shallow depths of this part of the basin.

The clean, massive sandstone forming the upper parts of the coarsening-upward units display features indicative of high energy settings. Some thin beds could have been deposited by storm-controlled processes. Some other beds, together with the thickest, wedge shaped units, represent sand bars formed in the upper shorface zone.

The duplex structure and the thrust faults recorded in the Nowogrodziec Member are of tectonic and not synsedimentary origin as suggested by Milewicz (1956). Their postsedimentary origin is indicated by only tectonic modification of the succession, without any changes of sedimentary features. Eastward dipping thrust planes indicate a southeast-northwest oriented compression in the area, that is perpendicular to that in which the whole Cretaceous basin was modelled during the Laramian orogeny. It seems that such compression could occur in the Miocene due to the intrusion of lava recorded in a basaltic neck located 2 km east of the quarry, in the village of Żerkowice.

Palaeogeographic implications

Depositional environments recorded in the Upper Cretaceous deposits of the Sudetes and their surroundings indicate distinct palaeogeographic reorganization of the region. Stratigraphic maps and facies distribution (see Milewicz, 1997; Voigt *et al.*, 2008) indicate sedimentation of the Żerkowice Member due to and during a forced regression. Its sedimentation was terminated due to sea retreat. In the North Sudetic Basin, the sea retreated to the northwest (Fig. 17A). At that time, the northwestern stretch of the Żerkowice Member lithosome marked the basin shore and its shoreface whereas its souteastern counterpart blanketed the adjoining, elevated coastal plain. The outer fragments of the lithosome, located outside of the present North Sudetic Basin, could experience erosion up to complete removal during final stages of the regression and the subsequent stillstand. Thus, the upper boundary of the Żerkowice Member in these areas can by deeply erosional, becoming older outside the lithosome. In contrast, in areas of basin shore and shoreface, located inside the present North Sudetic Basin, termination of the Żerkowice Member sedimentation resulted in its burial with deposits of lower energy environments, laid down during a new transgression. The latter development seems to have occurred in the study area. Such conclusion is inferred from the absence of either a saprolite cover on the sandstone or distinctive erosion of its top, which normally reflect prolonged emersion. This is also consistent with the upward transition of the sandstone into lacustrine clay passing upward into paludal deposits. This type of environmental alteration was attainable by a fast, tight separation of the area from the open sea by a sand barrier developed somewhere offshore (Fig. 17B). As a result, the area became transformed from a marginal part of sea into a coastal lake. Occurrence of clay resting on foreshore sandstone suggest rapid expansion of that lake.

One cannot exclude the possibility that the above inferred sand barrier is actually recorded by the zone of sandy deposits coeval with those of the Nowogrodziec Member, recognised by drillings in the central the North Sudetic Basin (Milewicz, 1997, 2006). This zone commences *ca.* 10 km northwest of the study area. The barrier could have been formed during a stillstand between the regression related to the sedimentation of the Żerkowice Member and commencement of a new transgression responsible for the deposition of the Nowogrodziec Member. Similar transformation of a coastal area was suggested by Carter (1979) for the Quaternary development of Gippsland (Australia). It is noteworthy that the above-presented evolution of the area does not exclude different developments of adjoining areas, particularly those located southeast of Rakowice Małe. These areas could experience erosion and non deposition before they became covered by the Czerna Formation.

The Nowogrodziec Member was that which started to develop in the lake and adjacent non-marine environments. Its middle part records transformation of the lake into marsh (Fig. 17C). This happened when sediment supply to the area outpaced the accommodation space in the lake. Local occurrence of two horizons containing root structures indicate lateral shift of pathways of increased sediment supply to the area. The appearance of the trace fossils *Teredolites clavatus* and *Thalassinoides* isp. in the upper part of this unit indicate time of marine incursion. Increased influence of marine waters occurred at least during the sedimentation of the unit overlying the upper coal seam, as is suggested by its intensive burrowing, including trace fossils indicative of the *Cruzian*a Ichnofacies. A new episode of gradual deepening of the area, associated with decreasing salinity of water, is recorded by the top part of the member (Fig. 17D). This part of the succession also implies sedimentation during the advanced transgression up to maximum flooding. The top part of the succession overlying the Nowogrodziec Member shows features indicative of the initiation of a regressive phase. Its character, that is whether this was a forced regression or a normal regression, remains unclear. The trace fossils and body fossils suggest the development of a setting showing increased water salinity relative to that associated with the deposition of the upper part of the Nowogrodziec Member. This suggestion implies some improvement of the connections of the area with the open sea (Fig. 17E).

