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# THE GRAJCAREK SUCCESSION (LOWER JURASSIC–MID PALEOCENE) IN THE PIENINY KLIPPEN BELT, WEST CARPATHIANS, POLAND: A STRATIGRAPHIC SYNTHESIS

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**Abstract:** A concise stratigraphic synthesis of the Grajcarek Succession of the Pieniny Klippen Belt (West Carpathians, Poland) is presented. This succession consists of 12 lithostratigraphic units with the rank of formation, and two with the rank of member, spanning the geological time from middle Toarcian (late Early Jurassic) to Maastrichtian (Late Cretaceous) and mid Paleocene. The stratigraphical column starts with deep-water flysch (the Szlachtowa Fm; Toarcian–Aalenian through Bajocian–?lower Bathonian), followed by dysoxic shales, marls and limestones (the Opaleniec Fm; Bajocian–Bathonian). The previously distinguished Krzonowe and Stembrow formations, are downgraded to members. Late Bathonian–Oxfordian times were characterized by the widely occurring deposition of abyssal radiolarites and shales, which is represented by the Sokolica Radiolarite Fm and the Czajakowa Radiolarite Fm, common to both the Grajcarek and Klippen successions. Red nodular limestones and aptychus marls (the Czorsztyn Limestone Fm; Kimmeridgian–lower Tithonian) overlie the radiolarites. Above, pelagic cherty limestones occur (the Pieniny Limestone Fm; Tithonian–Aptian). These are followed by Lower Cretaceous predominantly dark shales and marls (the Kapuśnica Fm; Aptian–Albian, the Wronine Fm; Albian, and the Hulina Fm; Albian–Cenomanian), succeeded by abyssal, red shales (the Malinowa Shale Fm; upper Cenomanian–Campanian), and these in turn by grey, marly, flyschoid strata (the Hałuszowa Fm; ?Campanian). The Grajcarek Succession terminates with the Jarmuta Fm (Maastrichtian–mid Paleocene). It consists of sedimentary breccias, often with large olistoliths of Jurassic–Cretaceous rocks, and conglomerates and sandstones in a southern zone, giving way to proximal flysch and distal flysch facies further north. This was the time of orogenic Laramian folding events, associated with subaerial and submarine erosion. A sedimentary hiatus separates the Jarmuta Fm flysch (Maastrichtian) from the Szczawnica Fm (Upper Paleocene–Eocene) in both the Klippen and Grajcarek successions. This hiatus seems to diminish and finally close in a northward direction, in the Magura Nappe succession.

**Key words:** Pieniny Klippen Belt, Grajcarek Succession, West Carpathians, Poland, Jurassic, Cretaceous, stratigraphy.

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## INTRODUCTION

During early (1950s to 1960s) geological mapping at the 1:10,000 scale of the Pieniny Klippen Belt (PKB; Fig. 1) in Polish Spisz, between the village of Czorsztyn and the Białka River (Fig. 2), it was found that Jurassic klippes, located to the north of the Czorsztyn Succession row of klippes, show a strong similarity to the development of the Branisko Succession/Nappe. Consequently, they were included to the latter and the Czorsztyn Succession row of klippes was treated as being exposed in a tectonic window from below the Branisko Nappe (see, e.g., Birkenmajer, 1961, 1963b, 1965). This was later revised and reinterpreted and a new Grajcarek Unit/Succession was created (Birkenmajer, 1970a, b, 1977, 1979).

The Grajcarek Unit (tectonic; see Birkenmajer, 1970b) stretches along the northern part of the PKB (Fig. 2). It consists of strongly folded Jurassic through Maastrichtian and lower Palaeogene sedimentary formations, some of which are in common with the Klippen successions (i.e., the Czorsztyn, Czertezik, Niedzica, Branisko and Pieniny successions; see Fig. 3), while others are typical for the Grajcarek Unit itself. They form the stratigraphic Grajcarek Succession.

During Jurassic through mid Paleocene history, the Grajcarek Succession, belonging to the Northern Tethys realm (e.g., Michalík, 1994), was deposited in an oceanic trough (the Grajcarek Trough), that opened in the southernmost part of the Magura Basin, as a result of the break-up of

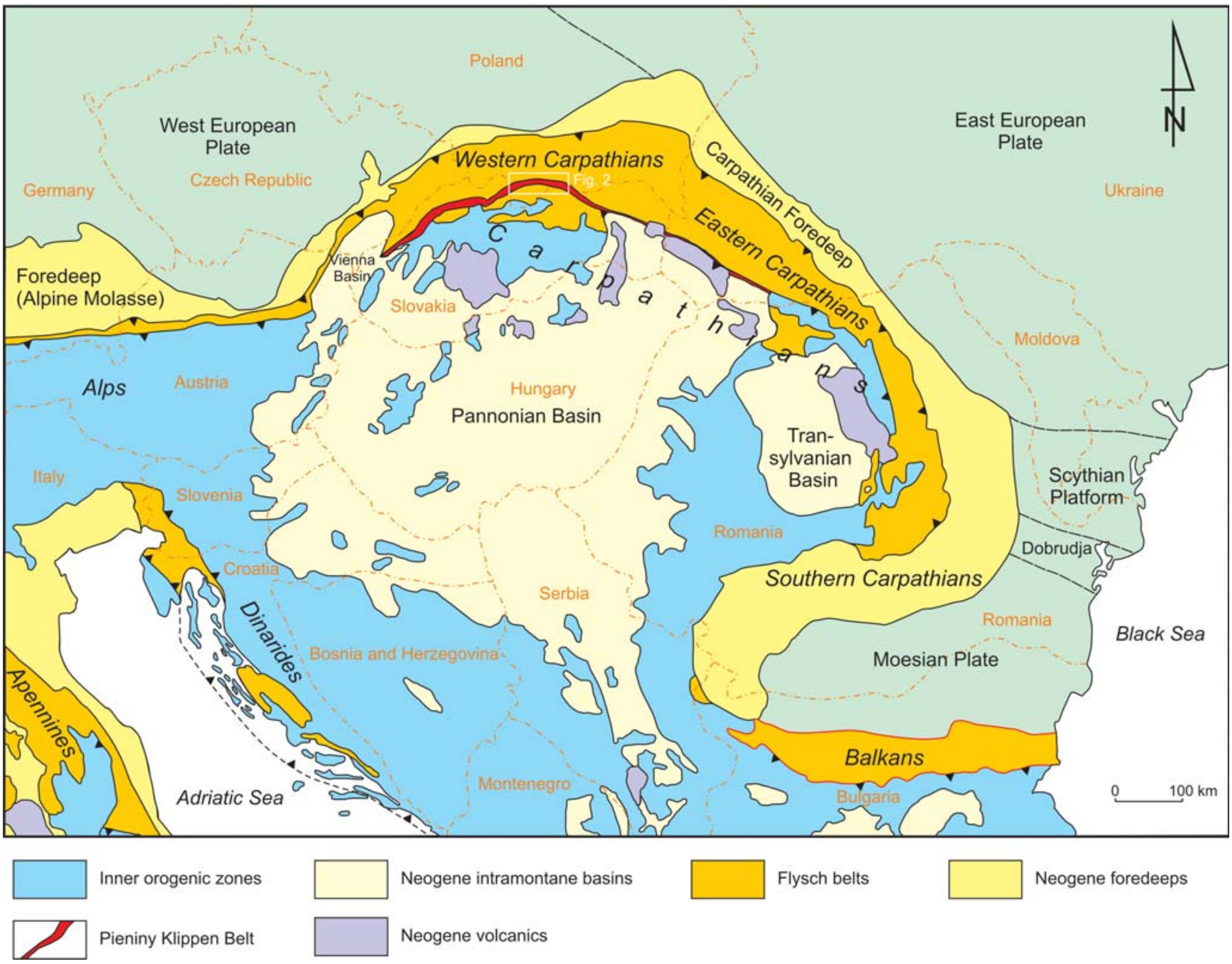


**Fig. 1.** Position of the Pieniny Klippen Belt in the Carpathians (based on Picha, 1996; from Picha *et al*., 2006; slightly supplemented).

the Triassic platform, due to rifting of the North European plate (e.g., Birkenmajer, 1986; Ślączka *et al*., 2006; Plašienka, 2012). During its history of nearly 130 Ma (Early Jurassic–mid Paleocene), the Grajcarek Trough was separated from the Pieniny Klippen Basin proper by the Czorsztyn Ridge, a splinter of the North European Platform (pre-Upper Carboniferous through Triassic; Fig. 3) with Triassic and pre-Triassic basement rocks and an open-sea Jurassic sedimentary cover. The division between the two basins – the Grajcarek Trough and the Klippen basins – was never complete. Particular sedimentary formations often crossed the Czorsztyn Ridge, becoming common to the two basins: e.g., the Lower–Middle Jurassic Szlachtowa Fm ("black flysch"), the Middle–Upper Jurassic radiolarites (Sokolica and Czajakowa Radiolarite formations), and pelagic cherty limestones (Pieniny Limestone Fm; uppermost Jurassic–Aptian). The Czorsztyn Ridge impacted on its Jurassic deposits with tremors and submarine faulting during times of an extensional regime that predominated in the adjacent Klippen and Magura (Grajcarek) basins (see Birkenmajer, 1958b; Birkenmajer and Gąsiorowski, 1963).

The Grajcarek Unit is best recognized in Poland between Nowy Targ in the west and Jaworki-Biała Woda in the east (Fig. 2). Its eastern prolongation is recognizable in East Slovakia, Transcarpathian Ukraine and as far away as NE Romania (Poiana Botizei). So far, its presence in the PKB of the western Slovakia is uncertain. The Grajcarek Unit consists of 12 lithostratigraphic formations: the Szlachtowa Fm (with the Krzonowe and Stembrow members, previously designated as formations), the Opaleniec Fm, the Sokolica Radiolarite Fm, the Czajakowa Radiolarite Fm, the Czorsztyn Limestone Fm, the Pieniny Limestone Fm, the Kapuśnica Fm, the Wronine Fm, the Hulina Fm, the Malinowa Shale Fm, the Hałuszowa Fm, and the Jarmuta Fm. They represent a succession of strata, starting from the Early Jurassic (Toarcian) and ending with the mid Paleocene (Birkenmajer, 1977, 1979). The age of the Bryjarka Fm (*sensu* Birkenmajer *et al*., 1979) is now under re-examination and this lithostratigraphic unit has been excluded from the Grajcarek Succession.

Since the 1970s, when the main framework of the Grajcarek Unit/Succession concept was created (e.g., Birkenmajer, 1970a, b, 1977, 1979), some new data, particularly biostratigraphic ones, were published. In this paper, the authors present a stratigraphic synthesis of this unique geological structure.

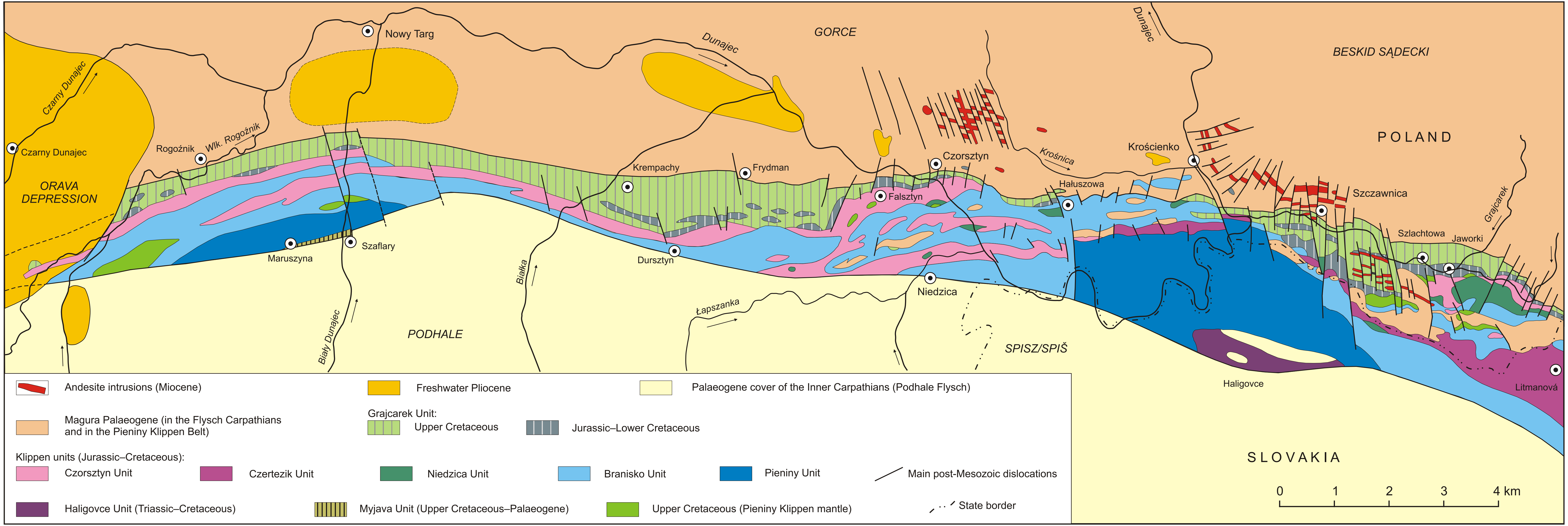


**Fig. 2.** Simplified geological structure of the Pieniny Klippen Belt of Poland (after Birkenmajer, 1979; slightly modified and updated after Birkenmajer, 2017).

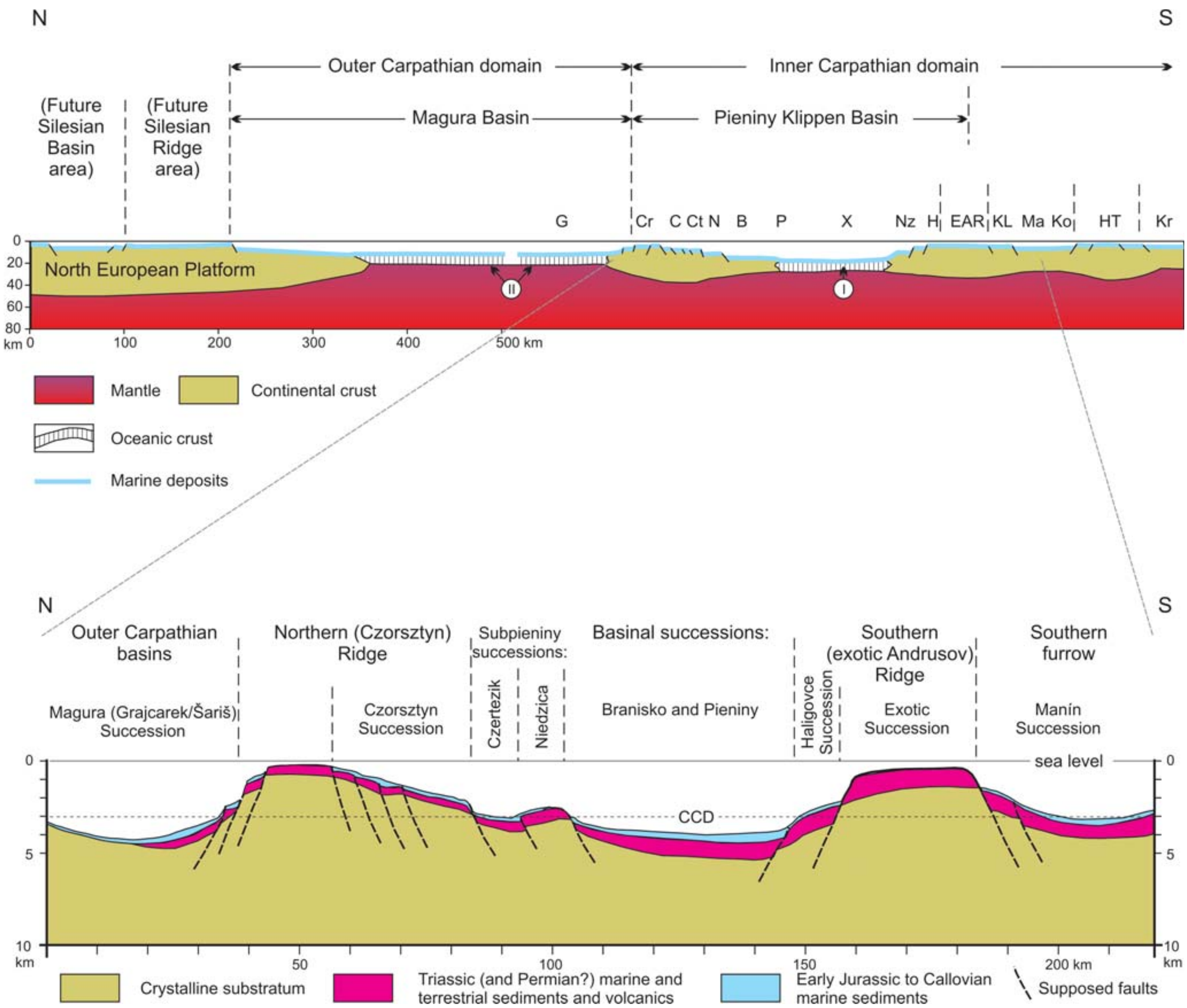


**Fig. 3.** Palinspastic reconstruction of the Pieniny Klippen Belt and adjoining areas during the Oxfordian and the relationship of the Grajcarek Succession to the Klippen successions (after Birkenmajer, 1986, explanations slightly modified). G – Grajcarek Succession; CR – Czorsztyn Ridge; C – Czorsztyn Succession; Ct – Czertezik Succession; N – Niedzica Succession; B – Branisko (+ Kysuca) Succession; P – Pieniny Succession; X – "Ultra-Pieniny succession"; N – Nižna Succession, H – Haligovce Succession; EAR – Exotic Andrusov Ridge; KL – Klape Succession; Ma – Manín Succession; HT – High Tatric Succession; Kr – Krížna (Subtatric) successions. Oceanic crust: I – Triassic–Early Jurassic; II – Early Jurassic.

## GEOLOGICAL BACKGROUND

The Pieniny Klippen Belt (PKB) – an important tectonic zone of the Western Carpathians, bordered both to the north and the south by strike-slip boundary fault zones of Miocene age (Birkenmajer, 1979, 1983) – separates the Inner Carpathian domain from the Flysch (Outer) Carpathians to the north (Fig. 1). It forms an elongated, arcuate structure that stretches over a distance of nearly 600 km from the vicinity of Vienna, Austria, through the territories of Poland, Slovakia, and Ukraine, to Romania, being rarely wider than 4–5 km, with a highly complicated tectonic structure (Fig. 1). The PKB consists of predominantly Jurassic–Lower Cretaceous carbonates forming isolated tectonic "klippen" or olistoliths, embedded mainly in Upper Cretaceous–Cenozoic marly or flysch deposits (e.g., Andrusov, 1945; Birkenmajer, 1977, 1986; Mišík, 1978, 1997; Plašienka and Mikuš, 2010; Plašienka *et al.*, 2012; Plašienka and Soták, 2015).

This complicated structure of the Pieniny Klippen Belt results from at least two folding phases that caused the strata accumulated in a once vast ocean (Lower Jurassic to Upper Cretaceous strata; Triassic deposits are infrequent) to assume their present tectonic form. During the first folding phase, which took place during the latest Cretaceous–earliest Paleocene (Laramian phase), a marginal part of the Magura Basin (i.e., southernmost part of the Outer Carpathian basins system), was tectonically incorporated into the Klippen Belt as the Grajcarek Unit in Poland (e.g., Birkenmajer, 1986; known as the Šariš Unit in the Slovak sector of the PKB; e.g., Plašienka and Soták, 2015). The subsequent folding phase took place during Late Oligocene–Early Miocene times.

Reconstruction of the basin systems under consideration shows a set of more or less parallel, longitudinal basins/facies zones with the shallowest zone (the Czorsztyn Ridge) separating them from the Outer Carpathian domain (i.e., the Magura Basin) to the north. The southern slopes of the Czorsztyn Ridge were occupied by the Czertezik and Niedzica successions, whereas the Branisko and Pieniny succssions were located in the basinal zone (e.g., Birkenmajer, 1977; Fig. 3).

In Poland, and in Eastern Slovakia, in the southern boundary fault zone, various Mesozoic units of the PKB are juxtaposed against the monotonous Oligocene flysch (Podhale Flysch) of the Inner Carpathians. In the northern boundary fault zone, Mesozoic rocks of the PKB make contact with strongly folded flysch sediments of the Miocene Magura Nappe, belonging to the Outer Carpathians. In Poland, in the area between Kluszkowce (in the west) and Jaworki (in the east), a number of mid Miocene andesite dykes and sills (e.g., Birkenmajer, 1957a, 1979, 2003; Birkenmajer and Pécskay, 1999, 2000; Pécskay *et al.*, 2015) traverse the adjoining Magura Nappe and the northern unit of the PKB, the Grajcarek Unit (Fig. 2).

The northern boundary fault zone was studied, i.a., with the use of detailed geological mapping (1:10,000 and 1:5,000 scales), and boreholes. The total depth of the deepest of these (PD-9, at Szczawnica) was nearly 1,200 m (Birkenmajer, 1968; Birkenmajer *et al.*,1979). The tectonic contact between the PKB and the Magura Nappe is readily recognizable in the Grajcarek Stream valley at Szczawnica.

The basement of the PKB structure is unknown. The deepest borehole, Maruszyna IG-1, reached a total depth of 4,843 m in almost vertically dipping strata of the Branisko Unit (e.g., Birkenmajer and Gedl, 2012).

## STRATIGRAPHY OF THE GRAJCAREK SUCCESSION

### The Szlachtowa Formation

The Szlachtowa Fm (Toarcian–Aalenian through Bajocian–?lower Bathonian) is the oldest lithostratigraphic unit recognized in the Grajcarek Succession. In the Klippen successions, it occurs in the Czertezik, Niedzica, and Branisko successions where, usually, it is poorer preserved, owing to tectonic reductions caused by Upper Cretaceous/Paleocene nappe thrusting (Birkenmajer, 1958a, 1963d, 1977, 1979). The maximal thickness of the Szlachtowa Fm is in the Grajcarek Unit, where (near Jaworki) it reaches 220 m (Fig. 4; e.g., Birkenmajer, 1963d).

Triassic sedimentary rocks might be expected to occur at the base of the Szlachtowa Fm. However, even in the deepest PKB borehole, Maruszyna IG-1, steeply folded Jurassic and Cretaceous sedimentary rocks of the Branisko Nappe instead were observed down to 4,843 m below the surface and no trace of the Triassic basement was seen (Birkenmajer and Gedl, 2012). Some dark shale (Sinemurian) and shallow-marine/estuarine sands (Pliensbachian?; Stefan Józsa, pers. inf.) that occur in the vicinity of Beňova Lehota and Zázrivá, near Dolný Kubín (Slovakia), are presumably the trace of an older, pre- or syn-rift period that preceded opening of the Magura Basin (see Birkenmajer, 1986). Upper Pliensbachian marine limestone (the Szopka Limestone Fm), the oldest strata of the Polish sector of the PKB (Birkenmajer, 2008; see also Birkenmajer and Myczyński, 1994), accumulated in the Branisko and Pieniny basins.

#### *Distribution, lithology and sedimentology*

**Black flysch facies.** Between Czorsztyn and Jaworki (Czorsztyn Range and Małe Pieniny Range; Fig. 2), the Szlachtowa Fm is developed principally as dark grey to black, fine- to medium-grained, usually highly micaceous turbidites. Whitish conglomeratic sandstone and thin intercalations of grey, graded, crinoidal limestone bands are infrequent; the latter occur mainly in a lower part of the formation (e.g., Birkenmajer, 1957b, c, 1958a, 1963d, 1977, 1979; Krawczyk and Słomka, 1986, 1987; Krawczyk *et al.*, 1987). With the exception of crinoid-bearing turbidite intercalations, the rocks are non-calciferous or only slightly calciferous. This is also expressed in the very minor presence of calcareous microfossils, and very seldom found, usually poorly preserved, ammonite shells. Delicate *Bositra* shells are often damaged in stronger tectonized parts of the formation and only massive *Gryphaea* shells (in the Krzonowe Mbr) are well preserved. The best exposures of the black flysch facies of the Grajcarek Unit presently are in the lower courses of Sztolnia and Krupianka creeks, near Jaworki (Figs 4, 5; Birkenmajer, 1979, pp. 205–207; Gedl, 2008d), Szlachtowa and Szczawnica-Rzeźnia (Figs 6–8; Birkenmajer, 1979, pp. 191–193; Gedl, 2013), and Krzonowe, Polish Spisz (Fig. 9; Birkenmajer and Tyszka, 1996). Poorer, though stratigraphically important exposures are in the Hałuszowa Stream, Czorsztyn Pieniny Range (Gedl, 2007a).

**Black shale facies.** The black shale facies often replaces the flysch facies, e.g. at Sztolnia Creek, Hulina, Tylka, and Krempachy–Dursztyn (Fig. 2). In Sprzycne Creek, north of Dursztyn (Polish Spisz; Birkenmajer, 1961, 1963b; Segit *et al.*, 2015), the Szlachtowa Fm is developed mainly as a black shale facies. In this exposure, Segit *et al.* (2015) described a shaly interval, interpreted as the uppermost part of the Skrzypny Shale Fm (on the basis of the presence of sideritic concretions), underlying the Szlachtowa Fm. In the opinion of the present authors, however, the presence of micaceous sandstone layers in this part of exposure (Segit *et al.*, 2015, fig. 6.3) shows that it represents a shaly facies of the Szlachtowa Fm. Sideritic concretions cannot be treated as indicators of the Skrzypny Shale Fm, since they are common also in the Szlachtowa Fm; e.g., Birkenmajer (1977, p. 27). The shales are often very similar to those of the Lower Cretaceous strata (i.e., the Wronine and Hulina formations). Without careful sampling and age determination of fossils (microfossils), this easily might cause misinterpretation of the geological structure (see Birkenmajer *et al.*, 2008).

At Mt. Hulina (Szczawnica Niżna, Małe Pieniny Range; Fig. 10), along an old forest road, a tectonically complicated section crops out to reveal the Jarmuta, Malinowa Shale, Hulina, Wronine, Pieniny Limestone, Sokolica Radiolarite, Opaleniec, and Szlachtowa formations in black flysch and black shale facies (Birkenmajer and Gedl, 2007). In Kręty Stream and Kiźlinkowy Stream, south of Krempachy (Polish Spisz – Birkenmajer, 1961; 1965; 1979, excursion 6; Gedl,

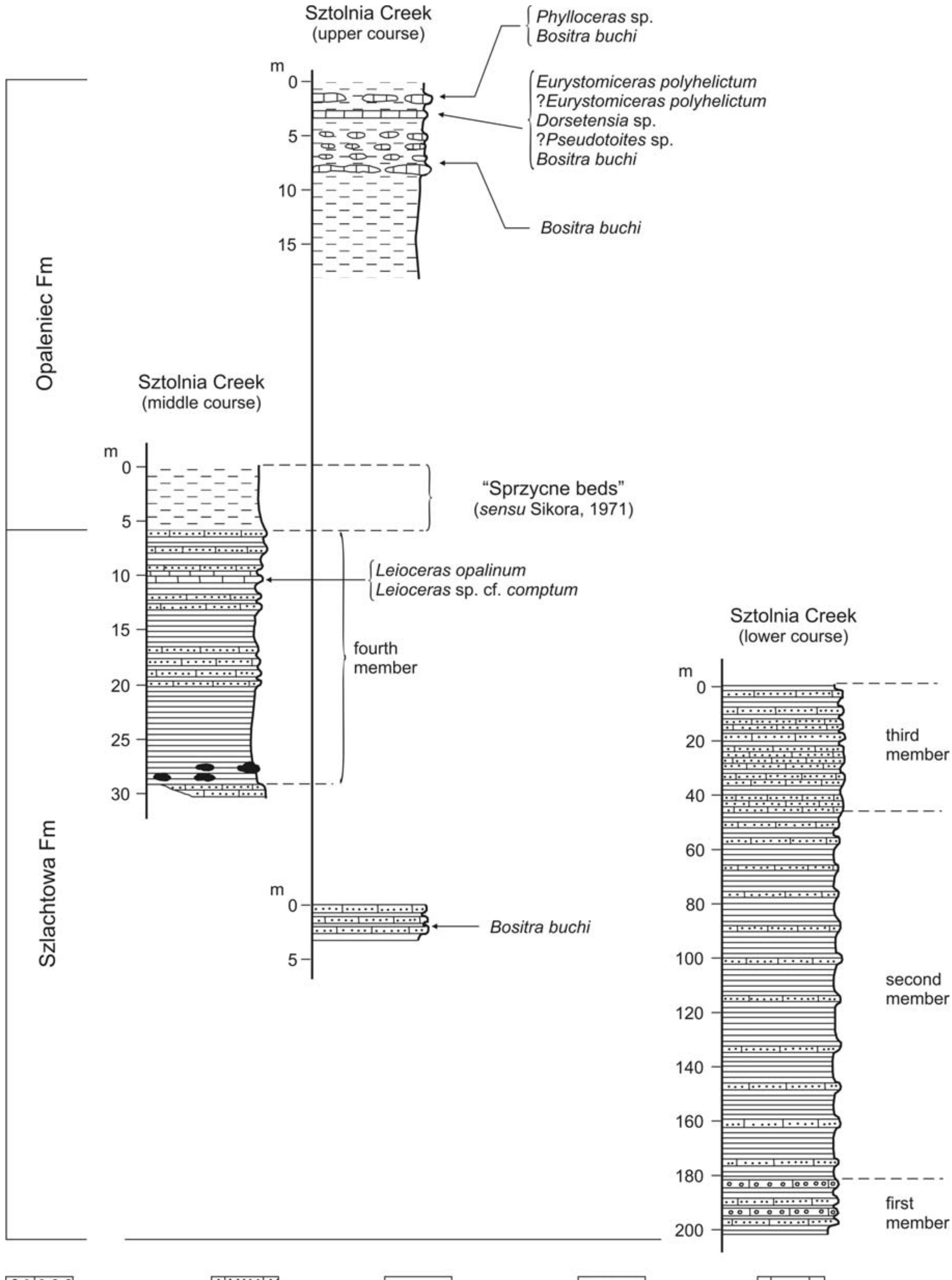


**Fig. 4.** Lithostratigraphic columns of the Szlachtowa Fm and the Opaleniec Fm (Grajcarek Succession) in Sztolnia Creek, near Szlachtowa (Małe Pieniny Range). From Birkenmajer and Myczyński (1977).

2008a; Fig. 11), the Szlachtowa Fm is developed both in black flysch and black shale facies.

**Sources of clastics: long-distance transport (turbidites).** The Szlachtowa Fm flysch represents a submarine turbidite fan, which was fed predominantly from a distant, eastern source. This is indicated by the measurements of infrequent current markings. The fan spread over the Grajcarek Trough, its terminal part crossing a submarine depres-

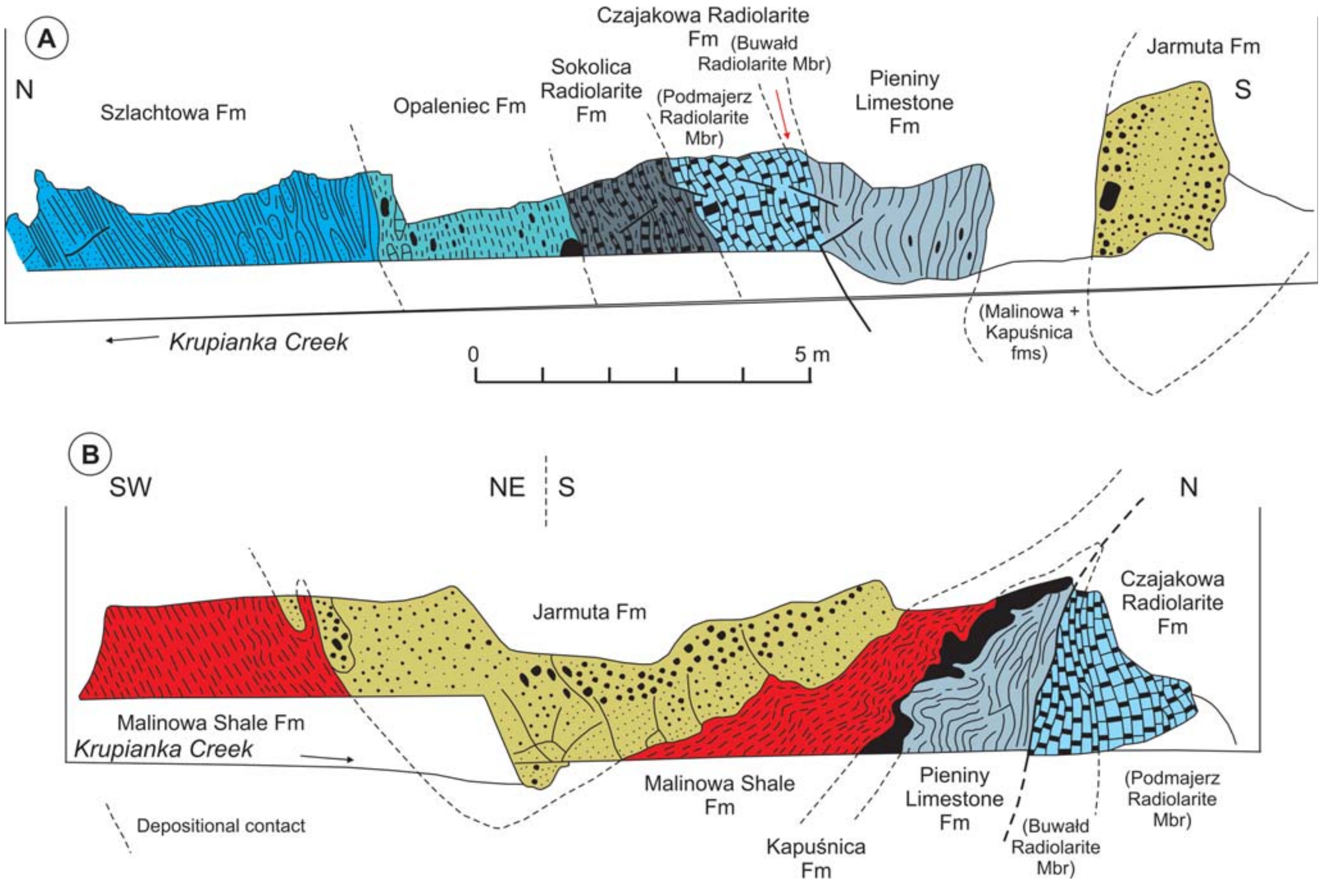


**Fig. 5.** Geological cross-section of the Grajcarek Unit in Krupianka Creek (after Birkenmajer, 1979). **A.** Eastern creek bank. **B.** Western creek bank.

sion on the Czorsztyn Ridge to reach the deepest part of the Klippen Basin (mainly the Branisko Succession). A possible source of the turbidites could be some Upper Carboniferous rock exposures in NW Romania (see below).

**Recycled Carboniferous microspores.** Thin, allochthonous coal intercalations in a turbiditic sandstone bed of the Szlachtowa Fm (lower part), once exposed below Czorsztyn Castle (see Birkenmajer, 1958a, III: fig. 66; now underwater in the artificial Czorsztyn Lake) yielded a recycled Late Carboniferous microspore spectrum (Birkenmajer and Turnau, 1962): *Sporonites unionus* (Horst) Dybova et Jachowicz, *Punctatisporites* sp., *Calamospora* sp., *Granulatisporites* sp., *Tuberculatisporites permagnus* Dybova et Jachowicz, *Lycospora granulata* Kosanke, *Annulatisporites baccatus* Dybova et Jachowicz, *Densosporites spinosus* Dybova et Jachowicz, *D.* sp. and *Cirratriradites saturni* (Ibrahim) Schopf, Wilson et Bentall. This assemblage is younger than Namurian A (occurrence of *C. saturni*), and older than Westfalian C (occurrence of *D. spinosus*). The source of this allochthonous coal intercalation could be the Carboniferous strata of coal basins, located in the Romanian Carpathians, which yielded most of the species mentioned above (see Popa, 2005). Moreover, these Romanian strata are very rich in mica flakes, so common in the Szlachtowa Fm.

**Short-distance transport.** Infrequent clasts of quartz-feldspar-mica-schist and gneiss (derived from the pre-Upper Carboniferous basement), dacite and rhyolite lava, tuff and lamprophyre (probably Permian volcanics) were recognized by Krawczyk and Słomka (1987) and Krawczyk *et al.* (1987). These, together with coarser quartz sand and quartzite clasts (derived from Werfenian rocks), small to medium size clasts of dolostone and limestone (derived from Middle Triassic rocks), and red, blue and variegated shale (derived from the Carpathian Keuper rocks) indicate short-distance transportation from the then emerged Czorsztyn Ridge (Birkenmajer, 1958a, 1963c, 2007).

This ridge also might have been a source of the recycled Triassic dinoflagellate cysts recognized by Gedl (2008d) and Barski *et al.* (2012) in the Szlachtowa Fm, exposed along the northern shore of the artificial Czorsztyn Lake, between Czorsztyn Castle and Harcygrund Valley. The Szlachtowa Fm here belongs to the Branisko Succession, thrust from the south over the Czorsztyn Ridge (see Birkenmajer, 1963a).

**Mixed short/long distance transport (submarine slumps/turbidites).** At Krzonowe (Polish Spisz), there is an intercalation of fossiliferous beds, more than 30 m thick, with sideritic and oolitic-bioclastic limestone and ostreid coquinas, distinguished as the Krzonowe Mbr (previously a formation; see Birkenmajer, 1977; Birkenmajer and Tyszka, 1996). It yielded numerous, well preserved shells of Aalenian Gryphaeinae (see below). This member represents a mixture of submarine slumps of local origin (from the Czorsztyn Ridge), alternating with turbidites of long-distance transport.

The Czorsztyn Ridge also could be the source of Triassic algal limestone, Permian porphyry, and pre-Permian

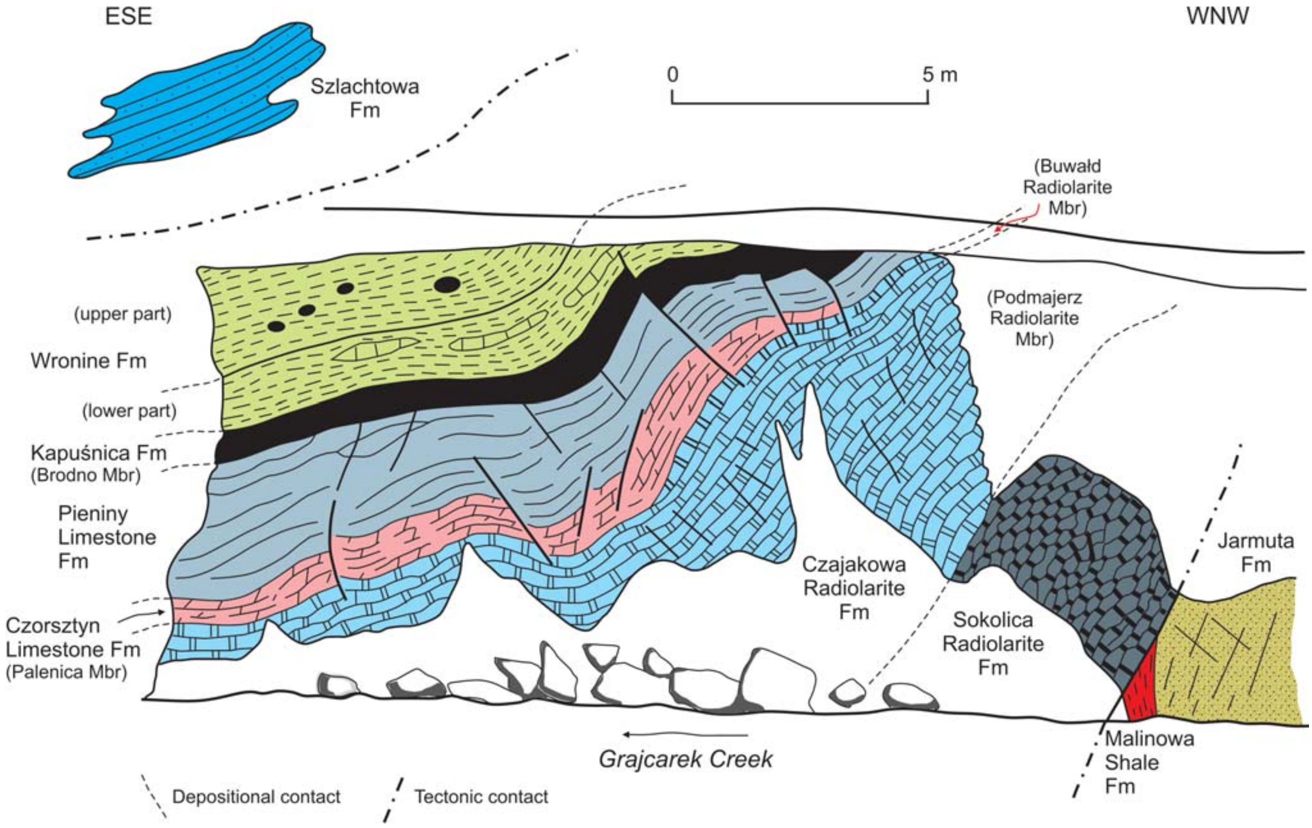


**Fig. 6.** A klippe of the Grajcarek Succession, near Rzeźnia, at Szczawnica – the Rzeźnia klippe (after Birkenmajer, 1979, slightly supplemented by Gedl, 2008d).

blocks that were deposited in the deep-water Niedzica Limestone Fm (Bathonian) of the Niedzica Succession (exposure in the Czajakowa Klippe, near Jaworki) after drifting for an unknown time in the roots of a tree or shrubs in this part of the Tethys (Birkenmajer *et al.*, 1960).

**Limestone intercalations.** In the exposure of the Szlachtowa Fm, in the middle course of the Sztolnia Creek (Fig. 4), a thin grey limestone intercalation (presently not visible) with poorly preserved ammonites of the genus *Leioceras,* and thin-shelled pelagic bivalves *Bositra buchi* (Roemer) was noted by Birkenmajer and Myczyński (1977) and is marked in Fig. 12.

The Szlachtowa Fm passes upward into grey to greenish shale with a few thin intercalations of graded blue-grey crinoid limestone and grey to brownish shaly marl, rich in *Bositra buchi* (Roemer) – the Stembrow Mbr (previously a formation; Birkenmajer, 1977). Lithologically, this member resembles the Harcygrund Shale Fm (middle Bajocian; see Myczyński, 1973; the "*Posidonia* shales" of Birkenmajer and Pazdro, 1968, p. 341).

### *Macrofossils and their age*

Macrofosils are rare in flysch rocks of the Szlachtowa Fm. Nevertheless, several locations yielded variably preserved shells of ammonites and aptychi, belemnites, thin pelagic bivalve shells of the genus *Bositra* (previously *Posidonia*), and even numerous, very well preserved Gryphaeinae shells (from the Krzonowe Mbr). The mode of occurrence of these Jurassic fossils in the sediment indicates that they occur *in situ* and have not been recycled (see Birkenmajer and Gedl, 2004; Birkenmajer *et al.*, 2008).

**Ammonites.** Ammonite shells are rare. In the limestone intercalation within this formation at Sztolnia Creek, *Leioceras opalinum* (Reinecke) and *L.* cf. *comptum* (Reinecke), zonal indices for the lower Aalenian Opalinum Zone were found (Birkenmajer and Myczyński, 1977; Birkenmajer, 1977); see Fig. 12.

An ammonite shell of the genus *Brasilia* has recently been found in shale of the Szlachtowa Fm at Malý Lipník Stream, near Litmanová in the Małe Pieniny Range, Eastern Slovakia (Gedl *et al*., 2012; Gedl and Józsa, 2015).

**Aptychi.** The basal part of the Szlachtowa Fm at Czorsztyn Castle Hill yielded *Cornaptychus* gr. A *lythensis* (Quenstedt) Trauth var. aff. *sigmopleura* Trauth (Gąsiorowski, 1962), indicating an upper Toarcian or lower Aalenian age (Birkenmajer, 1977).

**Belemnites.** Rostra of Jurassic belemnites, determined as *Holcobelus blainvillei* (Voltz) and *Holcobelus* sp., were found in the Szlachtowa Fm by Krawczyk *et al.* (1992). The first species is known, i.a., from Aalenian and Bajocian of France and from basinal upper Aalenian and Bajocian strata of the Branisko Succession in the Pieniny Klippen Belt (Myczyński, 1973).

**Bivalves.** Delicate, paper-thin, shells of pelagic bivalves *Bositra buchi* (Roemer) – previously determined as *Posidonia alpina* (Gras) – have been collected from shales in various parts of the stratigraphic column of the Szlachtowa Fm (see, e.g., Birkenmajer, 1977, figs 9, 11, 12). These bi-

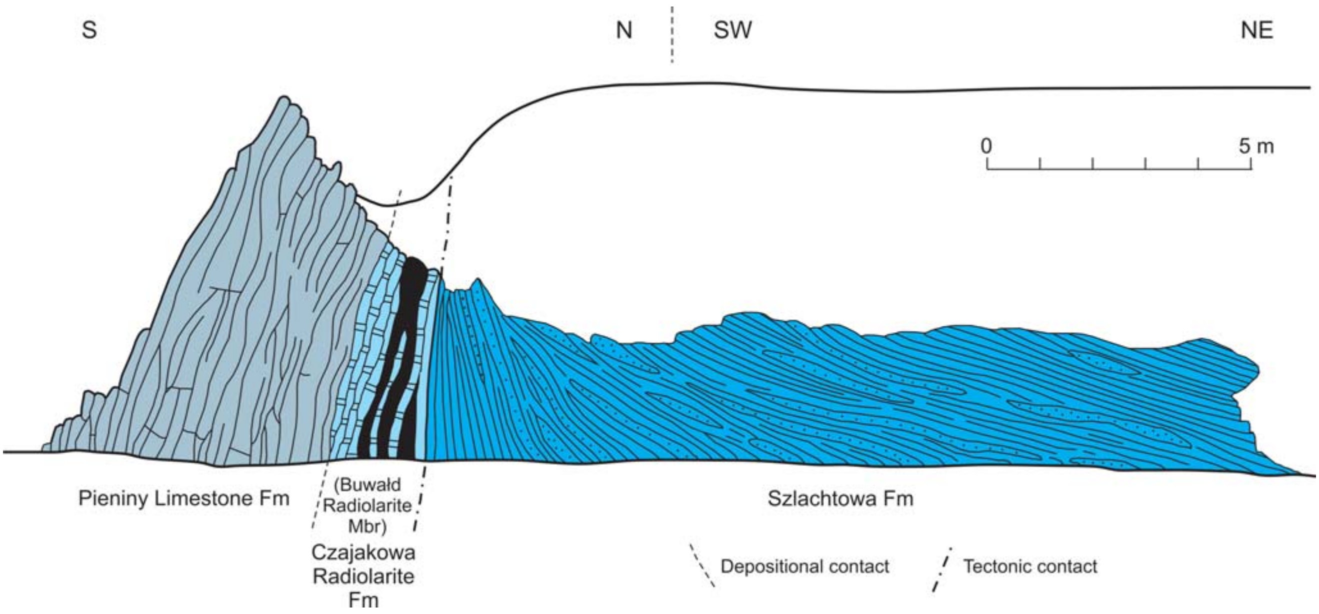


**Fig. 7.** A klippe of the Grajcarek Succession in the right bank of Grajcarek Stream, near Jarmuta (after Birkenmajer, 1979).

valves are typical of the Toarcian through Oxfordian strata (see Myczyński, 1973, 2004; Birkenmajer and Myczyński, 1977, 2000).

**Gryphaeinae.** Numerous shells of mainly Middle Jurassic Gryphaeinae have been collected from the Krzonowe Mbr (see the chapter titled *The Krzonowe Member*) of the Szlachtowa Fm.

**Crinoidea.** Well preserved, skeletal elements of Jurassic isocrinids, *Pentacrinites dargnesi* Terquem et Jourdy and *Chariocrinus andreae* (Desor) were found in the thin limestone (calcarenite) intercalations in the lower part of the Szlachtowa Fm (Głuchowski *et al.,* 1983; Głuchowski, 1987).

Though rare, the macrofossils listed above indicate a Jurassic age for the Szlachtowa Fm in the Grajcarek Succession (cf. Birkenmajer, 1977; Birkenmajer and Gedl, 2004; Birkenmajer *et al.* 2008). The present authors refute a view held by Oszczypko and co-workers (2004, 2012, and other papers; see Gedl, 2008a–c) that these macrofossils were recycled during mid Cretaceous times. Intercalations rich in well preserved Gryphaeinae shells (the Krzonowe Mbr; see Pugaczewska, 1971; Birkenmajer, 1977; Birkenmajer and Tyszka, 1996), and paper-thin shells of the pelagic *Bositra buchi* (see Birkenmajer, 1977) are a good proof to the contrary (Birkenmajer *et al.*, 2008).

### *Microfossils and their age*

Microfossils in the Szlachtowa Fm are represented by benthic foraminifera, ostracods, radiolaria, calcareous nannoplankton and dinoflagellate cysts. The stratigraphic value of these microfossils and their assemblages is secondary to that of macrofossils, except for dinoflagellate cysts.

**Foraminifera.** Foraminifera from the Szlachtowa Fm are almost exclusively benthic, both agglutinated and calcareous forms; their assemblages consist of long-ranging taxa.

Samples of the Szlachtowa Fm taken from the middle and lower courses of Sztolnia Creek, determined by O. Pazdro (in Birkenmajer and Pazdro, 1968, pp. 353–358, tab. 2), yielded assemblages that do not allow precise dating; they included representatives of the genera *Hyperammina* sp. (very numerous), *Lenticulina* (at least 9 species), *Marginulinopsis*, *Planularia* (at least 5 species), *Vaginulina* (3 species), *Marginulina* (sp. div.), *Nodosaria* (at least 2 species), *Dentalina* (at least 6 species), *Frondicularia*, *Falsopalmula*, *Lagena* (at least 3 species), *Eoguttulina*, *Ramulina*, *Palaeomiliolina*, ?*Paalzowella*, *Ammodisus* (sp. div.), *Trochammina*, ?*Haplophragmoides*, and *Hyperammina*.