SUMMARY AND CONCLUSIONS

The Upper Cretaceous deposits that crop out at Rakowice Małe, North Sudetic Basin, comprise a conspicuous lithofacies and ichnofossil record of paralic sedimentation. Ichnofossils provide valuable data, particularly on the origin of the Czerna Formation. The occurrence of 14 ichnogenera and at least 16 ichnospecies is inferred from the recorded sediment features. The trace fossils represent the ichnofacies *Skolithos*, *Teredolites* and *Cruziana*. *Cruziana* Ichnofacies is represented by richest trace fossil assemblage and occurs in several expressions suggestive of stressed, brackish, and poorly oxygenated environments.

The Żerkowice Member is of upper shoreface to foreshore origin. This is indicated both by lithofacies and ichnofossils. Its large-scale cross-stratified sandstone was deposited as a fill of chutes and as wave-formed bars. The massive sandstone seems to have originated mainly from deposition by mass-sand flows (fluidised flows).

The ironstone crust at the top of the Żerkowice Member is of intraformational origin. It was formed together with colour banding and mottling of the overlying clayey mudstone of the Nowogrodziec Member due to the influence of a fluctuating redox front.

The Nowogrodziec Member comprises deposits of a gradually drowned area that was transformed from a lake through a marsh to a brackish lagoon. The lacustrine origin