Taxonomically impoverished and age-non-diagnostic are foraminifera assemblages, described near Jaworki and Szczawnica by Oszczypko *et al.* (2004, 2012) from the Szlachtowa Fm, but not from the truly Cretaceous strata, erroneously treated by these authors as the "Szlachtowa Formation" (see Birkenmajer *et al.*, 2008; Gedl, 2008a–c, 2014).

Benthic assemblages, diversified both quantitatively and qualitatively, with changing proportions of calcareous to agglutinated forms, were recently described from the Szlachtowa Fm from the vicinity of Litmanová, in the Slovak sector of the PKB, by Józsa (in Gedl and Józsa, 2015). Some samples contained impoverished, agglutinated assemblages with *Rhabdammina* and/or *Hyperammina*, and rare to common *Trochammina*. Others yielded rich and diversified assemblages of mostly calcareous benthic foraminifera with dominant *Epistomina*, smooth-walled *Lenticulina*, and *Spirillina* (commonly only as pyritised moulds), accompanied by common *Dentalina*, *Citharina*, *Falsopalmula*, *Ichtyolaria*, *Pseudonodosaria*, and *Nodosaria*. Still other samples yielded assemblages dominated by medium- to coarsely agglutinated *Rhabdammina*. A single sample from the Jar-1 borehole yielded broken specimens of *Lenticulina*, assigned to *L.* cf. *chicheryi* (Payard). Most of these Slovak assemblages may be correlated with the upper Toarcian–Aalenian foraminiferal Lenticulina d'orbignyi Zone; the oldest seems to be an assemblage with *Lenticulina* cf. *chicheryi* (Payard), which is an index fossil for the middle Toarcian Lenticulina chicheryi Zone (Gedl and Józsa, 2015).

**Ostracoda.** The above foraminifer samples from Sztolnia Creek also yielded ostracods (Błaszyk, 1968) *Cytherella woltersdorfi* Oertli (known from the Oxfordian of Switzerland and France) and *Cardobairdia inflata* Szczechura et Błaszyk (known from the Middle Jurassic of the Częstochowa area, Poland). Numerous, not yet determined ostracoda occur in the Szlachtowa Fm at Litmanová, Slovakia (Gedl and Józsa, 2015).

**Calcareous nannoplankton.** The distribution of calcareous nannoplankton is uneven in the Szlachtowa Fm. Some samples yielded rare and poorly preserved specimens, others yielded rich, commonly monospecific assemblages.

The same samples, which yielded foraminifera (Birkenmajer and Pazdro, 1968, see above), were studied by Dudziak (1986, tab. 1) for calcareous nannoplankton and were shown to contain rare and poorly preserved specimens, determined as, i.a., *Watznaueria communis* Reinhardt (Aalenian/Bajocian boundary–Coniacian), *Pororhabdus cylindratus* Noël (late Pliensbachian–Oxfordian), *Schizosphaerella* cf. *punctulata* Deflandre et Dangeard (late Hettangian–Oxfordian), *Discorhabdus biradiatus* (Worsley) Thierstein, and *Tetralithus gothicus* Deflandre.

Moderately to poorly preserved, calcareous assemblages were described by Švabenická (in Oszczypko *et al.*, 2004) from the Szlachtowa Fm at Údol (Eastern Slovakia) and the Jaworki area (Sztolnia, Krupianka, and Grajcarek creeks; Poland). From Údol, she reported almost monospecific *Lotharingius contractus* Bown et Cooper assemblages, associated with *Lotharingius crucicentralis* (Medd), *Watznaueria barnesiae* (Black), *W. britannica* (Stradner), *Carinolithus magharensis* (Moshkovitz et Ehrlich), *Discorhabdus striatus* Moshkovitz et Ehrlich, *Ethmorhabdus gallicus* Noël, and the transitional forms of the *Lotharingius–Watznaueria* plexus, dated as late Aalenian–earliest Bajocian (Oszczypko *et al.*, 2004). Similar, nearly monospecific assemblages of *L. contractus* were reported by Švabenická (in Oszczypko *et al.*, 2004) from Sztolnia Creek. Poorly preserved assemblages, also dominated by *L. contractus*, associated with *Lotharingius–Watznaueria* specimens and other rare taxa (e.g., *Watznaueria barnesiae*, *Discorhabdus striatus*, *Retacapsa incompta* Black, *Tubirhabdus patulus* Rood Hay et Barnard, *Carinolithus superbus* (Deflandre), *Watznaueria* cf. *manivitiae* Bukry) were described from Krupianka Creek and correlated with the lower Bajocian NJ9. Also samples from the Szlachtowa Fm from Grajcarek Creek yielded nearly monospecific (99% in one sample) *L. contractus*, accompanied by rare specimens of *Carinolithus* cf. *magharensis*, *Discorhabdus striatus*, *Ethmorhabdus gallicus*, *Lotharingius crucicentralis* (Medd), *Podorhabdus grassei* Noël, *Tubirhabdus patulus*, *Triscutum tiziense* de Kaenel et Bergen, *Watznaueria britannica*, and *W. barnesiae* (Švabenická in Oszczypko *et al*., 2004).

**Dinoflagellate cysts.** Shales of the Szlachtowa Fm contain a relatively high amount of palynological organic particles, which are dominated by terrestrial elements, particularly cuticles and woody particles. Aquatic palynomorphs, represented mainly by dinoflagellate cysts, are evidently subordinate. The latter were studied at several sites of this lithostratigraphic unit in both the Polish and Slovak sectors of the PKB.

Birkenmajer and Gedl (2004, tab. 1) reported various dinoflagellate cyst assemblages from the highly tectonized section of the Szlachtowa Fm in the upper course of Sztolnia Creek (Fig. 9), at and above the small waterfall (for the location, see Birkenmajer and Gedl, 2004, fig. 4). Stratigraphically, the lower part of the section yielded a rich dinoflagellate cyst assemblage, dominated by the representatives of three genera *Nannoceratopsis*, *Dissiliodinium* and *Kallosphaeridium.* From the highest part of the section, just above the strata, which yielded early Aalenian ammonites *Leioceras opalinum* (Reinecke) and *L.* cf. *comptum* (Reinecke) – see Birkenmajer and Myczyński (1977) – representatives of the genera *Ctenidodinium*, *Endoscrinium*, *Moendicodinium*, *Lithodinia* and *Epiplosphaera* were reported. This dinoflagellate cyst assemblage continues to occur in the Bajocian Opaleniec Fm. An upper Aalenian–?lower Bajocian age thus was accepted for the Szlachtowa Fm at this site (Gedl and Birkenmajer, 2004, p. 255).

Further assemblages were found in the Szlachtowa Fm during subsequent studies of the Jurassic dinoflagellate cysts from the PKB (e.g., Birkenmajer and Gedl, 2007, Gedl, 2007a). The interpretation of their sequence resulted in a proposal of a local dinoflagellate cyst zonation (Gedl, 2008d).

According to this scheme, the oldest assemblage from the Szlachtowa Fm consists of the predominant *Nannoceratopsis* (mainly *N. gracilis* Alberti and subordinate *N. ambonis* Drugg, *N. deflandrei deflandrei* Evitt, *N. plegas* Drugg, *N. raunsgaardii* Poulsen, and *N. spiculata* Stover). *Kallosphaeridium* (*K. praussii* Lentin et Williams and *K. capulatum* Stover), *Scriniocassis priscus* (Gocht); undetermined thin-walled forms occur in these assemblages. This assemblage was found in the basal part of the Szlachtowa Fm in Sztolnia and Krupianka creeks and in Grajcarek Creek; its age was tentatively assigned to the late Toarcian. Rare occurrences of *N. dictyambonis* Riding in some samples were interpreted as being indicative of the uppermost Toarcian (Gedl, 2008d). Similar assemblages were subsequently found at other sites of the Szlachtowa Fm in the vicinity of Litmanová, Slovakia (Gedl and Józsa, 2015). This assemblage was also recognized in a single sample, taken from the Jar-1 borehole, in the Slovak part of the PKB; it was here associated with broken specimens of the foraminifer *Lenticulina* cf. *chicheryi* (Payard), indicating the middle Toarcian (Gedl and Józsa, 2015; see subchapter *Foraminifera* above). However, the Toarcian ages of these assemblages were criticised by Segit *et al.* (2015; see *Discussion*).

A younger, latest Toarcian–Aalenian dinoflagellate cyst assemblage, with a characteristic *Phallocysta elongata* (Beju) and common *Nannoceratopsis dictyambonis* Riding, has been found in the Szlachtowa Fm at Krzonowe (Gedl, 2008d) and at Szczawnica–Zabaniszcze (Gedl, 2013). This assemblage is widely distributed in the PKB in the Skrzypny Shale Fm (Gedl, 2008d). A presumably younger assemblage with *Nannoceratopsis evae* Prauss, widespread in the Skrzypny Shale Fm, is missing in the Szlachtowa Fm; this may reflect a sedimentary hiatus during the Aalenian in the southernmost part of the Magura Basin (Gedl, 2008d).

The occurrence of frequent *Dissiliodinium* species allows dating of a higher part of the Szlachtowa Fm. The pre-

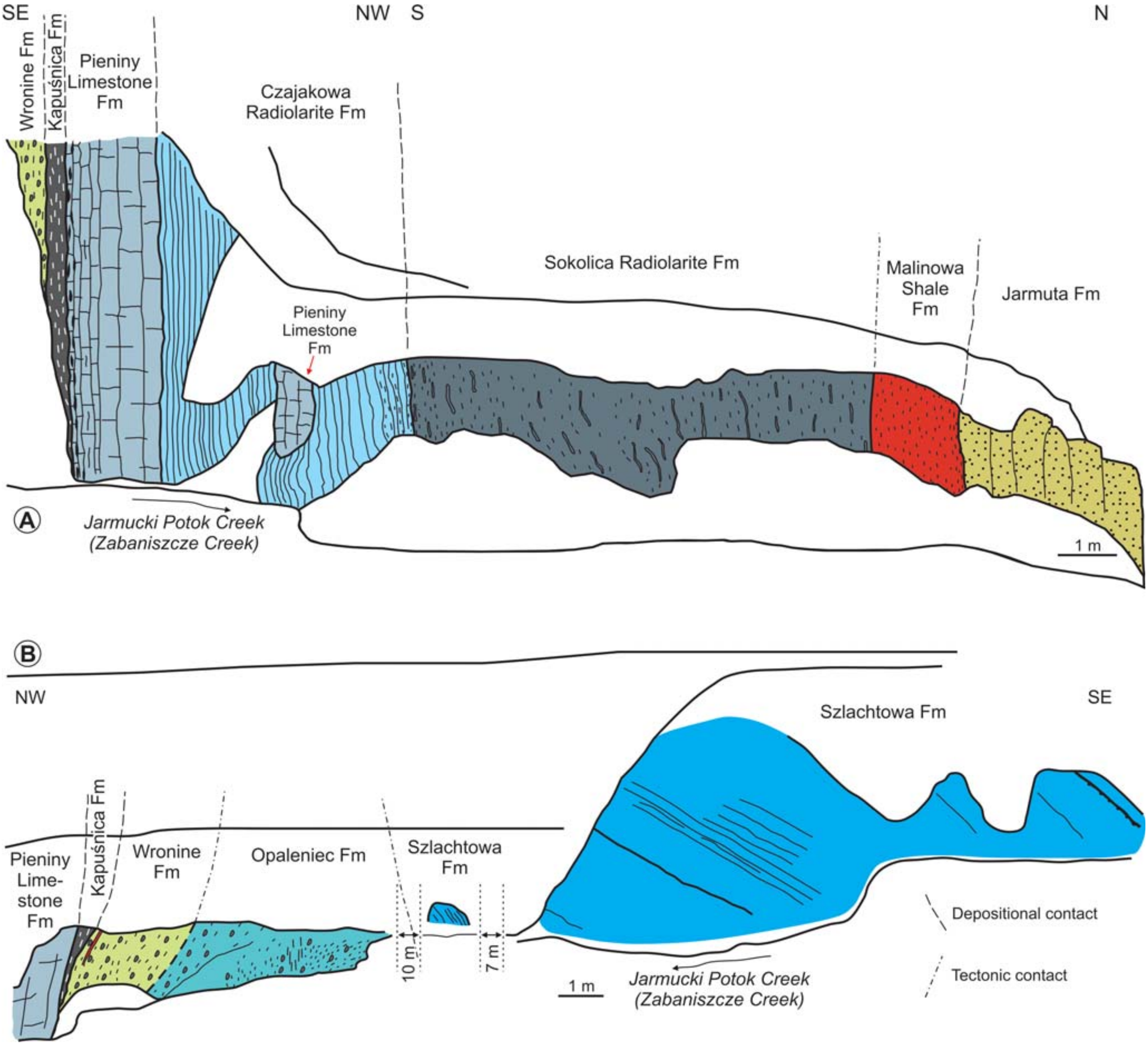


**Fig. 8.** Grajcarek Succession, near Rzeźnia, at Szczawnica – the Zabaniszcze klippe and exposures along the Jarmucki Potok Creek (Zabaniszcze Creek; after Gedl, 2013). **A.** A klippe and adjacent strata exposed in the western creek bank. **B.** Poorly exposed strata overlying the klippe, exposed in the northern creek bank.

sence of *Dissiliodinium lichenoides* Feist-Burkhardt et Monteil is typical for uppermost Aalenian strata (Gedl, 2008d). A similar assemblage with *D. lichenoides* Feist-Burkhardt et Monteil associated with i.a., *Nannoceratopsis evae* Prauss, *N. dictyambonis* Riding, *Evansia eschachensis* Below, and *Phallocysta elongata* (Beju) was described by Segit *et al*. (2015) from the vicinity of Dursztyn, and correlated with the latest Aalenian–earliest Bajocian. The occurrence of *Dissiliodinium giganteum* Feist-Burkhardt is characteristic, in turn, of the lower Bajocian part of the unit (Gedl, 2008d). This species frequently occurs in the Szlachtowa Fm in the vicinity of Jaworki (Birkenmajer and Gedl, 2004; Gedl, 2008d, 2013). From the same area (Krupianka Creek), Švabenická (in Oszczypko *et al.*, 2004) reported her early Bajocian calcareous nannoplankton. Segit *et al.* (2015) described an assemblage with *D. giganteum* Feist-Burkhardt (with *D. lichenoides* Feist-Burkhardt et Monteil, *Pareodinia ceratophora* Deflandre, *Phallocysta elongata* (Beju), *Nannoceratopsis dictyambonis* Riding, and *Durotrigia daveyi* Bailey) from the lower Bajocian strata. The appearance of this characteristic species that commonly forms acmes allows correlation of the lower Bajocian Magura Basin strata (parts of Szlachtowa and Opaleniec formations) with coeval strata of the Klippen basins (e.g., the Harcygrund Shale Fm and the Podzamcze Limestone Fm of the Branisko Succession; Gedl, 2008d).

Younger dinoflagellate cyst assemblages in the Szlachtowa Fm of the Grajcarek Succession may be correlated with the late Bajocian. They differ significantly from the older Toarcian–early Bajocian forms, which consist chiefly of *Nannoceratopsis*, *Phallocysta* and/or multiplate archaeopyle forms. The late Bajocian assemblages are characterized by the absence of *D. giganteum* Feist-Burkhardt and the appearance of species like *Aldorfia aldorfensis* (Gocht), *Rhynchodiniopsis*? *regalis* (Gocht) and *Ctenidodinium combazii* Dupin (Gedl, 2008d). Segit *et al*. (2015) described their youngest assemblage with *Aldorfia aldorfensis* (Gocht) from the Szalchtowa Fm at Sprzycne Stream, correlated with the upper Bajocian ammonite Niortense Zone.

*Aldorfia aldorfensis* (Gocht) co-occurs with *Ctenidodinium ornatum* (Eisenack), *C. continuum* Gocht, *C. cornigerum* (Valensi), and *Ellipsoidictyum cinctum* Klement, *Epiplosphaera reticulata* (Valensi), *Lithodinia reticulata* (Dodekova), *Nannoceratopsis pellucida* Deflandre, and *Valensiella ovulum* (Deflandre) in a single sample, Szt39A, from the upper course of Sztolnia Creek (Gedl, 2008d). This is presumably the youngest stratum of the Szlachtowa Fm, which might be even of lower Bathonian age (Gedl, 2008d).

***Szlachtowa Formation in the Branisko Succession***

Strongly folded flysch rocks of the Szlachtowa Fm have long been recognized in the PKB at the bases of overthrust Upper Cretaceous nappes, i.e., the Czertezik Nappe, the Niedzica Nappe and the Branisko Nappe. This formation is missing in the Czorsztyn, Pieniny and Haligovce tectonic units (e.g., Birkenmajer, 1958a, 1959a, b, 1963b, 1977, 1979, and 2009).

The Szlachtowa Fm of the Branisko Succession between Czorsztyn Castle and the Harcygrund Valley, at Podubocze Creek and in small creeks nearby, is directly overlain by ammonite-bearing marls of the Krempachy Marl Fm, previously called the "Opalinus marls" (see Birkenmajer, 1963b; Birkenmajer 1977, figs 14A, 15A). From a good exposure in Podubocze Creek, Myczyński (1973, pp. 19 sequ., fig. 2) determined a rich ammonite fauna: *Ptychophylloceras tatricum* (Pusch), *Calliphylloceras nilssoni* (Hébert), *Megalytoceras rubescens* (Dumortier), *Tmetoceras scissum* (Benecke), *Leioceras opalinum* (Reinecke), *L. comptum* (Reinecke), *L. subacutum* (Buckman), *L.* cf. *paucicostatum* Rieber, *Costileioceras costosum* (Benecke), *Ludwigia* cf. *baylii* (Buckman), *Hammatoceras* cf. *insigne* (Zieten), *H. procerinsigne* Vaček and bivalves *Inoceramus* sp. ex gr. *fuscus* Quenstedt and *Bositra buchi* (Roemer). This fauna includes ammonite index fossils of the lower Aalenian – Leioceras opalinum Zone and the Tmetoceras scissum Zone. Moreover, the occurrence of the ammonites *Leioceras subacutum* (Buckman) and *Ludwigia* cf. *baylii* (Buckman) indicates the presence of the Staufenia Zone (lowest part of upper Aalenian).

## The Krzonowe Member

In this paper, the authors have downgraded the Krzonowe Fm (Birkenmajer, 1977) to the rank of member within the Szlachtowa Fm. This is due to the very limited distribution of this unit, known so far from only a single site (Fig. 9). The detailed, formal description of this unit, as provided for the formation by Birkenmajer (1977, p. 33–34) remains unchanged.

***Distribution, lithology and sedimentology***

Rocks assigned to this unit are known only from the Grajcarek Succession. They crop out at only one place, in the Krzonowe Forest, south of Frydman (Birkenmajer, 1977, fig. 7M). The rocks were excavated and described in detail by the senior author in the fifties of the previous century. Nowadays, due to the relative softness of the rocks forming the Krzonowe Mbr, both artificial and natural exposures of this unit are scarce (see Birkenmajer and Tyszka, 1996; Gedl, 2008d, fig. 43).

The bulk of the rocks making up the more than 30 m of the Krzonowe Mbr consists of calcareous, pale-coloured (yellowish, greenish, greyish) clay shale. They are intercalated with arenaceous shale (with frequent *Gryphaea* shells) and fine-grained sandstones and coquinas. Relatively infrequent sideritic concretions occur.

The Krzonowe Mbr mostly is composed of resedimented rocks that originally settled down in higher parts of the northern slopes of the Czorsztyn Ridge (see Fig. 3) and, subsequently, in the form of submarine slumps of local origin, slipped into the deeper part of the Magura Basin, where the flysch sedimentation of the Szlachtowa Fm was taking place.

***Macrofossils and their age***

**Gryphaeinae.** More than 200 shells of Gryphaeinae were collected from the Krzonowe Mbr of the Szlachtowa Fm ("*Liogryphaea* beds", Birkenmajer 1957b, 1977; Birkenmajer and Tyszka, 1996) at Krzonowe. They were determined by Pugaczewska (1971) as:

– *Gryphaea dewalquei* Rollier: Levesquei Zone (upper Toarcian) to Sowerbyi Zone (middle Bajocian);

– *Gryphaea ferruginea–champigneullensis* Charles et Maubeuge: Opalinum Zone (lower Aalenian) to Concavum Zone (uppermost Aalenian);

– *Gryphaea sublobata* Deshayes – the most common species in the collection of the senior author: Opalinum Zone (lower Aalenian) to Sowerbyi Zone (middle Bajocian); and

– *Gryphaea lampada* Rollier: Murchisonae Zone (upper Aalenian) to Humphresianum Zone (middle Bajocian).

This assemblage is of Aalenian (Pugaczewska, 1971), possibly even middle Aalenian age (Birkenmajer, 1977; Birkenmajer and Tyszka, 1996).

***Microfossils and their age***

**Foraminifera.** Foraminifera determined from the Krzonowe Mbr at its type locality by O. Pazdro (in Birkenmajer and Pazdro, 1963a) included *Ammobaculites agglutinans* (d'Orbigny), *Dentalina (= Laevidentalina)* spp., *D. pseudocommunis* Franke, *D. digitalis* Franke, *Geinitzina tenera pupoides* Nørvang, and *Nodosaria nitidiana* Brand.

Foraminifera determined from the Krzonowe Mbr by Tyszka (in Birkenmajer and Tyszka, 1996 pp. 30 sequ., fig. 22, tabs 3, 4) included, i.a., *Eoguttulina* sp., *Laevidentalina vetusta* (d'Orbigny), *Lingulina tenera* Bornemann, *Marginulina* aff. *spinata* Terquem, *Marginulinopsis inaequistriatus* (Terquem), and *Lenticulina varians* (Bornemann).

From the basal part of the Krzonowe Mbr comes abundant *Lenticulina* gr. *tenera* (Bornemann, 1854) with dominating *L. tenera pupa* (Terquem), a characteristic species

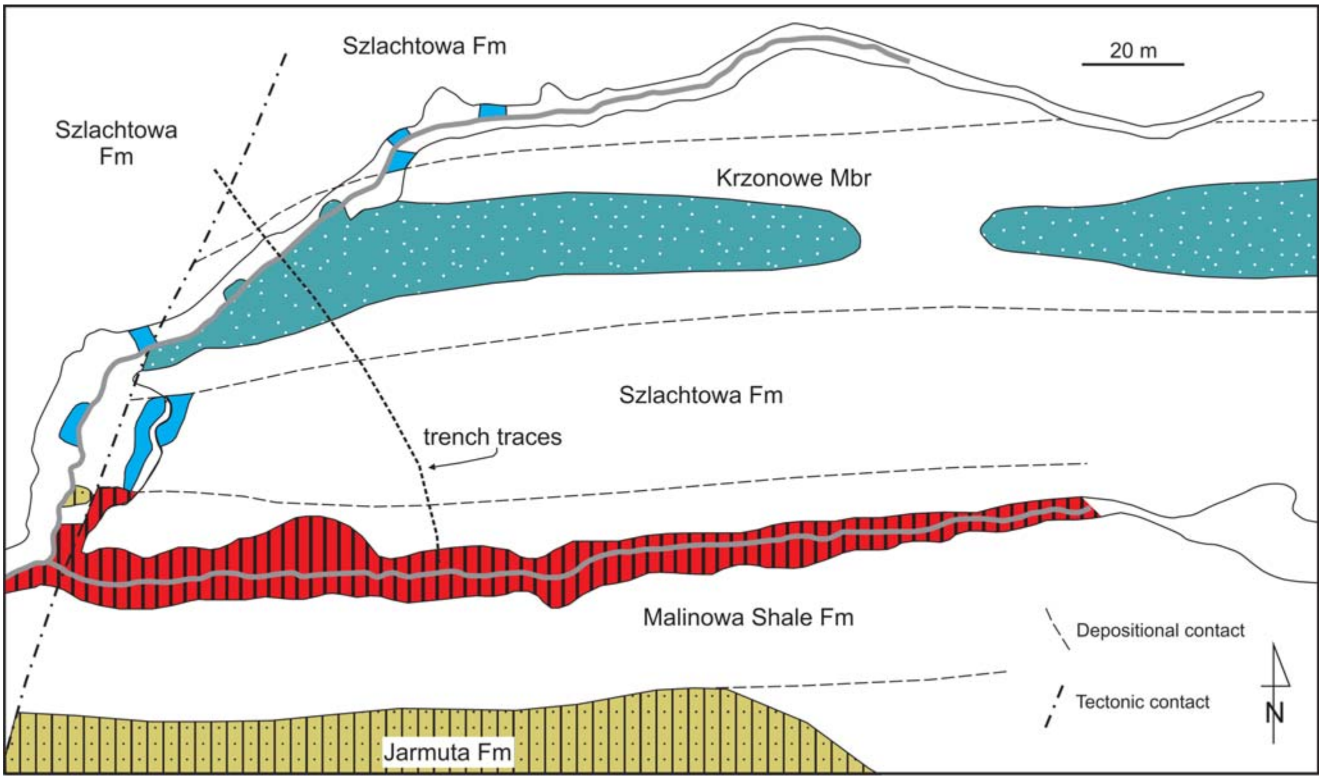


**Fig. 9.** Geological map of the Krzonowe site, showing relationship of the Krzonowe Mbr to the Szlachtowa Fm (based on Birkenmajer's unpublished data from 1953; from Birkenmajer and Tyszka, 1996).

(resp. a group of varieties and subspecies) for the Early Jurassic of NW Europe (Birkenmajer and Tyszka, 1996). In the Tethyan Realm, it ranged from Hettangian through earliest Toarcian (Birkenmajer and Tyszka, 1996, p. 34). Thus, the lowest part of the Krzonowe Mbr with *Lenticulina* gr. *tenera* (Bornemann) is of pre-Aalenian age (Birkenmajer and Tyszka, 1996, p. 35).

**Ostracoda.** The Krzonowe Mbr yielded frequent ostracods (Pugaczewska, 1971; Birkenmajer and Pazdro, 1963a; Birkenmajer and Tyszka, 1996, p. 28), which have not been determined yet.

**Dinoflagellate cysts.** Palynological studies of the Krzonowe Mbr were limited to its lowermost part (Gedl, 2008d). They show almost a complete lack of dinoflagellate cysts in the samples studied; its palynofacies is almost entirely composed of terrestrial elements with sporomorph proportions of up to 20%. Two dinoflagellate cyst specimens found in different samples were determined as *Phallocysta elongata* (Beju) and *Nannoceratopsis evae* Prauss. This material that is so scarce does not allow precise dating. However, an uppermost Toarcian–Aalenian age was suggested for the basal part of the Krzonowe Mbr (Gedl, 2008d). It generally overlaps the age interpretations based on foraminifera, namely the Toarcian lowermost part of the unit (Birkenmajer and Tyszka, 1996), and the Aalenian age based on gryphaeids (Pugaczewska, 1971).

## The Stembrow Member

This lithostratigraphic unit, formerly with the rank of a formation (Birkenmajer, 1977), is downgraded now to the rank of a member of the Szlachtowa Fm. As in the case of the Krzonowe Mbr, this is due to its small thickness and very restricted distribution. The formal characteristics of this unit, as proposed by Birkenmajer (1977) for the Stembrow Fm, remain unchanged.

### *Distribution, lithology and sedimentology*

The Stembrow Mbr is known only from the Grajcarek Succession. The rocks assigned to this unit (in the older literature referred to as the "supra-flysch beds") are known from its type locality in Kiźlinkowy Stream, below Stembrow Hill, east of Krempachy (Birkenmajer, 1977, figs 7O, 13), and from a single site on the NE slope of Mt. Jarmuta, at Szczawnica (Birkenmajer, 1956b, fig. 1; Fig. 2).

The rocks of the Stembrow Mbr (5–8 m thick) are mainly pale coloured, greenish-yellow, occasionally spotted, moderately calcareous shale. Rare intercalations of thin (3–5 cm), graded crinoid limestone beds (see Gedl, 2008d, fig. 48B, C) have been found at its type locality; they are absent at the Jarmuta site, where thin sandstone intercalations occur instead (Birkenmajer, 1977).

The Stembrow Mbr is underlain by the Szlachtowa Fm; the contact between them is transitional and the boundary is placed at the highest occurrence of a micaceous sandstone layer; the upper boundary has not been observed so far (Birkenmajer, 1977).

### *Macrofossils and their age*

**Bivalves.** Shells of *Bositra buchi* (Roemer) are the only macrofossils (apart from echinoderm remains in the limestone beds and a single gastropod specimen; Birkenmajer and Pazdro, 1963a, table) that have been described so far from the Stembrow Mbr. They were reported from both sites (Birkenmajer, 1977). This long-ranging species is known from the Early to Late Jurassic.

***Microfossils and their age***

**Foraminifera.** Pazdro (in Birkenmajer and Pazdro, 1963a) described from the type locality a relatively rich foraminifera assemblage, including *Astacolus inaequistriatus* (Terquem), *Dentalina integra* (Kuebler et Zwingli), *Glomospira gordialis* (Jones et Parker), *Lagena ovata* (Terquem), *L. globosa* (Montagu), *Lenticulina toarcense* Payard, *Ramulina laevis* Jones, *Vaginulinopsis exarata* Hagenow; its age was interpreted as late Early to early Middle Jurassic.

**Ostracoda.** Relatively frequent ostracoda, not yet determined, were reported from the Stembrow Mbr in the Kiźlinkowy Stream (Pazdro in Birkenmajer and Pazdro, 1963a, table).

**Dinoflagellate cysts.** The palynology of the Stembrow Mbr was studied at its type section in the Kiźlinkowy Stream (Gedl, 2008d). Its characteristic feature is a low amount of palynological matter, composed chiefly of black opaque phytoclasts. The only exception is the basal sample, which yielded a higher amount of organic particles with increased proportions of cuticles and sporomorphs (this could be related to the proximity of the flysch strata of the Szlachtowa Fm, which underlie the strata studied at this site (Birkenmajer, 1977, fig. 13B), nowadays not exposed. Dinoflagellate cysts from the Stembrow Mbr are moderately diversified (except for the basal sample, which yielded single *Nannoceratopsis* specimens only); their assemblage includes *Carpathodinium predae* (Beju), *Chytroeisphaeridia chytroeides* (Sarjeant), *Ctenidodinium cornigerum* (Valensi), *C. combazii* Dupin, *C. continuum* Gocht, *Epiplosphaera* sp., and *Nannoceratopsis pellucida* Deflandre. The age of this assemblage is most probably late Bajocian, although the possibility of a slightly younger age cannot be excluded (Gedl, 2008d).

## The Opaleniec Formation

***Distribution, lithology and sedimentology***

The Opaleniec Fm was distinugished in the Grajcarek Succession at Szczawnica and Jaworki (Birkenmajer, 1977; Pazdro, 1979; Birkenmajer and Gedl, 2007; Gedl, 2008d, 2013). It was described subsequently from more western settings near Dursztyn (Polish Spisz) in Kręty Creek (Gedl, 2008d) and in Sprzycne Creek (Segit *et al.*, 2015).

In most of the known exposures, the Opaleniec Fm is strongly disturbed tectonically. It is either incomplete or is tectonically in contact with other lithostratigraphic units in the upper course of Sztolnia Creek (Fig. 12; Birkenmajer and Gedl, 2004); on Mt. Hulina (Fig. 10; Birkenmajer and Gedl, 2007) and in Zabaniszcze Stream, at Szczawnica (Fig. 8; Gedl, 2013). The most complete and relatively undisturbed section of the Opaleniec Fm is exposed in Krupianka Creek, near Jaworki (Fig. 5), where its passage into the underlying Szlachtowa Fm and the overlying Sokolica Radiolarite Fm, respectively, are present (Birkenmajer, 1979, fig. 99B; Gedl, 2008d, fig. 19G). A contact of the Opaleniec Fm with the Szlachtowa Fm is also visible in Sprzycne Creek, near Dursztyn (Segit *et al.*, 2015). Its passage into the Sokolica Radiolarite Fm in Kręty Creek (Fig. 11) is not exposed nowadays (Gedl, 2008d, fig. 46).

The Opaleniec Fm consists of blue-grey to greenish, soft shale and marly shale, often fucoidal, locally with fine mica. A coating of orange weathering may sometimes occur. The shales contain aggregates and concretions of pyrite, as well as concretions, lenses and lenticular layers of blue-grey spotty, ferruginous dolomite and limestone, up to 1 m thick. In Sztolnia Creek, the formation is 16–18 m thick (Fig. 4; Birkenmajer, 1977).

The rocks of the Opaleniec Fm may be very similar in lithology to the Wronine Fm of Lower Cretaceous age (see Birkenmajer, 1977, p. 32), within which they were originally included by Birkenmajer and Pazdro (1968).

***Macrofossils and their age***

**Ammonites and bivalves.** Poorly preserved ammonites, *Eurystomiceras polyhelictum* (Böckh), *Dorsetensia* sp., and ?*Pseudotoites* sp., and better preserved bivalves, referable to *Bositra buchi* (Roemer), were collected from the Opaleniec Fm at its type section, near Szlachtowa. They indicate a Bajocian (?middle Bajocian) age for the formation (see Birkenmajer and Myczyński, 1977; Birkenmajer, 1977).

***Microfossils and their age***

**Foraminifera.** Pazdro (1979) devoted much care to cleaning and determining the foraminifer assemblages from samples, collected at the type locality of the Opaleniec Fm in Sztolnia Creek, near Szlachtowa. According to her, the assemblages consist mainly of species from the genus *Lenticulina*, with *L. muensteri* Roemer predominating. This species is known from both the Jurassic and the Lower Cretaceous. Other genera (*Dentalina*, 4 species, *Nodosaria*, and others) and particular species discussed by Pazdro (1979, pp. 107–109 and tab. 1) resemble more those from Jurassic, resp. Middle Jurassic, than from Cretaceous strata.

Tyszka (1995) from the same site described benthic assemblages, composed of both agglutinated and calcareous species. The agglutinated foraminifera are dominated by tubular morphogroups, such as *Rhabdammina*, *Hyperammina*, and *Rhizammina*, associated with *Verneuilinoides mauritii* (Terquem). Among the calcareous forms, nodosariids are the most frequent, represented by smooth-tested *Lenticulina*, mainly *L. muensteri* (Roemer), *L. polygonata* Franke, and *L. varians* (Bornemann). Ornamented *Lenticulina quenstedti* (Gümbel) and *L. toarcense* (Payard) are subordinate. The other foraminifera described by Tyszka (1995) include relatively frequent *Laevidentalina*, represented by *L. pseudocommunis* (Franke), *L. vetusta* (d'Orbigny) and *L. vetustissima* (d'Orbigny), and subordinate *Falsopalmula deslongchampsi* Terquem, *Marginulinopsis* spp., *Spirillina infima* Strickland, *Ramulina* sp. and questionably determined *Paalzowella* sp.

Although the taxa listed above are long-ranging (the most age-diagnostic are *Lenticulina quenstedti*, ?Toarcian–Bajocian through Tithonian, and *Falsopalmula deslongchampsi*, Toarcian–Oxfordian), but the whole assemblage is

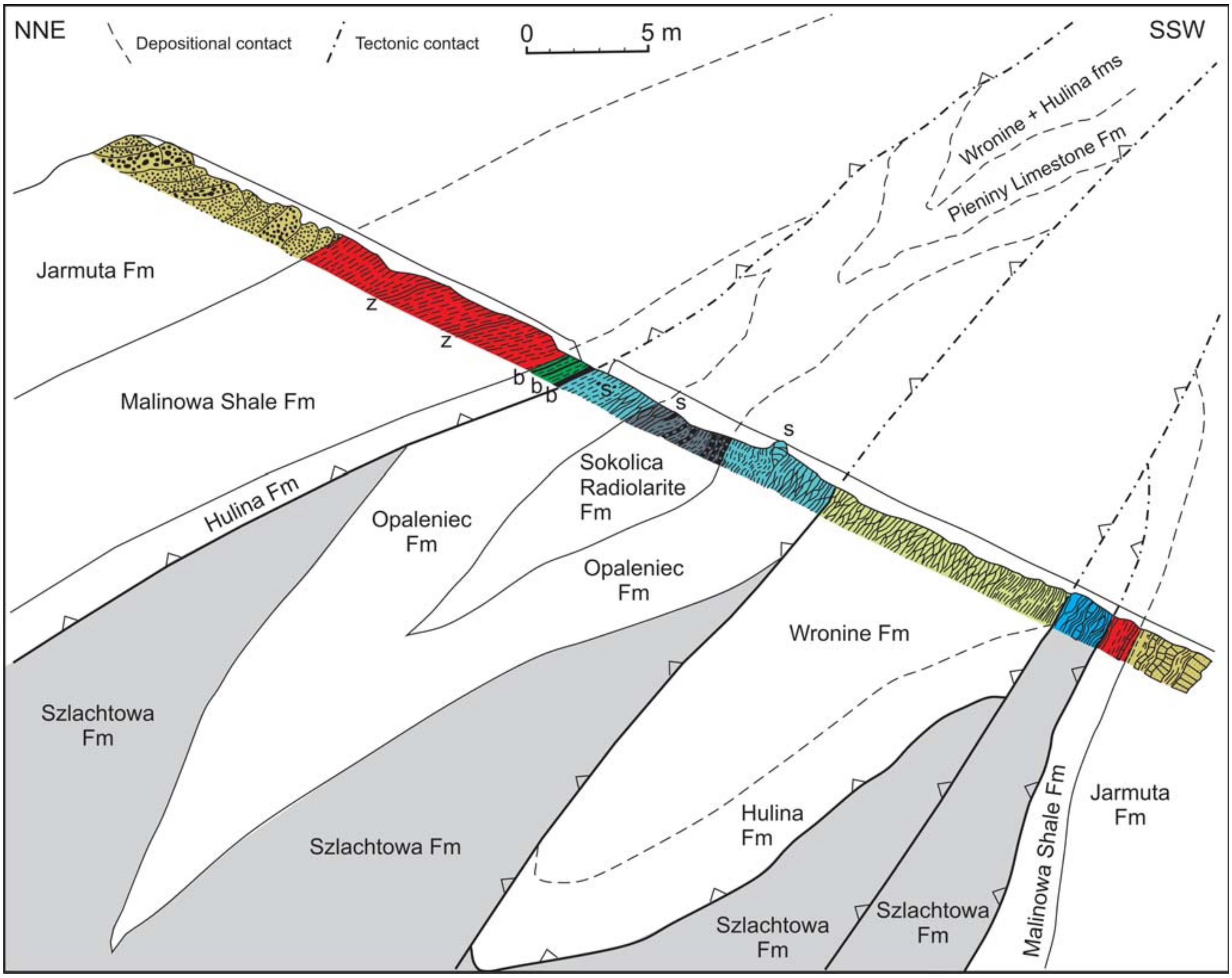


**Fig. 10.** Geological cross-section and tectonic interpretation of the Grajcarek Unit on the SW slope of Mt. Hulina, Szczawnica Niżna (cross-section by Birkenmajer, 1973, re-interpreted by Birkenmajer and Gedl, 2007). Abbreviations: z – green shale intercalations; b – bentonitic layers; s – siderite concretion. Barbed – main tectonic contacts.

very similar to the one described from the Bajocian Podzamcze Limestone Fm (Tyszka, 1994, 1995). A comparison with the local foraminiferal zonation allows correlation of the Opaleniec Fm from Sztolnia Creek with the uppermost lower–upper Bajocian (Tyszka, 1999).

Oszczypko *et al.* (2004, 2012) studied the Opaleniec Fm from Sztolnia Creek and Mt. Hulina, respectively, for foraminifera. Their samples, however, were collected either from tectonic contacts with Cretaceous strata (at Sztolnia Creek) or were barren (at Mt. Hulina, samples 34/07–38/07 were erroneously indicated as being from the Hulina Fm; Oszczypko *et al.*, 2012, fig. 9); see Birkenmajer and Gedl (2004, 2007), Birkenmajer *et al.* (2008), Gedl (2008a–d, 2013) for a comparison and discussion.

**Calcareous nannoplankton.** These microfossils have been studied by Švabenická (in Oszczypko *et al.*, 2004) from two samples, collected from the Opaleniec Fm in the upper course of Sztolnia Creek. Moderately preserved fossils from one sample (20), dominated by *Watznaueria britannica* (Stradner) and *Lotharingius contractus* Bown et Cooper and associated with rare *Cyclagelosphaera margerelii* Noël, were dated as late Bajocian. The almost monogeneric assemblage of *Watznaueria* (*W. barnesiae* (Black) and *W. britannica*), accompanied by rare *Watznaueria manivitiae* Bukry, *Cyclagelosphaera margerelii* and *Discorhabdus* sp. from another sample (26), cannot be precisely dated; *Watznaueria*-dominated assemblages are characteristic for the Tithonian and Jurassic/Cretaceous boundary interval (Oszczypko *et al.*, 2004).

**Dinoflagellate cysts.** Rocks assigned to the Opaleniec Fm yielded various dinoflagellate cyst assemblages reflecting different ages.

The oldest assemblages have been recorded from the rocks exposed in Kręty Creek; they included a characteristic species *Dissiliodinium giganteum* Feist-Burkhardt, associated with i.a., *Nannoceratopsis* spp., *Batiacasphaera* sp., that allow their correlation with the lower Bajocian (Gedl, 2008a). *D. giganteum* Feist-Burkhardt forms acmes in some samples.

Younger assemblages are devoid of *D. giganteum* Feist-Burkhardt, but they include species that appeared for the first time during the late Bajocian, such as, e.g., *Aldorfia*

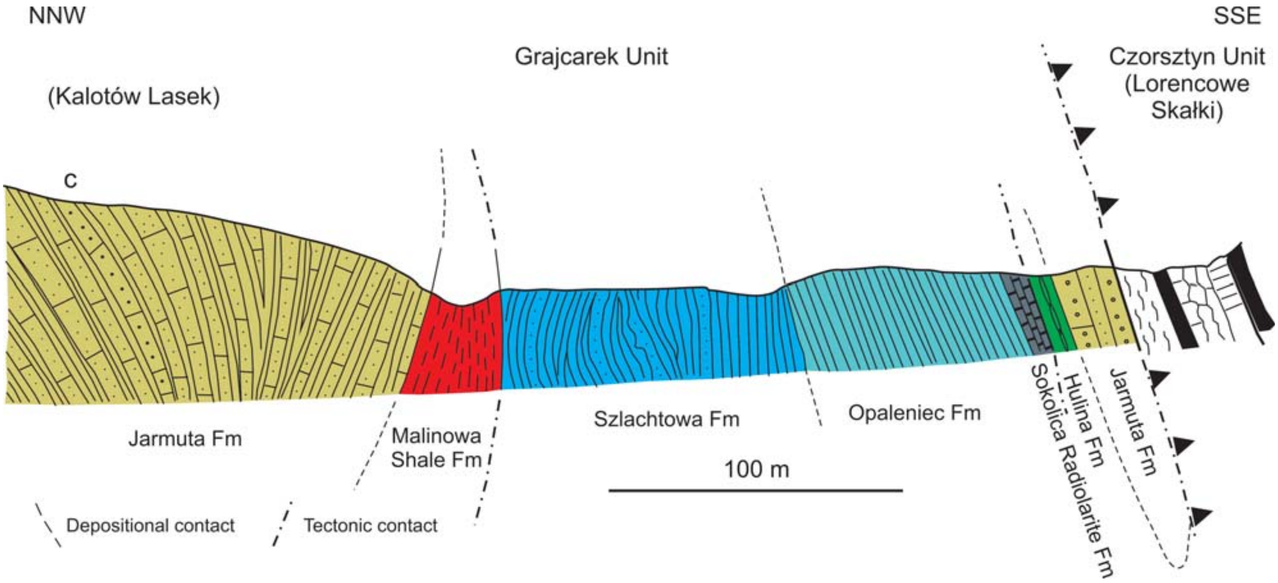


**Fig. 11.** Geological cross-section of the Grajcarek Unit in Kręty Creek (after Birkenmajer, 1979, slightly modified by Gedl, 2008d). C – conglomerate.

*aldorfensis* (Gocht), *Ctenidodinium continuum* Gocht, *C. combazii* Dupin, *Endoscrinium asymmetricum* Riding and *Nannoceratopsis pellucida* Deflandre. They come from rocks exposed in the Sztolnia Creek section below the large waterfall (Birkenmajer and Gedl, 2004; Gedl, 2008d), in Krupianka Creek (Gedl, 2008d), on the slopes of Mt. Hulina (Birkenmajer and Gedl, 2007; Gedl, 2008d), and in Sprzycne Creek (samples SC-11 to SC-13; Segit *et al.*, 2015). *Ctenidodinium combazii* Dupin appears in some samples (the Mt. Hulina section) as acmes (Gedl, 2008d).

Some samples that yielded late Bajocian assemblages, however, can be treated as lower upper Bajocian; this refers to samples that include late Bajocian species, but are devoid of *Ctenidodinium* specimens, e.g., sample Szt30 from Sztolnia Creek with *Aldorfia* and *Rhynchodiniopsis* species (Gedl, 2008d), sample SC-10 collected by Segit *et al.* (2015) from the lowest part of the Opaleniec Fm, just above its contact with the Szlachtowa Fm in Sprzycne Creek (with *Meiourogonyaulax valensii* Sarjeant, *Chytroeisphaeridia chytroeides* (Sarjeant), *Valensiella*/*Ellipsoidictyum* spp.).

Younger dinoflagellate cyst assemblages from the Opaleniec Fm are of Bathonian, presumably early Bathonian age. They include *Atopodinium prostatum* Drugg, *Dingodinium minutum* Dodekova, *Tubotuberella dangeardii* (Sarjeant), and some poorly preserved chorate species with an apical archaeopyle assigned to the genera *Systematophora* and *Surculosphaeridium*. Rocks of this age have been reported from Sztolnia Creek, Krupianka Creek, Mt. Hulina, and Sprzycne Creek (Birkenmajer and Gedl, 2004, 2007; Gedl, 2008d; Segit *et al.*, 2015).

In an exposure of highly tectonized Opaleniec Fm, near the Zabaniszcze klippe, at Szczawnica, Gedl (2013) found dinoflagellate cysts with common *Chytroeisphaeridium chytroeides* (Sarjeant), *Endoscrinium asymmetricum* Riding, *Ctenidodinium combazii* Dupin, *Meiourogonyaulax caytonensis* (Sarjeant), *Atopodinium* sp. A, *Dingodinium minutum* Dodekova, and *Epiplosphaera* spp. These assemblages contain also frequent specimens of *Surculosphaeridium*? *vestitum*, *Systematophora penicillata*, *S.* ?*orbifera*, and *Cleistosphaeridium iaculigerum*, which can be compared with the poorly preserved chorate specimens of *Systematophora* and *Surculosphaeridium* from some other sites of the Opaleniec Fm (see above). Gedl (2013), on the basis of some species (*Surculosphaeridium*? *vestitum*, *Systematophora penicillata*, and *Atopodinium* sp. A), suggested even a Callovian age for the topmost part of the Opaleniec Fm.

## The Sokolica Radiolarite Formation

The strata of the Grajcarek Unit, beginning from the Bathonian–Callovian radiolarites (the Sokolica Radiolarite Fm and the Czajakowa Radiolarite Fm) through the Tithonian–Aptian limestones and marly limestones (the Czorsztyn Limestone Fm, the Pieniny Limestone Fm) occur as small, hard klippes. Their stratigraphic succession and lithologic development is so similar to that of the Branisko Succession/Nappe that during early mapping (1950–1960) of the PKB on the detailed scale of 1:10,000, these Grajcarek Unit klippes were not separated from those of the Branisko Nappe (see, e.g., Birkenmajer, 1963a; this was corrected in Birkenmajer, 1979, map).