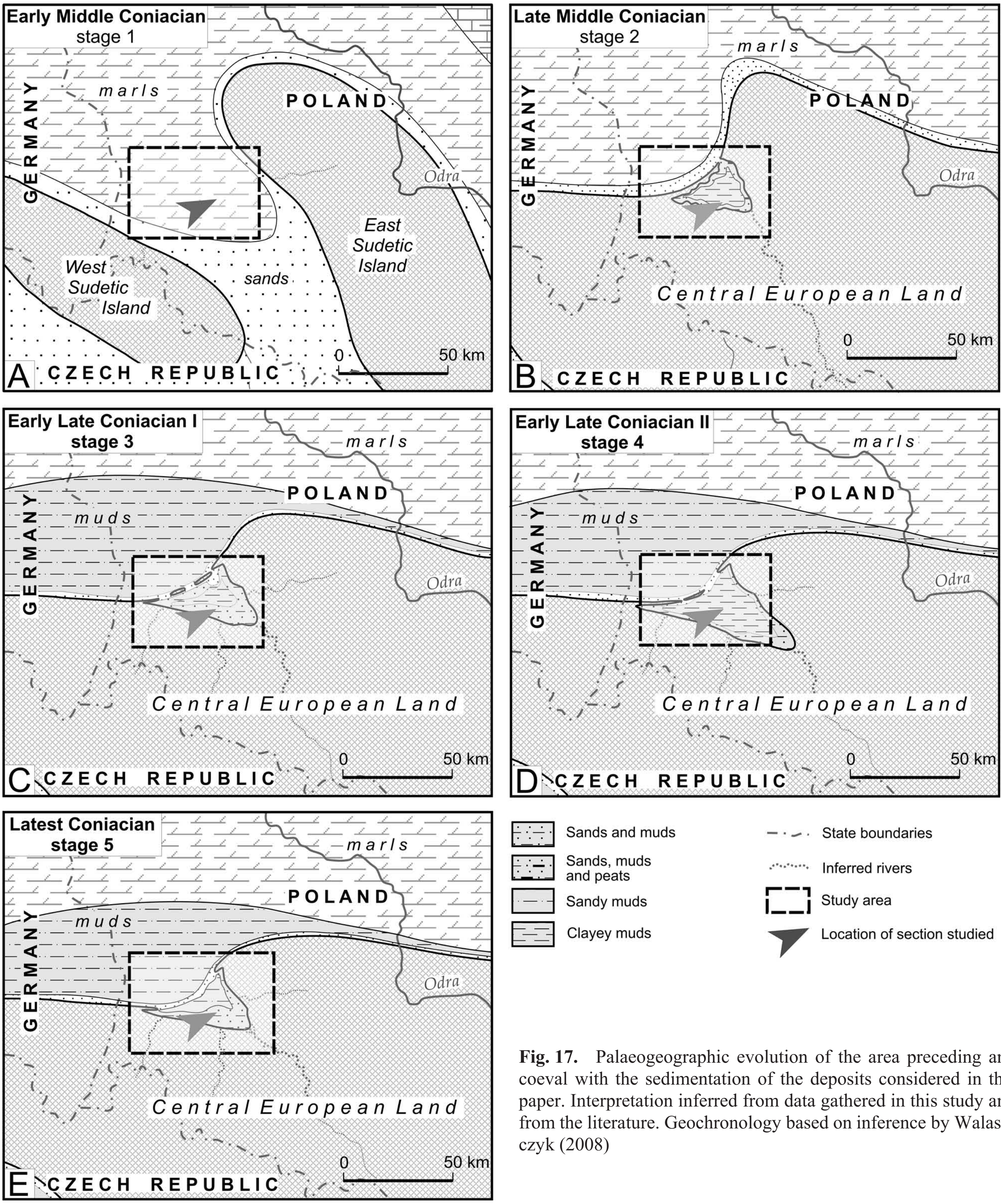

Fig. 17. Palaeogeographic evolution of the area preceding and coeval with the sedimentation of the deposits considered in this paper. Interpretation inferred from data gathered in this study and from the literature. Geochronology based on inference by Walaszczyk (2008)

refers to variegated, clayey mudstone at the base of the Nowogrodziec Member and is inferred from the dominance of kaolinite and the lack of burrows in these deposits. Paludal sedimentation is documented in the overlying part of the succession by two beds containing plant roots and fragments of driftwood. Incursion of marine waters to the area is indicated in muddy sandstone separating the coal seams by the appearance of wood fragments containing the bioerosion trace fossil *Teredolites clavatus* and the burrow *Thalassinoides* isp.

Maximum flooding related to deposition of the succession occurred during the sedimentation of coaly mudstone that is located at the top of the Nowogrodziec Member. At that time, the area obtained a broader connection with the open sea as is indicated by the appearance of thick bodies of clean sand, shelly fauna and the trace fossils *Asterosoma*, *Ophiomorpha* and *Skolithos*. Some shallowing due to normal regression is recorded in this part of the Czerna Fomation. It was deposited on an intermittently progressing shore of a bay adjacent to the delta .

There was probably no significant gap between the termination of the Żerkowice Member sedimentation and commencement of the Nowogrodziec Member sedimentation in this area. The change of depositional environments recorded between these units resulted from the stopping of the forced regression and separation of the area from the open sea by a sand barrier.

The occurrence of brackish-water deposits in the examined succession is related to deposition in a marginal-marine sedimentary system developed in a low relief area, showing restricted connection with the open sea and richly fed with fresh water. Saline water was probably supplied by tides.

The Czerna Formation segment examined in this paper seems to represent a 5th order T-R cycle topped by sediments of normal regression. The location of the upper boundary of this cycle is not clear because the overlying deposits were removed during a post-Santonian erosion.

The duplex structure and the thrust faults recorded in the Nowogrodziec Member are of postsedimentary, volcano-tectonic origin. They were formed due to upbulging of the area during the initiation of the volcano recorded as a basaltic neck at Żerkowice village. The volcanotectonic initiation is indicated by only structural modification of the entire sedimentary succession.

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