### *Distribution, lithology and sedimentology*

The Sokolica Radiolarite Fm consists of thin-bedded, spotty, grey-green, grey-blue to black radiolaria cherts, alternating with similarly coloured, radiolaria-bearing, siliceous shale (1–2 cm thick). The most representative exposure of this unit of the Grajcarek Succession is in the Rzeźnia klippe (see Birkenmajer, 1977, fig. 26B; 1979, pp. 191–192, fig. 88), exposed in the left bank of the Grajcarek Stream, at Szczawnica (Fig. 6). The Sokolica Radiolarite Fm is here about 6 m thick. It consists of thin-bedded, spotty, grey-green, grey-blue to black radiolarian cherts, alternating with similarly coloured radiolaria-bearing, silice-

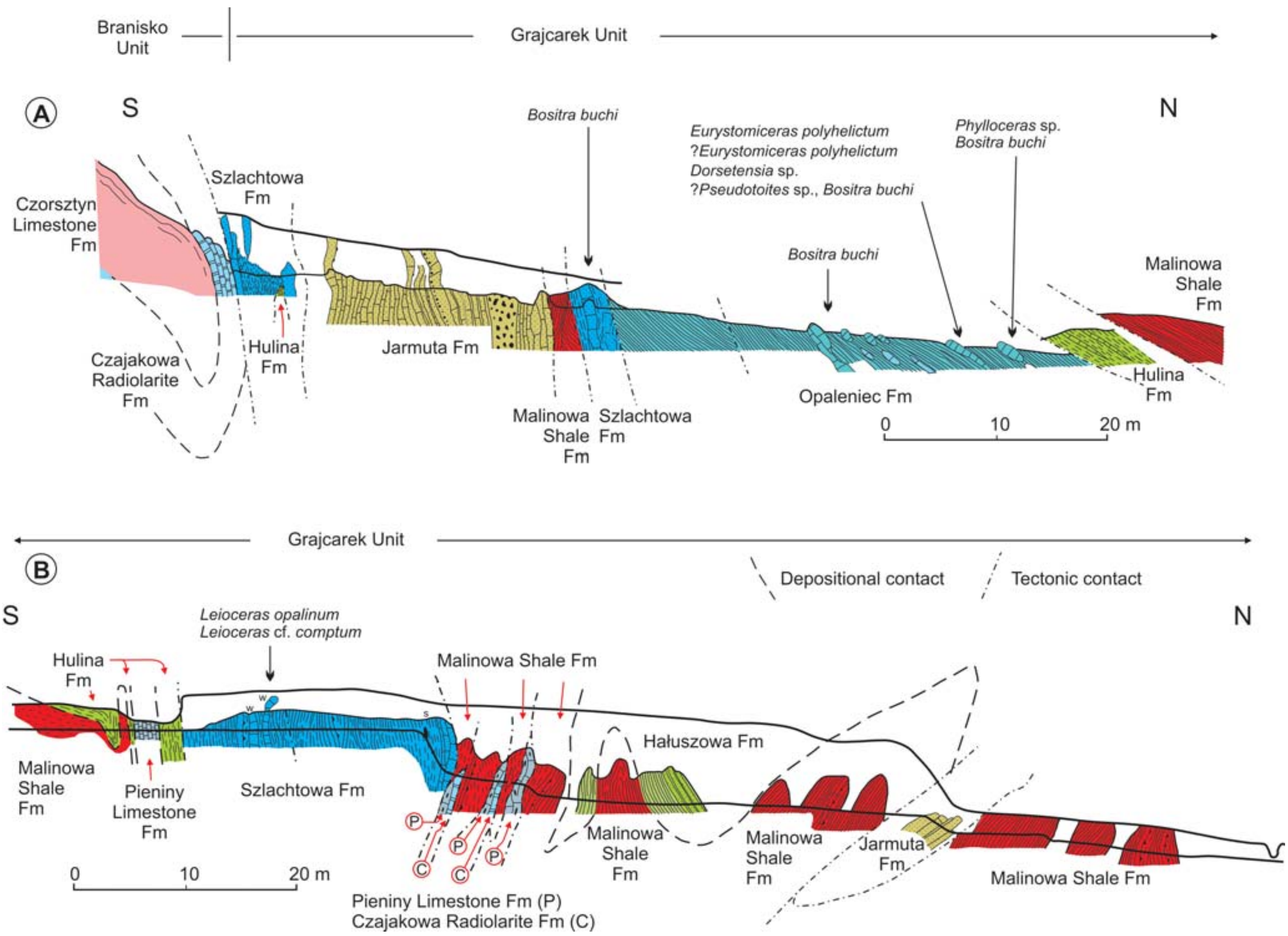


**Fig. 12** Geological cross-sections through the Grajcarek Unit in the upper course of Sztolnia Creek (based on original drawings by Birkenmajer, published for the first time in Birkenmajer and Pazdro, 1968, with subsequent modifications by Birkenmajer and Myczyński, 1977, Birkenmajer and Gedl, 2004, Birkenmajer *et al*., 2008, and Gedl, 2008a) with macrofossil discoveries after Birkenmajer and Myczyński (1977). **A.** Section just below the large waterfall, composed of the Branisko Unit. **B.** The small waterfall section, some tens of metres downstream from the large waterfall section; w – limestone beds.

ous shale (1–2 cm thick). Another exposure of the Opaleniec Fm is below the Zabaniszcze klippe in Jarmucki Potok (Zabaniszcze) Creek (Fig. 8; see Sikora, 1971; Oszczypko *et al*., 2012, fig. 4C, D; Gedl, 2013, fig. 5A, B). A transition between the underlying Opaleniec Fm and the overlying Czajakowa Radiolarite Fm is visible in the vicinity of Jaworki, in Krupianka Creek (Fig. 5; Birkenmajer, 1979, fig. 99B; Gedl, 2008d, fig. 19G).

In the more western sector of the PKB in Poland, the Sokolica Radiolarite Fm is exposed in Kręty Creek, near Dursztyn (Fig. 11; Gedl, 2008d, fig. 46A, E, F).

### *Microfossils and their age*

This lithostratigraphic unit for a long time was treated as being devoid of fossils; its age was estimated on the basis of fossils from the underlying and overlying units (Birkenmajer, 1977). Subsequently, radiolarians, foraminifera, and organic-walled dinoflagellate cysts have been found.

**Foraminifera.** Oszczypko *et al.* (2012, p. 426, fig. 4C, D) reported rare agglutinated foraminifera (*Hyperammina* sp., *Trochammina* sp., and *Verneuilinoides* cf. *graciosus* Levina) as an admixture with rich, undetermined radiolarians in samples from this unit, where it is exposed just below the Zabaniszcze klippe.

**Radiolarians.** Widz (1991) described a radiolarian assemblage from a single sample (3/47) collected from the top of the Sokolica Radiolarite Fm, exposed in the Rzeźnia klippe, at Szczawnica. He reported, i.a., *Emiluvia orea* Baumgartner, *Homoeoparonaella argolidensis* Baumgartner, *Hsuum maxwelli* Pessagno gr., *Podobursa helvetica* Rüst, and *Tribrabs casmaliaensis* (Pessagno), and dated them as Oxfordian (Widz, 1991, 1992). Subsequently, this interpretation was changed to middle Callovian–early Oxfordian (Birkenmajer and Widz, 1995).

**Dinoflagellate cysts.** Organic-walled dinoflagellate cysts appear to be widely distributed in the dark rocks of this lithostratigraphic unit in the Grajcarek and Klippen successions (Gedl, 2008d). The Sokolica Radiolarite Fm, exposed in the Rzeźnia klippe, was also studied for dinoflagellate cysts; samples, collected from the same position as Widz's sample, yielded *Adnatosphaeridium caulleryi*, *Batiacasphaera* sp., *Chlamydophorella* sp., *Chytroeisphaeridia chytroeides* (Sarjeant), *Epiplosphaera* sp., *Impletosphaeridium* sp., *Lithodinia jurassica* Eisenack, *Meiouro-*

*gonyaulax caytonensis* (Sarjeant), *Sentusidinium* sp., *Systematophora* spp., and *Tubotuberella dangeardii* (Sarjeant). These assemblages were dated as Oxfordian (Gedl, 2008d).

Similar assemblages, also referred to as Oxfordian, were described from the Sokolica Radiolarite Fm at Mt. Hulina (Birkenmajer and Gedl, 2007; Gedl, 2008d); they included the most frequent representatives of *Epiplosphaera* (*E. areolata* Klement, *E. gochtii* (Fensome), *E. reticulata* (Valensi)) and *Systematophora*, associated with common *Chytroeisphaeridia chytroeides* (Sarjeant), *Dichadogonyaulax sellwoodii* Sarjeant, *Compositosphaeridium polonicum* (Górka), *Chlamydophorella* spp., and rare *Gonyaulacysta fastigiata* Duxbury, *G. jurassica* (Deflandre), *Nannoceratopsis pellucida* Deflandre, *Taeniophora iunctispina* Klement, *Tubotuberella dentata* Raynaud, *T. apatela* (Cookson et Eisenack), and *Atopodinium prostatum* Drugg.

Assemblages described from this unit, where it is exposed in Krupianka Creek, were dated as latest middle Bathonian–Callovian (Gedl, 2008d). Dinoflagellate cysts from the basal part of the unit are similar to those from the topmost part of the underlying Opaleniec Fm; they differ, however, in the less frequent occurrence of *Ctenidodinium combazii* Dupin. The presence of this species and *Atopodinium polygonale* (Beju) at the base of the unit indicates that here it is no older than upper Bathonian. The occurrence of *Compositosphaeridium polonicum* (Górka) in a higher part of the unit indicates that it also spans the Callovian at this site (Gedl, 2008d).

The oldest dinoflagellate cysts assemblages of the Sokolica Radiolarite Fm come from the exposures of this unit in Kręty Creek (Gedl, 2008d). They are characterized by mass occurrences of *Ctenidodinium combazii* Dupin. The age of these assemblages is most likely late Bajocian (basal part) and Bathonian (early?) in the upper part, where *Tubotuberella dangeardii* (Sarjeant) was found. Similar *Ctenidodinium combazii*-acme assemblages were found in the Sokolica Radiolarite Fm of the Branisko Succession, exposed at Niedzica (Gedl, 2008d, fig. 40).

### The Czajakowa Radiolarite Formation

***Distribution, lithology and sedimentology***

This formation in the Grajcarek Succession is identical to that in the Czertezik and Branisko successions (Birkenmajer, 1977). It consists of two members: the lower Podmajerz Radiolarite Mbr (green radiolarites about 6 m thick) and the upper Buwałd Radiolarite Mbr (red radiolarites; in the Rzeźnia klippe they are tectonically reduced from 1 m down to zero m thick; at other sites the red radiolarites are 1–2 m thick). The third member of this formation, the Kamionka Radiolarite Mbr, is missing in the Grajcarek Succession (as in the Czertezik and Branisko successions; Birkenmajer, 1977).

The Czajakowa Radiolarite Fm in the Grajcarek Succession is best exposed in the Rzeźnia klippe at Szczawnica (see above, Fig. 6; Birkenmajer, 1979) and in the Zabaniszcze klippe at Szczawnica (Fig. 8; Sikora, 1971; Oszczypko *et al.*, 2012, fig. 4C, D; Gedl, 2013, fig. 5A, B), where it reaches about 4 m in thickness. Another good exposure of this formation is in Krupianka Creek, near Jaworki (Birkenmajer, 1979). There, a passage between the green radiolarites of the lower Podmajerz Radiolarite Mbr (app. 2 m thick) and the black shale of the underlying Sokolica Radiolarite Fm is exposed (Fig. 5). Above, tectonized red radiolarites of the Buwałd Radiolarite Mbr occur; they are in contact with the Pieniny Limestone Fm. In the western sector of the PKB in Poland, the Czajakowa Radiolarite Fm of the Grajcarek Succession is exposed in Szeligowy Creek, near Rogoźnik (Fig. 2; e.g., Widz and De Wever, 1993).

***Macrofossils and their age***

The Czajakowa Radiolarite Fm is generally devoid of determinable fossils; so far it has yielded only ammonite aptychi (Gąsiorowski, 1962). The age of the Czajakowa Radiolarite Fm is upper Oxfordian on the basis of aptychi (e.g., Birkenmajer and Gąsiorowski, 1960; Gąsiorowski, 1962).

***Microfossils and their age***

Radiolarians are the most common microfossils described so far from this lithostratigraphic unit. Attempts to find organic-walled dinoflagellate cysts failed (e.g., Gedl, 2008d). Crinoids (*Saccocoma*) were reported by Golonka and Sikora (1981) from this unit exposed in Krupianka Creek, near Jaworki.

**Radiolarians.** Nowak (1971) described undeterminable Spumellaria from the Czajakowa Radiolarite Fm (sample 31/5), exposed in the Zabaniszcze klippe, in Zabaniszcze Stream, Szczawnica (see also Nowak, 1976). Widz (1991) described *Andromeda crassa* Baumgartner, *Archaeodictyomitra apiarium* Rüst, *Cinguloturris carpatica* Dumitrică et Mello, *Emiluvia orea* Baumgartner, *Hsuum maxwelii* Pessagno gr., *Podobursa spinosa* Ozvoldova, *P. triacantha* Wisniowski, *Tetratrabs bulbosa* Baumgartner, *Tritrabs casmaliaensis* (Pessagno), and *T. exotica* Pessagno from the Podmajerz Radiolarite Mbr exposed in the Rzeźnia klippe, Szczawnica. They were dated as Oxfordian–early Kimmeridgian in the lower part and middle–late Oxfordian to late Kimmeridgian–early Tithonian in the uppermost part (Birkenmajer and Widz, 1995).

Other radiolarian assemblages, described from the Podmajerz Radiolarite Mbr exposed in Szeligowy Creek, include *Birkenmajeria cometa* Widz et De Wever, *Gongylothorax szeligoviensis* Widz et De Wever, *Parahsuum carpathicum* Widz et De Wever, *Spongocapsula dumitricai* Widz et De Wever, *Williriedellum carpathicum* Dumitrică, and *W. sujkowskii* Widz et De Wever; they were dated as Oxfordian (Widz and De Wever, 1993). Slightly different assemblages, with *Birkenmajeria cometa*, *B.* aff. *cometa*, *B. sphaerica* (Ozvoldova), *Hsuum*? sp. A, *Obesacapsula nodosa* Widz et De Wever, *Saitoum dercourti* Widz et De Wever, *S.* sp. A, *Spongocapsula dumitricai* Widz et De Wever, and *Tetracapsa zinckenii* Rüst, were reported from the upper part of the section (the Buwałd Radiolarite Mbr), dated as late Oxfordian–Kimmeridgian (Widz and De Wever, 1993).

**Calcareous microfossils.** Relatively frequent specimens of the calcareous dinoflagellate *Parastomiosphaera malmica* (Borza) were described from the exposures in the Zabaniszcze klippe, Zabaniszcze Stream, Szczawnica (Nowak, 1971, 1976). The presence of *P. malmica* may indicate a lower Tithonian age of these strata (e.g., Nowak, 1973; see also below).

**Foraminifera.** Rare *Protoglobigerina* were described by Golonka and Sikora (1981) from the Czajakowa Radiolarite Fm exposed in Szeligowy Creek, near Rogoźnik.

### The Czorsztyn Limestone Formation

#### *Distribution, lithology and sedimentology*

In the Grajcarek Succession, the Czorsztyn Limestone Fm is represented by the Palenica Marl Mbr (Birkenmajer, 1977). This unit is distinguished by its marly character – it consists of red or variegated marls, marly limestones and shales with frequent aptychus shells – in contrast to the nodular limestone nature in the Klippen successions. The thickness of this unit in the Grajcarek Succession, by comparison with the Klippen successions (up to 15–17 m), is reduced: merely 1 m or less near Szczawnica (in the Rzeźnia klippe, this member it is up to 1 m thick; Fig. 6), reaching a maximum of 3.5 m in Szeligowy Creek, near Rogoźnik (western sector of the PKB in Poland; Widz, 1992).

#### *Macrofossils and their age*

The aptychi shells are the only macrofossils described so far from the Palenica Marl Mbr (Gąsiorowski, 1962); they indicate a Kimmeridgian age (the lower part of the aptychus Subzone VI 1 of Gąsiorowski; see Birkenmajer, 1965).

#### *Microfossils and their age*

Nowak (1971) described assemblages of calcareous microfossils, including calcareous dinoflagellates *Parastomiosphaera malmica* (Borza), the microfossil *Globochaete alpina* Lombard (Chlorosphaeraceae; see e.g., Skompski, 1982), and the crinoid *Saccocoma*, from the Palenica Marl Mbr, exposed in the Rzeźnia klippe at Szczawnica (see also Nowak, 1976). A similar assemblage, associated with another species of calcareous dinoflagellate (*Carpistomiosphaera borzai* Nowak), was described by Nowak (1971) from an overlying part of the unit exposed in the Zabaniszcze klippe. The presence of *P. malmica* allowed correlation of these strata with the lower Tithonian calcareous dinoflagellate Parastomiosphaera malmica Zone (Nowak, 1971, 1973, 1976); the total range of this species is nowadays correlated with the Tithonian uppermost Tithonica–lower Fortis zones (see Lukeneder *et al.*, 2010).

The differences between age determinations from Gąsiorowski (aptychi) and Nowak's calcareous microfossils were discussed by the latter author (Nowak, 1971, p. 217).

### The Pieniny Limestone Formation

#### *Distribution, lithology and sedimentology*

In the Grajcarek Succession, the Pieniny Limestone Fm is very strongly condensed in thickness (2–6 m), as compared to the majority of the Klippen successions: the Czertezik (40–60 m), the Branisko (115–125 m), the Pieniny (?90 m to over 180 m), and the Haligovce (30 m) successions (see Birkenmajer, 1977, pp. 94–100, and Birkenmajer and Gąsiorowski, 1959).

The Pieniny Limestone Fm of the Grajcarek Succession consists of well bedded light grey, grey, spotty limestone with black chert bands and nodules in the lower part of the unit. The limestone becomes marly upwards; the limestone bands alternate with thin, black shales.

The best sections of the Pieniny Limestone Fm are exposed between Szczawnica and Jaworki: the Rzeźnia klippe at Szczawnica (Fig. 6; Birkenmajer, 1979), the Zabaniszcze klippe at Szczawnica (Fig. 8; Sikora, 1971; Oszczypko *et al.*, 2012; Gedl, 2013), exposures in Grajcarek Creek near Mt. Jarmuta (Fig. 7; Birkenmajer, 1979, p. 192–193), a klippe at the mouth of the Sielski Stream near Szlachtowa (Oszczypko *et al.*, 2012; Pszczółkowski, 2015), and exposures in Krupianka Creek near Jaworki (Fig. 5; Birkenmajer, 1979; Gedl, 2008d). Small scales of the Pieniny Limestone Fm occur also in a highly tectonized section of the Grajcarek Succession, exposed in the upper course of Sztolnia Creek below and above a small waterfall (see Birkenmajer and Myczyński, 1977; Birkenmajer and Gedl, 2004); some of them subsequently have been destroyed or covered by stream rubble (Fig. 12B).

Several klippes of the Pieniny Limestone Fm, originally assigned to the Branisko Succession, have been marked on the 1:10,000-scale Sheet 4, Nowa Biała (Birkenmajer, 1965). At Krempachy (Birkenmajer, 1965), between the streams Kiźlinkowy (= Kremlitzabach in Uhlig, 1890) and Kręty (Durstiner Bach in Uhlig, 1890) ), these limestone klippes belong to a belt of Grajcarek Unit rocks that in the south makes contact with the Czorsztyn Unit klippes.

One of the Pieniny Limestone Fm klippes is the Kiźlinkowy Stream klippe (on the right slope of Kiźlinkowy Stream, near Mt. Kramnica and Krempachy, Polish Spisz) known already to Uhlig (1885; 1890, fig. 8C, fig. 9, "Neocomklippe", fig. 24, pp. 653–654). A description of it and its relationship to the overlying strata were given by Birkenmajer and Gąsiorowski (1959). Below, the present authors provide an updated description (Fig. 13).

#### *Microfossils and their age*

There is a good macrofaunal evidence for the Tithonian (resp. upper Kimmeridgian) through Barremian age of the Pieniny Limestone Fm in the Klippen successions on the basis of ammonite and belemnite faunas (see Uhlig, 1890; Andrusov, 1945, 1953; Gąsiorowski, 1962; Scheibner, 1968; Birkenmajer, 1977; Pszczółkowski and Myczyński, 2004). Presently, more attention is being paid to the microfossil and nannofossil content of the limestones, as these fossils provide a more detailed age determination (e.g., Birkenmajer, 1977; Birkenmajer and Dudziak, 1987; Pszczółkowski and Myczyński, 2004). Their stratigraphic importance in the Grajcarek Succession is even greater, as macrofossils are rare in the Pieniny Limestone Fm there.

**Calcareous microfossils.** Nowak (1971) described two different nannofossil assemblages from the Pieniny Limestone Fm exposed in the Zabaniszcze klippe (see Sikora, 1971). The older one, collected from the base of this unit, showed a mass occurrence of *Nannoconus* ex gr. *steinmannii*; it was correlated with the lower part of the upper Tithonian. A younger assemblage from the upper part of the klippe included frequent nannofossils, such as *Nannoconus*

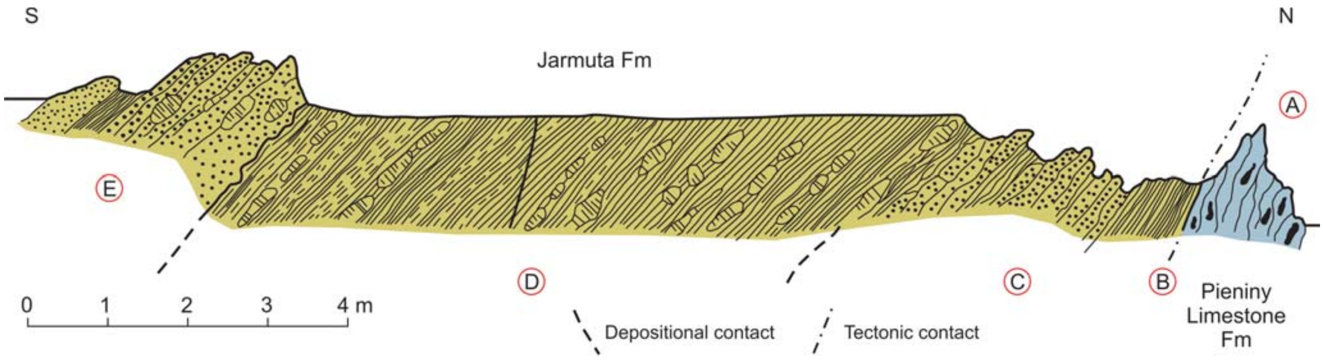


**Fig. 13.** Relationship between the Jarmuta Formation (C–E) and the Pieniny Limestone Formation (A) in Kiźlinkowy Potok, near Krempachy (Polish Spisz). From Birkenmajer and Gąsiorowski (1959). **A.** A klippe formed by the Pieniny Limestone Fm: cherty limestone, greyish, in beds 5–15 cm thick, with spots and lenses of black cherts. Fossils (*in situ*): *Lamellaptychus angulocostatus* (Peters) var. ind. (L. Horwitz's collection, determined by Gąsiorowski in Birkenmajer and Gąsiorowski, 1959). **B.** Erosional break – overlying mid–Upper Cretaceous strata, i.e., the Kapuśnica Fm through the Malinowa Shale Fm, were removed by pre-Maastrichtian erosion/abrasion. **C–E.** Jarmuta Fm (cliff facies, Maastrichtian). **C.** Marly shales, green, with fragments of the Pieniny Limestone Fm (white limestone and black chert) and of other Lower Cretaceous rocks, moreover fine-detrital limestone and breccia/limestone. Fossils (recycled): *Lamellaptychus* ex gr. α Trauth (coll. K. Birkenmajer and S. M. Gąsiorowski); *L. angulocostatus* (Peters) cf. f. typ. Trauth, *L. angulocostatus* (Peters) var. cf. *atlantica* (Henning) – from L. Horwitz's collection; moreover *Lamellaptychus angulocostatus* (Peters), *Terebratulina* sp., *Pseudobelus bipartitus* Blainville and *Sphenodus* sp. from Uhlig's (1890, fig. 24 c, p. 653) collection. **D.** Alternating, thin, cherry-red, variegated and green, marly shales (originated from reworked, soft rocks of Lower and mid Cretaceous, and Jurassic rocks). Fragments of dark green chert (derived from Lower Cretaceous strata), green and red radiolarite (from the Czajakowa Radiolarite Fm), red marly limestone (from the ?Czorsztyn Limestone Fm) and lenses of fine-detrital limestone (from the Pieniny Limestone Fm) are present. **E.** Conglomerate, fine-grained, and sedimentary quartz and limestone breccias, consisting of sharp-edged clasts of the Pieniny Limestone Fm (limestone and black cherts), and red radiolarite (Czajakowa Radiolarite Fm); numerous, pink crinoid-stem fragments. Clast fragments 1–3 mm, up to 5 cm in size. Poorly marked graded bedding. Note: in Uhlig's (1890, p. 654, fig. 24) this is bed "d", correlated with Middle Jurassic crinoidal limestone. A recycled aptychus fragment *Lamellaptychus angulocostatus* (Peters) var. cf. *atlantica* (Henning) was found.

spp. (*N. steinmannii* Kamptner, *N. bermudezi* Brönnimann, ?*N. elongatus* Brönnimann), Tintinnida (*Tintinnopsella carpathica* (Murgeanu et Filipescu), *Amphorellina subacute* Colom), and calcareous dinoflagellates (*Colomisphaera minutissima* (Colom) and *Cadosina semiradiata* ex aff. *olzae* (Nowak)); the assemblage was dated as ?Valanginian–Hauterivian.

Obermajer (1986, see also 1987a) described rich, calcareous microfossils from four sections in the Szczawnica–Jaworki area (partly overlapping those studied by Nowak, 1971) that form several microfacies, which follow each other sequentially. The oldest is an upper Kimmeridgian microfacies with *Stomiosphaera moluccana* Wanner (at Jarmuta-Malinów). The Parastomiosphaera malmica Zone (lower Tithonian) was found at Szlachtowa; the same zone was described by Nowak (1971) from the Palenica Marl Mbr in the Szczawnica sections. The Colomisphaera pulla Zone, characterized by the mass occurrence of the index species, was found stratigraphically above (Obermajer, 1986), although in some other sections (e.g., Nowak, 1968) this zone occurs below the Parastomiosphaera malmica Zone. Middle Tithonian parts of the sections of the Pieniny Limestone Fm investigated are characterized by the *Saccocoma* horizon, which contains the lowest occurrences of the chitinelloids. Above, calpionellid microfacies occur: the Calpionella Zone of Berriasian age was distinguished here (the latest Tithonian–earliest Berriasian zones were not found by Obermajer, 1986). The *Nannoconus* microfacies with its characteristic *Colomisphaera tenuis* Nagy and *Stomiosphaera echinata* Nowak that occur above belongs to the upper Valanginian–Hauterivian zone with *Colomisphaera vogleri* Borza. The youngest part of the Pieniny Limestone Fm studied by Obermajer (1986) consists of a *Hedbergella* microfacies (upper Hauterivian–Albian).

Oszczypko *et al*. (2012) reported from the same Zabaniszcze klippe frequent calcareous dinoflagellates *Parastomiosphaera malmica* (Borza) that indicate a lower Tithonian age of the Pieniny Limestone Fm at this site (i.e., in an older position than that observed by Nowak, 1971).

Golonka and Sikora (1981) reported Calpionellidae and Tintinnida (*Calpionella alpina* Lorenz, *C. elliptica* Cadisch, and *Crassicollaria parvula* Remane) and the calcareous dinoflagellates *Colomisphaera carpathica* (Borza), and *C. minutissima* (Colom) from the Pieniny Limestone Fm, near Szlachtowa; they named the exposure Malinowa.

Golonka and Sikora (1981) described the calcareous dinoflagellates *Stomiosphaera wanneri* Borza and rare specimens of *Pithonella ovalis* (Kaufmann) from an outcrop at Szlachtowa.

From exposures in Krupianka Creek, they described rare Calpionellidae and Tintinnida (*Calpionella alpina* Lorenz, *Crassicollaria colomi* Doben, and *Tintinnopsella carpathica* (Murgeanu et Filipescu)). Calpionellidae *Lorenziella hungarica* Knauer et Nagy and *Calpionellites darderi* (Colom) were found in the uppermost part of the unit (Golonka and Sikora, 1981).

From another locality of the Pieniny Limestone Fm of the Grajcarek Succession in Szeligowy Creek, near Rogoźnik, Golonka and Sikora (1981) described Tintinnida (*Tintinnopsella carpathica* (Murgeanu et Filipescu)), calcareous dinoflagellates (*Bonetocardiella conoidea* (Bonet), *Cadosina fusca* Wanner, *C. oraviensis* Borza, *Pithonella ovalis* (Kaufmann), *P. trejoi* Bonet, *Stomiosphaera wanneri* Borza), and Calpionellidae (*Calpionellopsis oblonga* Colom).

Oszczypko *et al.* (2004) studied the calcareous nannofossils from a single sample (22), collected from a small klippe of the Pieniny Limestone Fm, exposed in the upper course of Sztolnia Creek (their "cherty limestone": Oszczypko *et al.*, 2004, fig. 7); this is presumably the same klippe indicated by Birkenmajer and Gedl (2004, fig. 4D), from which E. Gedl (2007) studied organic-walled dinoflagellate cysts (see below). It yielded very rare *Braarudosphaera bigelowii* (Gran et Braarud) and *Watznaueria biporta* Bukry, indicating an Albian–Cenomanian age, with much more frequent Tithonian–Early Cretaceous species (Oszczypko *et al.*, 2004).

From the top strata of the Pieniny Limestone Fm, exposed in a klippe at the mouth of the Sielski Stream near Szlachtowa, Pszczółkowski (2015) determined planktic foraminifera, e.g., *Globigerinelloides duboisi* (Chevalier), *G. maridalensis* (Bolli), *G. paragottisi clavatus* (Verga et Premoli Silva), *Gorbachikella kugleri* Bolli, *Leupoldina pustulans pustulans* (Bolli), *Praehedbergella excelsa* (Longoria), *P. occulta* (Longoria), *P. ruka* Banner, Copestake et White, *P. sigali* (Moullade), *Pseudoloeblichella*? *convexa* (Longoria), and *Pseudoschackoina saundersi* (Bolli); calcareous dinoflagellates (*Cadosina semiradiata olzae* (Nowak), *Cadosina* sp. cf. *C. semiradiata semiradiata* Wanner, *Cadosinopsis nowaki* Borza, *Colomisphaera heliosphaera* Vogler, *C. vogleri* (Borza), *Pithonella ovalis* (Kaufmann), and *Stomiosphaera wanneri* Borza); calcareous nannoplankton, e.g., *Biscutum ellipticum* (Górka), *Corollithion achylosum* (Stover), *Eprolithus floralis* (Stradner), *Hayesites* cf. *albiensis* Manivit, *Prediscosphaera* sp. ex gr. *P. spinosa-columnata*, *Watznaueria biporta* Bukry, *W. ovata* (Bukry), *W. barnesiae* (Black), *W. fossacincta* (Black), and *W. britannica* (Stradner); and nannofossils (e.g., *Nannoconus bonetii* Trejo, *N. colomii* (de Lapparent), *N. kamptneri* Brönnimann, *N. truittii truittii* Brönnimann, *N. vocontiensis* Deres et Achéritéguy, and *N. steinmannii steinmannii* Kamptner). In his opinion (Pszczółkowski, 2015, p. 32) "the nannofossil data are consistent, in general, with the Aptian age of the samples studied and corresponding limestone beds...".

**Organic-walled dinoflagellate cysts.** In a condensed section of the Pieniny Limestone Fm in Sztolnia Creek, above a small waterfall, E. Gedl (2007) recognized two dinoflagellate cyst assemblages: Hauterivian or older, and early Barremian. The older assemblage was identified in a sample collected from the northern part of the klippe (E. Gedl, 2007, fig. 2); it included, i.a., *Bourkidinium* spp. (incl. *B. granulatum* Morgan), *Cerbia* cf. *tabulata* (Davey et Verdier), *Cymososphaeridium validum* Davey, *Dingodinium cerviculum* Cookson et Eisenack, *Gonyaulacysta diutina* Duxbury, *Kleithriasphaeridium corrugatum* Davey, *K. fasciatum* Davey et Williams, *Meiourogonyaulax stoveri* Millioud, *Muderongia staurota* Sarjeant, *Nexosispinum vetusculum* (Davey), *Odontochitina imparilis* (Duxbury), and *Phoberocysta neocomica* (Gocht). Its age was interpreted as being not younger than Hauterivian (E. Gedl, 2007, p. 78). Samples collected from the southern part of the klippe yielded younger assemblages, including, i.a., *Batioladinium jaegeri* (Alberti), *Cribroperidinium sepimentum* Neale et Sarjeant, *Florentinia interrupta* Duxbury, *Gonyaulacysta perforobtusa* Duxbury, *Meiourogonyaulax stoveri* Millioud, *Muderongia staurota* Sarjeant, *Nexosispinum vetusculum* (Davey), *Occisucysta tentorium* Duxbury, *Phoberocysta tabulata* (Raynaud), *Pseudoceratium anaphrissum* (Sarjeant), *Rhynchodiniopsis aptiana* Deflandre, *Tanyosphaeridium boletus* Davey, and *Wallodinium krutzschii* (Alberti). Their age was determined as early Barremian (E. Gedl, 2007, p. 78).

A younger, late Barremian age of dinoflagellate cysts assemblages from two samples, collected from the top of the Pieniny Limestone Fm in the Rzeźnia klippe at Szczawnica, was suggested (E. Gedl, 2007, fig. 3). There, they included, i.a., *Aprobolocysta neista* Duxbury, *Cauca parva* (Alberti), *Cerbia tabulata* (Davey et Verdier), *Dingodinium* spp., *Hystrichodinium ramoides* Alberti, *Muderongia staurota* Sarjeant, *Odontochitina imparilis* (Duxbury), *O. operculata* (Wetzel), *Phoberocysta neocomica* (Gocht), *Prolixosphaeridium parvispinum* (Deflandre), *Pseudoceratium pelliferum* Gocht, and *P. solocispinum* (Davey). However, E. Gedl (2007, p. 80) noted the presence of *Membranosphaera* sp. A of Davey (1979) in both samples and highlighted the fact that this species is typical for the early Aptian.

A similar, late Barremian–earliest Aptian age was determined for the dinoflagellate cyst assemblage from a single sample, collected from the top of the Pieniny Limestone Fm in the Zabaniszcze klippe (Gedl, 2013). This assemblage includes, i.a., *Cerbia tabulata* (Davey et Verdier), *Ellipsodinium reticulatum* Duxbury, *Oligosphaeridium albertense* (Pocock), *O. asterigerum* (Gocht), *O. complex* (White), *Prolixosphaeridium parvispinum* (Deflandre), *Pterodinium spp*., *Rhynchodiniopsis aptiana* Deflandre, and *Tanyosphaeridium regulare* Davey et Williams; its age was based on the co-occurrence of *C. tabulata* and *R. aptiana* (Gedl, 2013).

## The Kapuśnica Formation

### *Distribution, lithology and sedimentology*

The Kapuśnica Fm was described formally by Birkenmajer (1977, pp. 101–105). It is a lithostratigraphic unit, transitional between the Pieniny Limestone Fm and the Wronine Fm. An Aptian–Albian age was suggested on palaeontological evidence in the Klippen successions (Birkenmajer, 1977). Its thickness varies between 10–45 m in the Pieniny Succession, 10–30 m in the Branisko Succession, 15–30 m in the Czertezik Succession, 9–10 m in the Niedzica Succession, and 0.5–1 m in the Grajcarek Succession.

This formation has been subdivided into 2 members: the Brodno Mbr and the Rudina Mbr. In the Grajcarek Succession, the formation is represented by only the Brodno Mbr, which consists of black or dark grey shales and marly shales, alternating with thin beds of spotty, cherty limestone (the Pieniny Limestone Fm type). This indicates a transition between the Kapuśnica Fm and the underlying Pieniny Limestone Fm in the Grajcarek Succession; in some sections of the Klippen successions, this "transition" instead shows an erosional character (e.g., Obermajer, 1987b).

Nowadays, the best exposures of the Kapuśnica Fm of the Grajcarek Succession are in Krupianka Creek, near Jaworki (Fig. 5; Birkenmajer, 1979, figs 98, 99A), and in the vicinity of Szczawnica, namely, in the Rzeźnia klippe (Fig. 6; Birkenmajer, 1979, fig. 88), and the Zabaniszcze klippe (Fig. 8; e.g., Gedl, 2013, fig. 5A, D, E).

***Microfossils and their age***

**Dinoflagellate cysts.** In the Rzeźnia klippe at Szczawnica, two samples were taken by E. Gedl (2007) from calcareous, black shales and very hard, silicified, black shales (the Brodno Mbr), just above the contact with the Pieniny Limestone Fm. The lower sample yielded *Cerbia tabulata* (Davey et Verdier), *Dingodinium albertii* Sarjeant, *Exochosphaeridium phragmites* Davey, Downie, Sarjeant et Williams, *Gonyaulacysta diutina* Duxbury, *Occisucysta tentorium* Duxbury, *Odontochitina operculata* (Wetzel), *O. rhakodes* Bint, *Oligosphaeridium pulcherrimum* (Deflandre et Cookson), *Rhynchodiniopsis aptiana* Deflandre, *Tanyosphaeridium regulare* Davey et Williams, and frequent *Cassiculosphaeridia* (*Valensiella*) *reticulata* Davey. The co-occurrence of *O. operculata* and *C. tabulata*, with *R. aptiana* (a typical Barremian species in the Tethyan realm) indicates a late Barremian age for this assemblage (E. Gedl, 2007, p. 81). The higher sample yielded a different assemblage, with, e.g., *Ctenidodinium elegantulum* Millioud, *Gardodinium trabeculosum* (Gocht), *Kleithriasphaeridium simplicispinum* (Davey et Williams), *Odontochitina imparilis* (Duxbury), *O. operculata* (Wetzel), and *Tehamadinium sousense* (Below), characterized by the absence of *Rhynchodiniopsis aptiana* Deflandre. The absence of the last mentioned species and the subsequent co-occurrence of *O. operculata* and *C. elegantulum* indicate its early Aptian age (E. Gedl, 2007, p. 81).

Gedl (2013) described other assemblages from the Kapuśnica Fm in the neighbouring Zabaniszcze klippe (Fig. 11). A sample collected directly above the Pieniny Limestone Fm yielded, i.a., *Pseudoceratium securigerum* (Davey et Verdier), *Cassiculosphaeridia* (*Valensiella*) *reticulata* Davey, *Diphasiosphaera stolidota* Duxbury, *Gonyaulacysta*? *kleithria* Duxbury, *Odontochitina imparilis* (Duxbury), *O. operculata* (Wetzel), *Prolixosphaeridium parvispinum* (Deflandre), *Rhynchodiniopsis aptiana* Deflandre, *Taleisphaera hydra* Duxbury, and *Tanyosphaeridium regulare* Davey et Williams. The age of this assemblage was interpreted as earliest Aptian (Gedl, 2013). Assemblages that were taxonomically impoverished, but rich in *Cassiculosphaeridia* (*Valensiella*), were reported from samples taken from a higher part of the unit.

## The Wronine Formation

The term "Wronine beds" was introduced by Birkenmajer (in Birkenmajer and Pazdro, 1963b) for a part of the deposits, previously described as the "sub-flysch beds" (Birkenmajer, 1953) and incorrectly regarded as being of Aalenian or Toarcian–Aalenian age (see discussion by Birkenmajer and Pazdro, 1963b). A Lower Cretaceous age (?Barremian to ?Albian) was suggested on the basis of microfaunal evidence for part of the "sub-flysch beds" (Birkenmajer, 1977, pp. 127–128).

***Distribution, lithology and sedimentology***

The Wronine Fm is known only from the Grajcarek Succession. It consists of argillaceous or marly shales, black or dark green, sometimes variegated or spotty, with pyrite, siderite and ferruginous dolomite concretions. A malachite coating may sometimes be observed on cleavage planes. In the lower part of the formation, the shales are often siliceous and contain thin intercalations of limestone, coated with black manganese oxides. This unit thickness is 13 m in the type section (Wronine Hill, near Czorsztyn Castle; Birkenmajer and Pazdro, 1963b, fig. 1), but often is much less (2–5 m). A thickness of up to 100 m (?) probably results from tectonic repetition (Birkenmajer, 1977, p. 128).

Lithologically, the shales of the Wronine Fm resemble the Opaleniec Fm. In the absence of an age-diagnostic macro- or microfauna, it may often be difficult to distinguish the Wronine Fm from the Opaleniec Fm (Bajocian). The type section of the Wronine Fm (near Czorsztyn Castle) is presently not available for examination; it is flooded by the artificial Czorsztyn Lake.

At present, the Wronine Fm is best exposed in the Rzeźnia (Fig. 6) and Zabaniszcze klippes near Szczawnica (Fig. 8; Birkenmajer, 1979; Gedl, 2013, respectively) and on the northern slope of Mt. Hulina, at Szczawnica Wyżna (Fig. 10; Birkenmajer and Gedl, 2007, figs 3, 4; E. Gedl, 2007, fig. 4).

***Microfossils and their age***

**Foraminifera.** Foraminifera from the Wronine Fm were studied by Pazdro (in Birkenmajer and Pazdro, 1963b) from the following sites: Wronine Hill (Czorsztyn, section 32), the northern slope of Czorsztyn Castle Hill (section 31), Głęboki Potok Stream (Szczawnica Niżna = Mt. Hulina section in Birkenmajer and Gedl, 2007; E. Gedl, 2007; Gedl, 2008d and later papers), Jarmuta-Siodło (Szczawnica Wyżna; section 56A), and on an alp to the north of Mt. Branisko (at Polish Spisz; section 54B). Foraminifera from these sites are usually poorly preserved and taxonomically impoverished; they are associated with frequent radiolaries and rare ostracods (Birkenmajer and Pazdro, 1963b).

The samples from the Wronine Hill section yielded various microfaunal assemblages. Some were barren, while others contained only radiolarians; three samples (8, 10, 11) yielded foraminifera, i.a., *Discorbis* cf. *turbo* (d'Orbigny), *Dorothia* sp., *Gaudryina richteri* Grabert, *Gavelinella* cf. *barremiana* Bettenstaedt, *Hedbergella trocoidea* (Gandolfi), and *Pleurostomella* sp. Their age was interpreted as Barremian–Aptian. A similar age was interpreted on the basis of the presence of *Gyroidina* cf. *infracretacea* Morozova in sample (3) from an exposure on the northern slope of Czorsztyn Castle Hill. The same species was found in a sample from the alp to the north of Mt. Branisko (section 54B). A questionably determined *G.* cf. *infracretacea*, and *Thalmannammina neocomiensis* Geroch were found in Kręty Creek; their presence was the only basis for the uncertain assigning of a Cretaceous age to the strata exposed in Kręty Creek (Birkenmajer and Pazdro, 1963b, p. 437).

Of the three samples from the Jarmuta-Siodło section, only one sample (4c) yielded *in situ* foraminifera. These are the Jurassic *Astacolus scalptus* (Franke), *Nodosaria mutabilis* Terquem, and *Paalzowella* sp. Three samples from Głęboki Potok Stream (i.e., the Mt. Hulina section) yielded various assemblages (for their locations, see Birkenmajer and Dudziak, 1987, fig. 2). Samples “a” and “b” yielded very rare, long-ranging specimens (e.g., *Haplophragmoides*), associated with rich, but undeterminable radiolarians. Sample “c” yielded a much richer assemblage, but also was composed of long-ranging species (i.a., *Discorbis* cf. *turbo*, *Dorothia* cf. *filiformis* (Berthelin), Epistominidae, *Gaudryina* cf. *richteri*, *Lenticulina* ex gr. *muensteri* (Roemer), *L.* ex gr. *varians* (Bornemann), and *Planularia complanata* (Reuss)); no radiolarians were found in this sample.

Blaicher (1973) described rich foraminifera assemblages from the Wronine Fm, exposed in the Zabaniszcze klippe section. The lowermost part of this unit yielded frequent planktic species (*Globigerinelloides gyroidinaeformis* Moullade, *Hedbergella planispira* Tappan, and *H. trocoidea*) associated by, i.a., *Gavelinella* sp. cf. *berthelini* (Keller), *Lenticulina incurvata*, *L. muensteri*, and *Marsonella hauteriviana* Moullade. Higher up the section, the taxonomical composition of foraminifera assemblages changes: frequent forms, i.a., *Discorbis wassoewizi* Djaffarov and Agalarova, *Gaudryinella sherlocki* Bettenstaedt, *Gyroidina infracretaceae* Glaessner, *Plectorecurvoides alternans* Noth, and *Trochammina vocontiana* Moullade, are associated with planktic species (the same as in the basal part). Blaicher (1973) noted a qualitative and quantitative similarity between the rich assemblages from the Wronine Fm, exposed at Rzeźnia klippe (without any detailed description). Blaicher’s material was re-examined by Oszczypko *et al.* (2012, p. 432, Appendix 1).

The foraminifera from the Wronine Fm also were studied by Oszczypko *et al*. (2012) from a single sample (Zab.10/10) from the Zabaniszcze klippe section. The sample is indicated in the text as the Wronine Fm, but is shown in their fig. 4D as the Kapuśnica Fm (Oszczypko *et al*., 2012. fig. 4D, p. 426). It yielded a mixture of poorly preserved, agglutinated and calcareous forms, i.a., *Caudammina crassa* (Geroch), *Gaudryina* sp., *Glomospira gordialis* (Jones et Parker), *Glomospirella gaultina* (Berthelin), *Gyroidinoides* sp., and *Planomalina* sp., associated with the pyritized moulds of radiolarians. Oszczypko *et al.* (2012, p. 426) also reported poor assemblages of agglutinated and calcareous foraminifera of Early Cretaceous age (i.a., *Hyperammina* cf. *gaultina* Ten Dam, *Trochammina* cf. *neocomiana* Myatliuk, and *Dentalina* aff. *nana* Reuss) from dark shale of this unit. No information is given on the origin of this material and their table 3 lacks these species (Oszczypko *et al.*, 2012. tab. 3).

**Calcareous nannoplankton.** Calcareous nannoplankton from the Wronine Fm were investigated by Dudziak (in Birkenmajer and Dudziak, 1987, fig. 2) from the same set of samples studied by Pazdro (in Birkenmajer and Pazdro, 1963b); see above. Additional samples from the Rzeźnia klippe (Szczawnica Wyżna) were studied. The samples yielded various calcareous nannoplankton assemblages, commonly characterized by very low frequencies and a poor state of preservation; the overwhelming predominance of *Watznaueria* was noticeable in the samples showing higher frequencies of nannoplankton. The most diversified assemblages were described from the *locus typicus* of the formation, Wronine Hill; they included, i.a., *Corollithion achylosum* (Stover), *Cyclagelosphaera deflandrei* (Manivit), *Lithastrinus floralis* Stradner, *Parhabdolithus asper* (Stradner), *P. embergeri* (Noël), *Prediscosphaera cretacea* Bukry, *Tetralithus pyramidus* Gardet, *Watznaueria barnesiae* (Black), *W. britannica* (Stradner), and *W. communis* Reinhardt. The ages of these assemblages, depending on the sample, were latest early Albian–middle Albian and late Aptian–Albian. A similar assemblage was found at the neighbouring site on Czorsztyn Castle Hill and was dated as late Aptian–Albian.

Presumably, the youngest, calcareous nannoplankton assemblages were found at the base of the Wronine Fm in the Rzeźnia klippe; the two basal samples (A and B) yielded *Eiffellithus turriseiffeli* (Deflandre), a species that appeared for the first time during the late Albian (Birkenmajer and Dudziak, 1987, tab. 1, p. 98). These authors concluded that its presence may indicate a younger age than that of the early–middle Albian and late Aptian–Albian assemblages from the exposures in the vicinity of Czorsztyn, which were also devoid of this species. Interestingly, samples “C” and “D” were also devoid of *Eiffellithus turriseiffeli*; they included, i.a., *Cruciellipsis chiasta* (Worsley), *Cyclagelosphaera deflandrei*, *Lithastrinus floralis*, *Vagalapilla matalosa* (Stover), *Watznaueria barnesiae*, *W. britannica*, and *W. communis*.

Three samples (a, b, c) from Głęboki Potok Stream (= Mt. Hulina) yielded impoverished assemblages, consisting of infrequent and poorly preserved specimens of taxa without stratigraphical significance: *Lithastrinus* sp., *Rucinolithus* cf. *irregularis* Thierstein, and *Tetralithus pyramidus* (Birkenmajer and Dudziak, 1987, tab. 1, p. 98). Of these three samples studied, sample “a” was collected from the Jurassic Opaleniec Fm and only samples “b” and “c” were taken from the Wronine Fm; this can be compared with later interpretations of the section in question by Birkenmajer and Gedl (2007) and E. Gedl (2007).

Similar, rare specimens without stratigraphical significance were found in a single sample, collected from an exposure on the northern alp of Mt. Branisko (section 54B; i.a., *Discorhabdus* cf. *biradiatus* (Worsley), *Rucinolithus* cf. *irregularis*, *Tetralithus pyramidus*; Birkenmajer and Dudziak, 1987). Of three samples from the Jarmuta-Siodło (section 56A), one was barren (4a), second (4c) yielded a poorly preserved, almost monospecific assemblage of *Watz-*

*naueria communis* associated with *Cyclagelosphaera deflandrei*, and only the third sample (4b) yielded the stratigraphically important species *Lithastrinus floralis*, as well as *Parhabdolithus embergeri* (Noël), *Watznaueria barnesiae*, *W. britannica*, and *W. communis*, dating as late Aptian–Albian (Birkenmajer and Dudziak, 1987). An assemblage from sample (4c) was questionably dated as Middle Jurassic; lithologically it is very similar to the Opaleniec Fm, as was the case for sample "a" from Głęboki Potok Stream (= Mt. Hulina). A similar correction also is applicable to strata exposed in Kręty Creek, which yielded poorly preserved, long-ranging, calcareous nannoplankton (*Discorhabdus* cf. *biradiatus*, *Watznaueria barnesiae*; Birkenmajer and Dudziak, 1987), but Gedl (2008d) proved their Middle Jurassic ages and assigned them to the Opaleniec Fm.

**Dinoflagellate cysts.** These microfossils so far have been studied from three sites: in the Rzeźnia and Zabaniszcze klippes at Szczawnica and on the slope of Mt. Hulina.

Samples from this unit in the Rzeźnia klippe (E. Gedl, 2007, fig. 2) yielded various palynological contents. Some samples, mainly from lower part of the section, were barren. The other samples yielded dinoflagellate cyst assemblages of various ages that might indicate tectonic disruption of the strata in question. Sample (5), from the middle part of the section studied, yielded an assemblage with *Litosphaeridium siphoniphorum* (Cookson et Eisenack), associated, i.a. with, *Chlamydophorella nyei* Cookson et Eisenack, *Cribroperidinium muderongense* (Cookson et Eisenack), *Heslertonia heslertonensis* (Neale et Sarjeant), *Odontochitina operculata* (Wetzel), *Oligosphaeridium albertense* (Pocock), and *Prolixosphaeridium deirense* Davey, Downie, Sarjeant et Williams, indicating its late Albian–Cenomanian age (E. Gedl, 2007, p. 81). The age of the following sample (7) is not older than Albian (from the presence of *Ellipsodinium rugulosum* Clarke et Verdier), but the presence of *Cepadinium ventriosum* (Alberti) and *Cribroperidinium sepimentum* Neale et Sarjeant indicates the reworking of Barremian–Aptian deposits; the same consideration may be applicable to some species from sample (5), such as *H. heslertonensis*. The following samples (8 and 9) yielded assemblages of late Barremian–latest Albian and early Aptian ages, respectively (E. Gedl, 2007, p. 81). Sample (8) included, i.a., *Cerbia tabulata* (Davey et Verdier), *Odontochitina operculata* (Wetzel), *Prolixosphaeridium parvispinum* (Deflandre), and *Tanyosphaeridium regulare* Davey et Williams, whereas sample (9) included a similar assemblage with the additional occurrence of *Achomosphaera verdieri* Below, *Aptea polymorpha* Eisenack, *Kiokansium unituberculatum* (Tasch), *Pseudoceratium securigerum* (Davey et Verdier), and *Systematophora silybum* Davey. According to E. Gedl (2007), such an age interpretation indicates that the strata of the Wronine Fm in the Rzeźnia klippe are tectonically disturbed.

The high degree of tectonic disruption of the Wronine Fm is visible in the exposures above the neighbouring Zabaniszcze klippe (Gedl, 2013, fig. 5D, E). Samples collected from the unit at this site showed a dinoflagellate cyst distribution pattern similar to those described by E. Gedl (2007) from an analogous position in the Rzeźnia klippe. Lower samples collected from shale interlayered with red beds yielded very rare specimens of *Odontochitinia operculata* (Wetzel) and ?*Hystrichosphaeridium* ?*phoenix* Duxbury (the equivalent samples from the Rzeźnia klippe are barren). Other samples yielded richer dinoflagellate cyst assemblages, with, i.a., *Cerbia tabulata* (Davey et Verdier), *Dapsilidinium warrenii* (Habib), *Oligosphaeridium complex* (White), *Prolixosphaeridium parvispinum* (Deflandre), and *Pterodinium* sp.; the poor preservation of most specimens indicates reworking of them; thus no precise age determination was possible on the basis of such assemblages (Gedl, 2013).

Dinoflagellate cysts from the Wronine Fm, exposed on the slope of Mt. Hulina, were studied by E. Gedl (2007). Poorly preserved and impoverished assemblages included, i.a., *Epelidosphaeridia spinosa* Cookson et Hughes, *Florentinia laciniata* Davey et Verdier, *F. mantellii* (Davey et Williams), *Hapsocysta peridictya* (Eisenack et Cookson), *Odontochitina costata* Alberti, *O. operculata* (Wetzel), and *Pterodinium* spp. Their age was interpreted as latest Albian–middle to late Cenomanian (E. Gedl, 2007, p. 85).

### The Hulina Formation

***Distribution, lithology and sedimentology***

The Hulina Fm is known only from the Grajcarek Unit, where it occurs along the northern boundary of the Pieniny Klippen Belt (Birkenmajer, 1977).

Radiolarian cherts (radiolarites) and radiolaria-bearing shales dominate the lower part of the formation, the Groń Radiolarite Mbr (2–6 m); argillaceous, bituminous, bentonitic and manganese-oxide-coated shales dominate the upper part of the formation, the Ubocz Shale Mbr (ca. 5 m according to Birkenmajer and Pazdro, 1963b; Birkenmajer, 1977).

The best exposures of the Hulina Fm now are located near Szczawnica (Mt. Hulina; Fig. 10) and Jaworki (Sztolnia Creek; Fig. 12; e.g., Birkenmajer and Gedl, 2004, 2007, respectively).

Oszczypko *et al.* (2012, p. 420, fig. 8C) described red and green radiolarites and white pelitic limestones (i.e., atypical lithologies of the Hulina Fm; see above) from exposures in Krupianka Creek above the Szlachtowa and Opaleniec formations and included them as the "Cenomanian Key Horizon" (compare with Birkenmajer's 1977, fig. 99, interpretation; see also Gedl, 2008d, and *Discussion* below).

***Microfossils and their age***

**Foraminifera.** Oszczypko *et al*. (2004, fig. 7) studied microfossils from the Hulina Fm (their "Cenomanian Key Horizon"), exposed in Sztolnia Creek. The samples generally yielded a rare and poorly preserved microfauna (no calcareous nannofossils have been found), although one sample (21) yielded abundant, recrystallized radiolarians. The foraminifera included *Haplophragmoides* cf. *falcatosuturalis* Neagu, *Plectorecurvoides alternans* Noth, and *Uvigerinammina praejankoi* Neagu; co-occurrence of the two last mentioned species was interpreted as being indicative of a latest Cenomanian–Turonian age.

Further studies on microfossils from the Hulina Fm (as the "Cenomanian Key Horizon") were carried out by Oszczypko *et al.* (2012) in exposures in the upper course of

Sztolnia Creek, Krupianka Creek (both in the vicinity of Jaworki), and on the slope of Mt. Hulina (Szczawnica Niżna). The samples from Sztolnia Creek mainly yielded variously preserved radiolarian moulds; long-ranging agglutinated foraminifera were found in one sample (8/06) only, namely *Ammosphaeroidina* sp., *Glomospira gordialis* (Jones et Parker), and undetermined nodosarids. A slightly richer assemblage were found in another sample (19/06): it was dominated by calcareous nodosarids (mainly *Lenticulina*), associated with rare agglutinated taxa (i.a., *Bulbobaculites* sp., *Glomospira gordialis*, and *Trochammina abrupta* Geroch), poorly preserved Late Cretaceous planktic foraminifera (*Globotruncana* sp., *Marginotruncana* sp.), and ostracoda.

Radiolarian moulds were the only microfossils from the majority of Mt. Hulina samples, assigned by Oszczypko *et al*. (2012, fig. 9) to the "Hulina Formation". However, their positions (samples 34-38/07) indicate that they were collected from the Middle Jurassic Opaleniec and Sokolica Radiolarite formations (see Birkenmajer and Gedl, 2007, fig. 3). Of two samples that yielded foraminifera, one sample (33/07; position unclear; Oszczypko *et al*., 20112, fig. 9) contained *Bulbobaculites* sp., *Cribrostomoides nonioninoides* (Reuss), *Jaculella depressa* (Vašíček), and *Trochammina abrupta*, nodosarids, radiolarian moulds and sponge spicules. Another sample (32/07), in turn, collected from the Hulina Fm (see Oszczypko *et al*., 2012, fig. 9, and Birkenmajer and Gedl, 2007, fig. 3) yielded an assemblage, composed of agglutinated (*Dorothia oxycona* (Reuss), *Glomospira gordialis*, *Glomospirella* sp., and *Trochammina* cf. *wetter* Stelck et Wall), calcareous benthic (*Gavellinella* sp., *Gyroidinoides* div. sp.), and rare planktic taxa (*Hedbergella* sp., *Whiteinella* sp., and rotaliporids).

**Organic-walled dinoflagellate cysts.** E. Gedl (2007, tab. 3) studied dinoflagellate cysts from the Ubocz Shale Mbr, exposed on the slope of Mt. Hulina (Szczawnica Niżna). Most samples studied were barren or yielded rare specimens, commonly poorly preserved and determined to the generic level; only the following species have been determined: *Dapsilidinium ambiguum* (Deflandre), *Gonyaulacysta extensa* Clarke et Verdier, *Kleithriasphaeridium loffrense* Davey et Verdier, *Litosphaeridium siphoniphorum* (Cookson et Eisenack), *Odontochitina costata* Alberti, *Palaeohystrichophora infusorioides* Deflandre, and *Pervosphaeridium pseudhystrichodinium* (Deflandre). A latest Albian–Cenomanian age was suggested for them (E. Gedl, 2007).

From the Sztolnia Creek section, E. Gedl (2007, p. 88) determined a latest Albian (Vraconian)–Cenomanian assemblage, consisting of poorly preserved specimens; among them *Callaiosphaeridium asymmetricum* (Deflandre et Courteville), *Litosphaeridium siphoniphorum* (Cookson et Eisenack), *Odontochitina costata* Alberti, and *Palaeohystrichophora infusorioides* Deflandre.

From the same section at the Sztolnia Creek comes a single sample (Szt34) questionably included in the Hulina Fm, and studied for dinoflagellate cysts by Birkenmajer and Gedl (2004, p. 253, fig. 14; for the more detailed location see Gedl, 2008a, figs 2$A_1$, 4A, $A_1$). It yielded poorly preserved specimens, among which *Spiniferites* sp. and questionably *Palaeohystrichophora infusorioides* Deflandre were determined.

**Discussion.** Oszczypko *et al.* (2012) described calcareous dinoflagellates from a thin section in cherty limestone, exposed in Krupianka Creek (their way-point 218). This was presumably the Pieniny Limestone Fm, erroneously treated by Oszczypko *et al.* (2012) as the Hulina Fm. *Colomisphaera* cf. *cieszynica* Nowak, *C. vogleri* (Borza) and Nannoconida determined by Oszczypko *et al.* (2012) were the basis for correlation with the Valanginian–Hauterivian, i.e., the age of the upper part of the Pieniny Limestone Fm (see the chapter devoted to this lithostratigraphic unit).

## The Malinowa Shale Formation

### *Distribution, lithology and sedimentology*

The Malinowa Shale Fm is an easily distinguishable stratigraphic unit of the Grajcarek Succession. It consists predominantly of cherry-red, subordinately green and variegated argillaceous or marly shales. The thickness is variable: 10 m in the southern zone and up to 180 m in the northern zone of the Grajcarek Succession. Thin hieroglyphic sandstone intercalations appear mainly in lower and upper parts of the unit (Birkenmajer, 1977). Biotite-feldspar tuffite intercalations may be found locally in the middle part of the formation (Birkenmajer and Wieser, 1956: age corrected – Birkenmajer and Geroch, 1961).

This formation corresponds to the abyssal, red clays of the present oceans.

The Malinowa Shale Fm is known mainly from the Grajcarek Unit, but according to Birkenmajer (1963c) some intercalations of this formation may be found in the Jaworki Marl Fm of the Czorsztyn Succession (see Birkenmajer and Jednorowska, 1987, p. 25 for a discussion). This unit forms many exposures located in the Jaworki-Szczawnica area, e.g., in Krupianka and Sztolnia creeks (Figs 5, 12), exposures along Grajcarek Creek at Szlachtowa and below Mt. Jarmuta, the Zabaniszcze and Rzeźnia klippes at Szczawnica (Figs 8 and 6, respectively), Głęboki Creek, and the slopes of Mt. Hulina at Szczawnica Niżna (Fig. 10; see, e.g., Birkenmajer, 1977 and references therein; Birkenmajer and Gedl, 2004, 2007; Oszczypko *et al*., 2012). Some exposures are known from the western sector of the Pieniny Klippen Belt in Poland, e.g., exposures in Trawne Creek near Rogoźnik (see Bąk *et al*., 2000; Gedl, 2007b).

### *Microfossils and their age*

**Foraminifera.** Macrofossils (except for trace fossils; see, e.g., Bąk *et al.*, 2000) are lacking in the Malinowa Shale Fm. The late Cenomanian to Campanian age of the formation is based on microfossils: mainly arenaceous foraminifers, and more rarely calcareous plankton (Birkenmajer and Geroch, 1961; Jednorowska, 1980). The following biostratigraphic zones were recognized (Birkenmajer *et al.*, 1987):

– the Rotalipora cushmani Zone (upper Cenomanian), with the infrequent planktic foraminifera *Rotalipora cushmani* (Morrow), *Praeglobotruncana delrioensis* (Plummer), and *P. stephani* Gandolfi. More frequent are benthic, arenaceous foraminifera, i.a., *Hippocrepina depressa* Vašiček, *Haplophragmoides gigas minor* Nauss, and *Plectorecurvoides irregularis* Geroch (the upper part of its age range is late Cenomanian), moreover with *Recurvoides godulensis*

Hanzliková, *R. primus* Myatlyuk, and *R. variabilis* Hanzliková, which appeared for the first time during the Cenomanian;

– a younger assemblage is characterized by the appearance of the planktic *Dicarinella hagni* Scheibnerová, known from the Turonian, and by the mass occurrence of arenaceous benthos;

– the Coniacian–Santonian assemblage is characterized by scarce, calcareous foraminifers with *Uvigerinammina jankoi* Majzon (characteristic of the Turonian in the Carpathians), and by the planktic foraminifers *Marginotruncana coronata* (Bolli), *M. sinuosa* Porthault, and *M. undulata* (Lehmann);

– the youngest is the Globotruncana elevata Zone of lower Campanian age, which yielded, besides the scarce planktic index *G. elevata* Brotzen, numerous arenaceous benthos with *Goesella rugosa* Hanzliková and *Hormosina ovulum gigantea* Geroch (Birkenmajer *et al.*, 1987).

Blaicher (1973) described foraminifera from the Malinowa Shale Fm, exposed in Sztolnia Creek. Her material was restudied and supplemented by Oszczypko *et al.* (2012, p. 433–434, Appendices 2 and 3). Foraminifera assemblages from two sections in Sztolnia Creek yielded mainly agglutinated forms, with a minor admixture of planktic species. Oszczypko *et al.* (2012) mentioned the presence of the stratigraphically important species *Globotruncana* cf. *lapparenti tricarinata* (Quereau), *Tritaxia gaultina* (Morozova), and *Uvigerinammina jankoi* in both secions (see their Appendices 2 and 3); on the basis of them, a Turonian–Campanian age was suggested for the sections studied.

Bąk *et al*. (2000) described foraminifera from the Malinowa Shale Fm, exposed in Trawne Creek (western sector of the Pieniny Klippen Belt in Poland). Their assemblages are composed almost exclusively of agglutinated forms (e.g., *Gerochammina stanislawi* Neagu, *Paratrochamminoides* spp., *Pseudonodosinella parvula* (Huss), *Rhizammina indivisa* Brady, *Rhabdammina* spp., *Recurvoides* spp., *Trochammina* sp., and *Uvigerinammina jankoi*); only a single planktic specimen was found (*Marginotruncana sigali*; Bąk *et al*., 2000, tab. 1). The presence of *Uvigerinammina jankoi* Majzon (associated in some samples with *U. praejankoi* Neagu) dated the Turonian–?Coniacian age of the strata studied (Bąk *et al*., 2000). Radiolarians from the same set of samples were studied (see below).

Oszczypko *et al.* (2004) described foraminifera from the Malinowa Shale Fm exposed in Sztolnia Creek, near Jaworki (their fig. 7). Some samples were barren; others yielded diversified assemblages, from poor to relatively rich. Sample (28) yielded an assemblage with *Bulbobaculites problematicus* (Neagu), *Pseudobolivina variabilis* (Vašiček), and *Pseudonodosinella parvula* (Huss), characteristic for the Cenomanian/Turonian boundary interval. A Turonian age was interpreted for a rich assemblage of agglutinated taxa with *Uvigerinammina jankoi* and *Bulbobaculites problematicus* in sample (13); the same age was given to sample (12); see Oszczypko *et al.* (2004, tab. 4). A younger, Coniacian age was assigned to sample (25), which yielded a relatively rich assemblage with, i.a., *Bulbobaculites problematicus*, *Pseudoclavulina carinata* (Neagu), *P. gaultina* (Morozova), *Spiroplectinella costata* (Huss), *S. dentata* (Alth), *S. subhaeringensis* (Grzybowski), and *Trochammina globolaevigata* Beckmann, associated with reworked Jurassic and Albian–Cenomanian taxa. Sample (6), in turn, yielded very rare specimens of *Caudammina gigantea* Geroch, *Globotruncana arca* Cushman, *Glomospira gordialis* (Jones et Parker), and *Nothia excels* (Grzybowski); the occurrence of the first two species shows that the age of this sample cannot be older than uppermost Santonian (Oszczypko *et al*., 2004).

Subsequently, Oszczypko *et al.* (2012) studied foraminifera from the Malinowa Shale Fm from several sites between Jaworki and Szczawnica: Sztolnia Creek near Jaworki, Szlachtowa, Sielski Creek, Kamionka Creek, the Zabaniszcze klippe at Szczawnica, and Mt. Hulina at Szczawnica Wyżna. The samples yielded various assemblages, mainly composed of agglutinated species. They include the following:

– the oldest ones are Turonian with the characteristic species *Uvigerinammina jankoi* Majzon (e.g., in the Zabaniszcze klippe and in Sztolnia Creek; Oszczypko *et al.*, 2012, tab. 4). Some samples from Sztolnia Creek lacked *U. jankoi*, but they were assigned to the Turonian or the Turonian/Coniacian on the basis of the co-occurrences of other species. Sample 1/05/07 yielded, i.a., *Caudammina ovula* (Grzybowski), *Spiroplectammina subhaeringensis* (Grzybowski), *Tritaxia amorpha* (Cushman), *T. gaultina* (Morozova), and *Trochammina globolaevigata* Beckmann, associated with rare and poorly preserved planktic *Praeglobotruncana* and rotaliporids; sample 7/06: i.a., *Ammodiscus siliceous* (Terquem), *Gerochammina stanislawi* Neagu, *Glomospira gordialis* (Jones et Parker), *G. irregularis* (Grzybowski), *Haplophragmoides bulloides* Boomgaart, and *Trochammina globigeriniformis* (Parker et Jones), associated with rare *Astacolus* sp. and rotaliporids;

– a younger, Coniacian–Santonian age (Oszczypko *et al.*, 2012, p. 431; erroneously indicated it as Turonian in their tab. 4) was assigned to an assemblage found in sample (14/06), which yielded, i.a., *Contusotruncana fornicata* (Plummer), *Uvigerinammina jankoi* Majzon, and *Tritaxia subparisiensis* (Grzybowski);

– the Coniacian–Santonian age also was assigned to an assemblage with *Spiroplectammina subhaeringensis* (Grzybowski), *Tritaxia gaultina* (Morozova), and *Dorothia oxycona* (Reuss) (sample 31/07 from Mt. Hulina);

– another sample from this site (41/07) yielded a mixed assemblage, typical for a long time span, from Turonian to Campanian (i.a., *Uvigerinammina jankoi* Majzon, *Spiroplectinella costata* (Huss), and *Caudammina gigantea* (Geroch) associated with rare planktic forms like *Globotruncana linneiana* (d'Orbigny) and *Globotruncanita stuartiformis* (Dalbiez)). A similar, long Turonian–Coniacian time span was suggested for agglutinated assemblages with, i.a., *Bulbobaculites problematicus* (Neagu) and *Uvigerinammina jankoi* Majzon from Szlachtowa, Sielski Stream, Jaworki, WP 222/444, and Kamionka Stream, WP 141 (Oszczypko *et al*., 2012, fig 1b, tab. 2);

– the youngest assemblage from the Malinowa Shale Fm, of Campanian age, was found in sample WP24, which yielded an agglutinated assemblage with *Caudammina gigantea* (Geroch) (Oszczypko *et al*., 2012).

**Radiolarians.** Relatively rare radiolarians have been found in the Malinowa Shale Fm in Trawne Creek (the western sector of the PKB in Poland, near Rogoźnik; Bąk *et al*., 2000). Samples (the same as for foraminifera; see above) were barren or yielded only single specimens, except for sample (Rog-11), which yielded a taxonomically rich assemblage, i.a., *Amphipyndax stocki* (Campbell et Clark), *Cryptamphorella conara* Foreman, *Dorypyle ovoidea* (Squinabol), *Holocryptocanium barbui* Dumitrică, *H. tuberculatum* Dumitrică, *Pseudoeucyrtis spinosa* (Squinabol), *Stichomitra communis* Squinabol, *Praeconocaryomma lipmanae* Pessagno, *P. universa* Pessagno, and *Quinquecapsularia ombonii* (Squinabol) (Bąk *et al*., 2000, tab. 2). The co-occurrence of *Holocryptocanium barbui*, *H. tuberculatum*, and *Praeconocaryomma lipmanae*, was interpreted as being indicative of a Turonian age for the Malinowa Shale Fm, exposed at the Trawne section (Bąk *et al*., 2000).

**Calcareous nannoplankton.** Oszczypko *et al.* (2004, tab. 3) reported a calcareous nannoplankton assemblage from sample (25), Sztolnia Creek, near Jaworki, which yielded, among long-ranging Jurassic–Cretaceous forms, species characteristic for the late Albian–earliest Cenomanian, e.g., *Eiffellithus turriseiffelii* (Deflandre), *Eprolithus floralis* (Stradner), *Prediscosphaera columnata* (Stover), and *Radiolithus orbiculatus* (Forchheimer). This age interpretation is contradictory to the Coniacian age, based on foraminifera from the same sample, and may be a result of reworking.

**Dinoflagellate cysts.** Organic-walled dinoflagellate cysts were studied from thin, dark-coloured beds within the predominantly red deposits (that are barren) of the Malinowa Shale Fm, exposed in Trawne Creek (Gedl, 2007b). The dark-coloured samples yielded assemblages dominated by *Palaeohystrichophora infusorioides* Deflandre and *Alterbidinium* sp. associated with frequent *Pterodinium cingulatum* (Wetzel) and *Spiniferites ramosus* (Ehrenberg). The age of these assemblages, based on the co-occurrence of *Endoscrinium campanula* (Gocht), *Dinogymnium albertii* Sarjeant, *Florentinia mantellii* (Davey et Williams), and *Senoniasphaera rotundata* Clarke et Verdier, was interpreted as being latest Turonian–Coniacian (Gedl, 2007b).

## The Hałuszowa Formation

### *Distribution, lithology and sedimentology*

The Hałuszowa Fm was distinguished by Birkenmajer (1977) for transitional strata between the Malinowa Shale Fm and the Jarmuta Fm. They show a flysch to flyschoid development, the latter occurring in the uppermost part.

Grey, marly shales, with variegated shale intercalations at the base, alternating with grey, calcareous sandstones, and with arenaceous siderite intercalations, occur in the lower part of the formation, which is a maximum of 100 m in thickness. Grey-green marls, 2–5 m thick, occur in the upper part of the formation. The age of this unit was originally correlated with the Campanian on the basis of superposition (Birkenmajer, 1977).

The Hałuszowa Fm is known only from the Grajcarek Succession; it crops out between Falsztyn and Hałuszowa (Fig. 2; Birkenmajer, 1977). It also was distinguished by Birkenmajer (in Birkenmajer *et al.*, 1979) in the PD-9 borehole at Szczawnica at the following depths: 223.5–244.5 m, 247.5–251.3 m, 254.8–257.6 m, 259.1–270.6 m, and 283.5–353.0 m.

### *Microfossils and their age*

**Foraminifera.** Jednorowska (in Birkenmajer *et al.*, 1979) reported from samples from the depth interval 283.5–353.0 m of the PD-9 borehole, the infrequent, commonly fragmentarily preserved agglutinated species *Dendrophrya robusta* Grzybowski, *D. excels* Grzybowski, *Hormosina ovulum gigantea* Geroch, and *Hyperammina subdiscretiformis* Myatlyuk. The presence of *H. ovulum gigantea* may indicate the Senonian age of the strata in question (Jednorowska in Birkenmajer *et al.*, 1979).

**Calcareous nannoplankton.** Dudziak (in Birkenmajer *et al.*, 1979) reported infrequent, calcareous nannoplankton from the Hałuszowa Fm from the PD-9 borehole, at Szczawnica: *Tetralithus pyramidus* Gardet and *T. obscurus* Deflandre. Their co-occurrence indicates a late Senonian age (see also Birkenmajer *et al.*, 1987, p. 290–291).

**Dinoflagellate cysts.** The palynology of the Hałuszowa Fm was studied from exposures along an inlet of Potok Hałuszowski Creek at Hałuszowa by Gedl (2007a, figs 2, 3A, B). Two samples yielded assemblages that included rather taxonomically impoverished and poorly preserved specimens, i.a., *Odontochitina operculata* (Wetzel), *Pterodinium cingulatum* (Wetzel), *Surculosphaeridium*? *longifurcatum* (Firtion), and questionably determined *Palaeohystrichophora infusorioides* Deflandre. Their co-occurrence was interpreted as indicative of the broad time range of Albian–early Campanian (Gedl, 2007a, p. 114).

## The Jarmuta Formation

### *Distribution, lithology and sedimentology*

The rocks referable to the Jarmuta Fm were distinguished by Horwitz (e.g., 1932, 1935a, b, 1963) as the Jarmuta sandstones (sandstones and conglomerates), *Inoceramus*-bearing sandstones, and Orbitoid-bearing sandstones and conglomerates (see the history of investigations in Birkenmajer, 1977).

Lithologically, the Jarmuta Fm of the Grajcarek Succession is very variable (e.g., Birkenmajer, 1956a, 1977, 1979). The lithologies include the following:

– multicoloured sedimentary breccias, grading from microbreccias to coarse breccias, consisting of angular fragments, derived from the Klippen successions and/or the Grajcarek Succession, sometimes with a small admixture of exotic rocks, occur in a zone close to the ancient Maastrichtian cliff line;

– calcareous sandstones, alternating with marly shales, blue grey (fresh), yellow or yellow-green (weathered) contain intercalations of conglomerate and sedimentary breccia and isolated lumps of various older rocks (olistoliths), often of large dimensions. This is a proximal flysch/Wildflysch facies. Further north, it passes into distal flysch facies;

– there is a gradual transition between the red Malinowa Shale Fm and the distal flysch facies. Flysch sandstones first appear in the abyssal, red shale as single bands of sandstone (turbidite), and at higher levels the shales become totally replaced by graded sandstones and conglomerates of the submarine turbidite fan.

### *Microfossils and their age*

**Large foraminifera.** Large foraminifera (orbitoids) and *Inoceramus* shell fragments (entire shells are infrequent) occur in the coarser sandstones and finer conglomerates of the zone adjacent to the coast; they may be recycled.

On the basis of the large foraminifera, *Lepidorbitoides socialis* (Leymerie), *Pseudosiderolites vidali* (Douvillé), and *Orbitoides* cf. *media* (d'Archiac), determined by Bieda (1935), the age of the Jarmuta Fm is Maastrichtian, possibly also referable to a higher part of Campanian.

**Small foraminifera.** A similar age is shown by scarce, small foraminifera, recovered from shale intercalations in the distal flysch-type of the Jarmuta Fm in the vicinity of Jaworki (Birkenmajer and Geroch, 1963); the samples yielded Maastrichtian or late Campanian to Maastrichtian assemblages, which consisted of mainly the agglutinated forms *Hormosina ovulum gigantea* Geroch, *Spiroplectammina dentata* Alth, *Dorothia trochoides* (d'Orbigny), and *Marssonella oxycona* (Reuss), and rare calcareous plankton, *Globotruncana linneiana* (d'Orbigny), ?*Globotruncanita* cf. *stuarti* (De Lapparent), and *Rosita fornicata* (Plummer) (Birkenmajer *et al*., 1987).

Jednorowska (in Birkenmajer *et al*., 1979) described relatively frequent foraminifera assemblages from the Jarmuta Fm, penetrated by the PD-9 borehole, at Szczawnica: *Cribrostomoides trinitatensis* Cushman et Jarvis, *Dendrophrya excelsa* Grzybowski, *D. maxima* Friedberg, *D. robusta* Grzybowski, *Hormosina ovulum gigantea* Geroch, *Hyperammina cylindrica* Parr, *H.* cf. *intermedia* Myatlyuk, *Kalamopsis grzybowskii* (Dylążanka), *Silicobathysiphon gerochi* Myatlyuk, and *Spiroplectammina dentata* Alth. The presence of *C. trinitatensis*, *H. ovulum gigantea*, and *S. dentata* indicates a Senonian age of these assemblages (Jednorowska in Birkenmajer *et al*., 1979).

Numerous, younger specimens of the early Paleocene *Globigerina triloculinoides* have been found in an exotic-bearing conglomerate (pebbly mudstone) intercalation in the Jarmuta Fm flysch in Czarna Woda Stream, near Jaworki (Birkenmajer and Jednorowska, 1979).

**Calcareous nannoplankton.** Calcareous nannoplankton in the Jarmuta Fm flysch unit are poorly preserved and infrequent. In the PD-9 borehole, at Szczawnica (Birkenmajer *et al.,* 1979), only three taxa were distinguished: *Tetralithus obscurus* Deflandre (Senonian), *T. descriptus* Martini (?early Danian), and *Marthasterites inconspicuus* Deflandre.

An exotic-bearing conglomerate (pebbly mudstone) intercalation in the Jarmuta Fm flysch in Czarna Woda Stream (Jaworki, see above: Birkenmajer and Jednorowska, 1979), yielded calcareous nannoplankton of the NP5 Fasciculithes tympaniformis Zone (mid Paleocene): *Fasciculithus tympaniformis* Hay et Mohler, *Coccolithus pelagicus* (Wallich), *Chiasmolithus consuetus* (Bramlette et Sullivan), *Coccolithus cavus* Hay et Mohler, *Markalius astroporus* (Stradner), *Prinsius bisulcus* (Stradner), *Ericsonia* sp., and *Chiasmolithus* sp., and some recycled taxa (Birkenmajer *et al*., 1987).

So far, there is no nannoplankton evidence for the presence of the NP1 through NP4 zones (i.e., Danian–lower Selandian; Berggren *et al.*, 1995) in the Jarmuta Fm flysch. This turbidite complex apparently is lithologically continuous; however, more stratigraphic hiatuses (omissions) may be present (Birkenmajer *et al.*, 1987).

### The Laramian hiatus

In the Pieniny Klippen Belt orogen, and in the Grajcarek zone adjacent to it, the Jarmuta Fm rests unconformably on older formations. This coarse, synorogenic deposit owes its origin to erosional destruction and redeposition of older (Jurassic and Cretaceous) sediments during the Laramian Orogeny. In the Pieniński Potok Stream valley, the basal conglomerates of the Szczawnica Fm directly cover the Pieniny Limestone Fm of the Pieniny Nappe (Birkenmajer, 2007).

In the Pieniny Klippen Belt Laramian orogen, the Szczawnica Fm represents the NP5 through NP11 zones (mid Selandian through earliest Eocene; Berggren *et al.*, 1995); see Birkenmajer and Dudziak (1981).

In the Grajcarek Unit, Laramian hiatuses were noted in the upper part of the Jarmuta Fm flysch (Birkenmajer *et al.*, 1987; Birkenmajer and Oszczypko, 1988, 1989; Birkenmajer and Dudziak, 1991) and in the Szczawnica Fm flysch cover, close to the Pieniny Laramian orogen. These hiatuses seem to close further north in the Grajcarek Unit and the Magura Nappe.

## SUMMARY

The Lower Jurassic–mid Paleocene Grajcarek Succession was deposited in the southern part of the Magura Basin, the largest and southernmost part of the Outer (Flysch) Carpathian basins system. It was incorporated tectonically as the Grajcarek Unit into the Inner Carpathian structure of the Pieniny Klippen Belt. The Grajcarek Unit was uprooted from older strata (?Lower Jurassic) and/or its basement (Triassic platform deposits) at the base of the Szlachtowa Fm.

The Grajcarek Succession in Polish part of the Pieniny Klippen Belt consists of 12 lithostratigraphic units with the rank of formations, and two with the rank of members (Fig. 14).

The oldest strata of the Grajcarek Succession are dark flysch and flyschoid facies of the Szlachtowa Fm were deposited during the initial stages of opening of the Magura Basin and the subsidence that followed break-up and rifting of the Triassic platform. The Szlachtowa Fm is the oldest flysch in the Alpine Belt. Micropalaeontological data indicate a middle Toarcian age of the beginning of its accumulation (Gedl and Józsa, 2015). According to Segit *et al.* (2015), the basal part of the Szlachtowa Fm is upper Aalenian. Rare ammonites from the Szlachtowa Fm (*Leioceras opalinum* (Reinecke) and *L.* cf. *comptum* (Reinecke) from the Polish part and *Brasilia* sp. from the Slovak part of the PKB; Birkenmajer and Pazdro, 1963b and Gedl *et al*., 2012, respectively) are of early–middle Aalenian ages (see e.g., Topchishvili *et al.*, 1998; Myczyński, 2004).

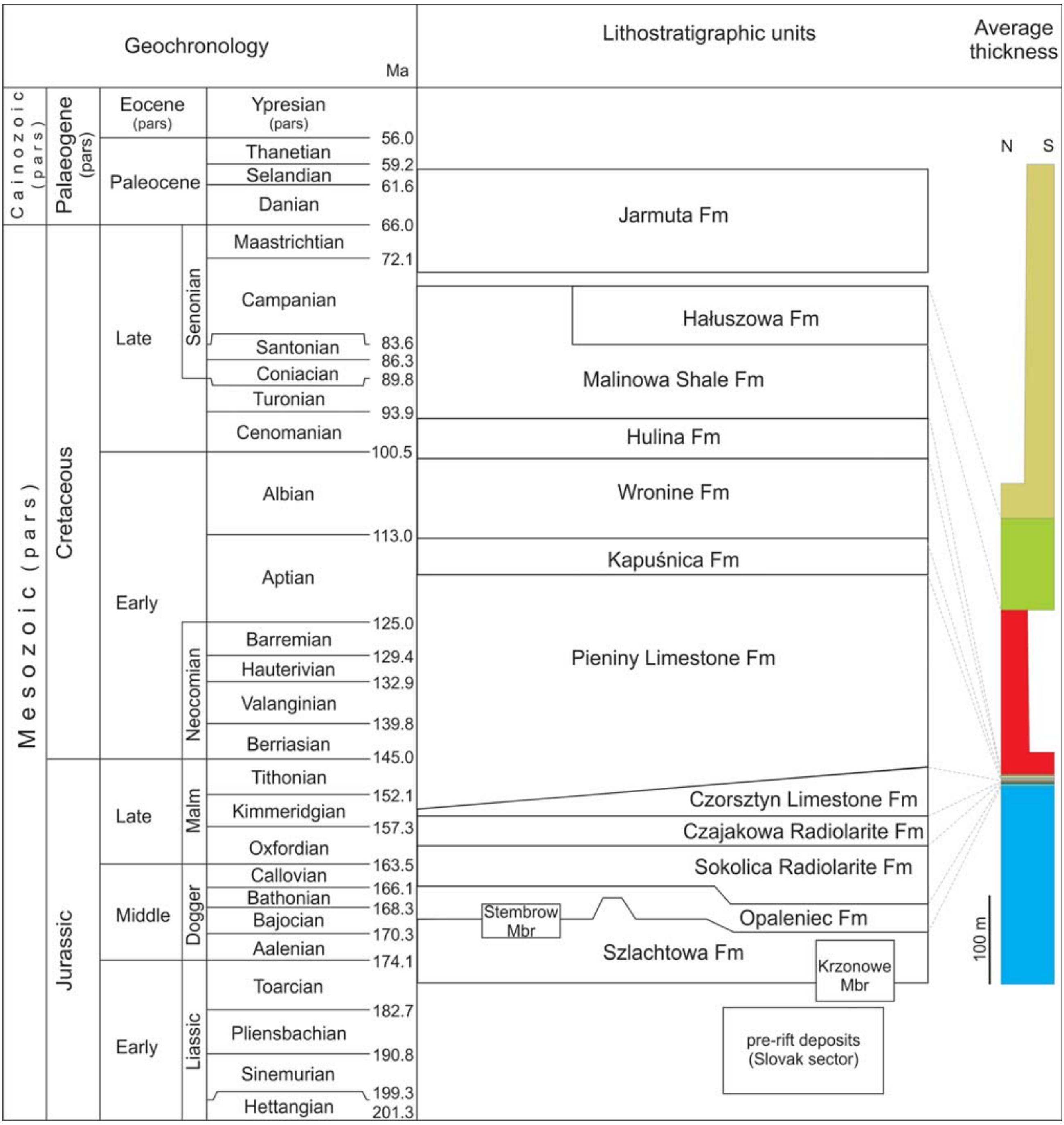


**Fig. 14.** Lithostratigraphic scheme of the Grajcarek Succession (Lower Jurassic–mid Paleocene) in the Pieniny Klippen Belt of Poland. Geochronology after Gradstein *et al*. (2012).

Sedimentation of the Szlachtowa Fm was not uniform. In the more distal areas and/or during periods of calmer sedimentation, a shale facies replaced the flysch. Turbidite sandstones are rare there, but micaceous shales, like the flysch facies, contain high proportions of terrestrial phytoclasts and palynomorphs, indicating an intense terrestrial influx during their deposition.

During the early Bajocian, the flysch facies of the Szlachtowa Fm crossed the Czorsztyn Ridge, which up to then had separated the flysch-dominated Magura Basin from the southern Klippen basins. At the same time, facies diversification started in the Magura Basin: flysch facies (the Szlachtowa Fm) interfingered with spotty shale and marly shale (the Opaleniec Fm, the Stembrow Mbr). Deposition of these pale coloured, shaly-marly strata was presumably an effect of further extension of the basin, gradually drifting apart from the source area, and, as a consequence being depleted in terrestrial organic matter.

During the late Bajocian, the accumulation of the flysch facies in the southern Magura Basin generally ceased; locally, some flysch appeared even in earliest Bathonian, as indicated by a single sample from the Szlachtowa Fm (Gedl, 2008d). Termination of the intense supply of clastic material to the Magura Basin and the development of hemipelagic sedimentation was manifested in the appearance of radiolarite facies, the Sokolica Radiolarite Fm. This event took place during the latest Bajocian, when marly sedimentation of the Opaleniec Fm (and the Stembrow Mbr) predominated in the Magura Basin. Clastic sedimentation (the Opaleniec Fm) interfingered with the accumulation of siliceous radiolarites in the Magura Basin during the Bathonian.

During the Callovian, sedimentation in the Magura Basin was already uniform; marly deposition of the Opaleniec Fm ceased in the late Bathonian, and dark radiolarites (the Sokolica Radiolarite Fm) were the only strata to be deposited in this basin, as in the Klippen basin offshore zones, the Branisko and Pieniny successions. The presence of frequent radiolaries and dinoflagellate cysts in these dark coloured strata indicates fertile surface waters in the Magura Basin, which, as a consequence, led to the development of dysoxic bottom environments, caused by the intense deposition of organic particles and by the lack of circulation in the basin.

The Late Jurassic–Early Cretaceous was the time of maximal width of the Magura and Klippen basins, with pelagic sedimentation characteristic for both areas (Birkenmajer, 1986; see also, e.g., Ślączka *et al.*, 2006). The uniform accumulation of red and green radiolarites (the Czajakowa Radiolarite Fm) extended into the early Oxfordian on both sides of the Czorsztyn Ridge. These strata consist mainly of radiolarian cherts and siliceous radiolarian limestones with minor additions of argillaceous and/or marly shales (Birkenmajer, 1977); their microfacies are mainly radiolarian (Golonka and Sikora, 1981). This indicates that their accumulation took place below the carbonate compensation depth.

A gradual increase in the productivity of pelagic calcareous microfossils during ?Kimmeridgian–Tithonian time, so typical for the Tethys (e.g., Reháková and Michalík, 1997; Reháková, 2000), gave rise to the beginning of accumulation of pelagic limestones (the Czorsztyn Limestone Fm and the Pieniny Limestone Fm). The Czorsztyn Limestone Fm contains microfacies with *Saccocoma* and *Globochaete*, stomiospheroidal and tintinnoidal microfacies (Golonka and Sikora, 1981), i.e., similar to the microfacies, occurring in some of the topmost sections of the underlying radiolarites. The higher Pieniny Limestone Fm contains mainly microfacies with *Nannoconus*, usually associated with radiolarians (Golonka and Sikora, 1981).

Accumulation of Upper Jurassic radiolarites and the uppermost Jurassic–mid Cretaceous limestones (the latter terminated in the Magura Basin during the Barremian–Aptian) lasted some 40 Ma, although their thickness is no more than a few metres. This shows their highly condensed mode of sedimentation.

The younger strata of the Magura Basin were accumulated in a transpression regime related to the gradual closing of the basin that started in the Early Cretaceous (e.g., Birkenmajer, 1986). During the early stages of this period, the accumulation of dark, organic-rich, hemipelagic strata (the Kapuśnica, Wronine, and Hulina formations) took place. An outstanding feature of the mid Cretaceous sequences of the Magura Basin is the lack of flysch deposits (the flysch of the Szlachtowa Fm is of Middle Jurassic age, see, e.g., Birkenmajer *et al.*, 2008; Gedl, 2008, 2013; Barski *et al.*, 2012; Gedl and Józsa, 2015; Segit *et al.*, 2015). The flysch appeared in the Aptian–Albian at the southern margins of the Klippen basins, on both slopes of the Andrusov Exotic Ridge, but mainly in the southern Klape and Manín zones (Birkenmajer, 1986; see Fig. 2).

The overlying red shale of the Malinowa Shale Fm reflects a subsequent period of pelagic sedimentation (Cenomanian–Campanian) below the calcite compensation depth, but during a well-ventilated, oxygen-rich regime of bottom water. It contrasts with the flyschoid and flysch sedimentation (the Jaworki Marl Fm, the Sromowce Fm; Birkenmajer, 1977) that appeared simultaneously to the south of the Czorsztyn Ridge.

Deep-water pelagic/hemipelagic sedimentation of the Malinowa Shale Fm lasted in the southern part of the Magura Basin till the Maastrichtian. It was terminated during the Maastrichtian–Paleocene Laramian folding and thrusting phase that led to the formation of the Pieniny Klippen Belt structure (Birkenmajer, 1986). During the late Senonian, flysch sedimentation (the Hałuszowa Fm) took place in the southern part of the Magura Basin as the presage of the approaching phase of folding. Folded during Laramian phase (Maastrichtian–Paleocene), the Klippen and Grajcarek (i.e., southern part of the Magura Basin profile) successions were unconformably covered by freshwater and marine molasse and sandy flysch (the Jarmuta Fm; Birkenmajer, 1986).

In the northern part of the Magura Basin, the Laramian movements did not exert any clear influence on the sedimentation; the flysch and hemipelagic deposits that accumulated there from the mid Cretaceous to the end of Oligocene and beginning of Miocene formed the future Magura Nappe (e.g., Oszczypko *et al.*, 2015).

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## REFERENCES

Andrusov, D., 1945. Geologický výskum vnútorného pásma v západných Karpatoch, IV & V: Stratigrafia doggeru, malmu a kriedy. *Práce Štatnoho Geologického Ústavu ČSR*, *(Bratislava)*, 13: 1–176. [In Slovak.]

Andrusov, D., 1953. Étude géologique de la zone des klippes internes des Carpathes Occidentales. *Geologické Práce Slovenskej Akademie Vied a Umeni (Bratislava)*, 34: 1–149.

Bąk, K., Uchman, A. & Bąk, M., 2000. Agglutinated foraminifera, radiolaria and trace fossils from Upper Cretaceous deep-water variegated shales at Trawne Stream, Grajcarek Unit, Pieniny Klippen Belt, Carpathians, Poland. *Bulletin of the Polish Academy of Scienes*, *Earth Sciences*, 48: 1–32.

Barski, M., Matyja, B. A., Segit, T. & Wierzbowski, A., 2012. Early to Late Bajocian age of the so-called „black flysch" (Szlachtowa Formation) deposits: implications for the history and geological structure of the Pieniny Klippen Belt, Carpathians. *Geological Quarterly*, 56: 391–410.

Berggren, W. A., Kent, D. V., Swisher, C. C. III, Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *SEPM Special Publication*, 54: 129–212.

Bieda, F., 1935. C.-R. des recherches sur les Foraminifères des Flysch de la Zone Piénine des Klippes. *Posiedzenia Naukowe Państwowego Instytutu Geologicznego,* 42: 38–39. [In Polish, with French title.]

Birkenmajer, K., 1953. Preliminary revision of the stratigraphy of the Pieniny Klippen belt series in Poland. *Bulletin de l'Académie Polonaise des Sciences*, *Classe 3*, 1 (6): 271–274.

Birkenmajer, K., 1956a. Sedimentary characteristics of the Jarmuta beds (Maastrichtian) of the Pieniny Klippen-belt (Central Carpathians). *Bulletin de l'Académie Polonaise des Sciences*, *Classe III*, 4 (10): 729–735.

Birkenmajer, K., 1956b. Badania geologiczne andezytów okolic Szczawnicy. *Przegląd Geologiczny*, 2: 72–74. [In Polish.]

Birkenmajer, K., 1957a. Andesite dykes of Bryjarka Mount in Szczawnica, Pieniny Range, Carpathians. *Przegląd Geologiczny,* 5: 62–65. [In Polish, with English title.]

Birkenmajer, K., 1957b. Remarks on the sedimentation of the Aalenian Flysch and Jarmuta Beds, Senonian, of the Pieniny Klippen Belt. *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 26: 165–178. [In Polish, with English summary.]

Birkenmajer, K., 1957c. Sedimentary characteristics of the Flysch-Aalenian in the Pieniny Klippen Belt (Central Carpathians). *Bulletin de l'Académie Polonaise des Sciences*, *Classe III*, 5: 451–456.

Birkenmajer, K., 1958a. *Przewodnik geologiczny po pienińskim pasie skałkowym, I–IV*. Wydawnictwa Geologiczne, Warszawa, I: 135 pp., II: 72 pp., III: 88 pp., IV: 55 pp. [In Polish.]

Birkenmajer, K., 1958b. Submarine erosional breaks and Late Jurassic synorogenic movements in the Pieniny Klippen Belt geosyncline. *Bulletin de l'Académie Polonaise des Sciences*, *Série des Sciences Chimiques, Géologiques et Géographiques*, 6: 545–549.

Birkenmajer, K., 1959a. *Przekroje geologiczne przez Polskę: Pieniny*. Wydawnictwa Geologiczne, Warszawa, 20 pp. [In Polish.]

Birkenmajer, K., 1959b. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.000, ark. 16 Niedzica*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1961. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.000, ark. 15 Dursztyn*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1963a. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.0000, ark. 6 Czorsztyn*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1963b. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.000, ark. 5 Frydman*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1963c. Stratigraphy and palaeogeography of the Czorsztyn Series, Pieniny Klippen Belt, Carpathians, in Poland. *Studia Geologica Polonica*, 9: 380 pp. [In Polish, with English summary.]

Birkenmajer, K., 1963d. Sedimentary problems of the flysch deposits of the Pieniny Klippen Belt of Poland. *Kwartalnik Geologiczny*, 7: 229–234. [In Polish, with English summary.]

Birkenmajer, K., 1965. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.000, ark. 4 Nowa Biała*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1968. Poszukiwania nowych wód mineralnych w Szczawnicy. *Wszechświat*, 9: 219–221. [In Polish.]

Birkenmajer, K., 1970a. *Mapa geologiczna pienińskiego pasa skałkowego, skala 1:10.000, ark. 3 Bór Na Czerwonem & ark. 13 Szaflary*. Instytut Geologiczny & Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Birkenmajer, K., 1970b. Pre-Eocene fold structures in the Pieniny Klippen Belt (Carpathians) of Poland. *Studia Geologica Polonica*, 31: 1–77. [In Polish, with English summary.]

Birkenmajer, K., 1977. Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica,* 45: 1–159.

Birkenmajer, K., 1979. *Przewodnik geologiczny po pienińskim pasie skałkowym*. Wydawnictwa Geologiczne, Warszawa, 237 pp. [In Polish.]

Birkenmajer, K., 1983. Strike-slip faults in the northern boundary zone of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 77: 89–112. [In Polish, with English summary.]

Birkenmajer, K., 1986. Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 88: 7–32.

Birkenmajer, K., 2003. Post-collisional late Middle Miocene (Sarmatian) Pieniny Volcanic Arc, Western Carpathians. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 51: 79–89.

Birkenmajer, K., 2007. The Czertezik Succession in the Pieniny National Park (Pieniny Klippen Belt, West Carpathians): stratigraphy, tectonics, palaeogeography. *Studia Geologica Polonica*, 127: 7–50.

Birkenmajer, K., 2008. The Szopka Limestone Formation – a new lithostratigraphic name for Upper Liassic beds of the Pieniny and Branisko successions, Pieniny Klippen Belt (West Carpathians). *Studia Geologica Polonica*, 131: 229–235.

Birkenmajer, K., 2009. The Branisko Succession (Jurassic–Cretaceous) in the Czorsztyn Range, Pieniny National Park (Pieniny Klippen Belt, West Carpathians, Poland): description of selected field sections. *Studia Geologica Polonica*, 132: 91–115.

Birkenmajer, K., 2017. Geology of the Pieniny National Park (Poland), West Carpathians. *Pieniny – Przyroda i Człowiek*, 14: 86 pp. [In Polish, with English summary.]

Birkenmajer, K. & Dudziak, J., 1981. Age of the Magura flysch (Palaeogene) along the northern boundary of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica*, 70: 7–36. [In Polish, with English summary.]

Birkenmajer, K. & Dudziak, J., 1987. Age of the Wronine Formation (Albian) of the Grajcarek Unit in the Pieniny Klippen Belt, Carpathians, based on calcareous nannoplankton. *Studia Geologica Polonica*, 92: 87–106. [In Polish, with English summary.]

Birkenmajer, K. & Dudziak, J., 1991. Middle to Late Paleocene nannoplankton zones in the Jarmuta Formation, Pieniny Klippen Belt, Carpathians. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 39: 47–54.

Birkenmajer, K., Dudziak, J. & Jednorowska, A., 1979. Subsurface geological structure of the northern boundary fault zone of the Pieniny Klippen Belt at Szczawnica, Carpathians. *Studia Geologica Polonica*, 61: 7–36. [In Polish, with English summary.]

Birkenmajer, K., Dudziak, J., Jednorowska, A. & Kutyba, J., 1987. Foraminiferal-nannoplankton evidence for Maastrichtian and Paleocene ages of the Jarmuta Formation: its bearing on dating Laramian Orogeny in the Pieniny Klippen Belt, Carpathians. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 35: 287–298.

Birkenmajer, K. & Gąsiorowski, S. M., 1959. Les Aptychus tithoniques et néocomiens comme dépôts secondaires dans le Senonien de la Zone Piénine des Klippes de Pologne. *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 28: 345–358. [In Polish, with French summary.]

Birkenmajer, K. & Gąsiorowski, S. M., 1960. Stratigraphy of the Malm of the Niedzica and Branisko Series (Pieniny Klippen Belt, Carpathians) based on Aptychi. *Bulletin de l'Académie Polonaise des Sciences, Série des Sciences Chimiques, Géologiques et Géographiques*, 8: 137–143.

Birkenmajer, K. & Gąsiorowski, S. M., 1963. Ruchy neokimeryjskie w polskich Karpatach Zachodnich (Neo-Cimmerian movements in the Polish Western Carpathians). *Przegląd Geologiczny*, 11: 314–318. [In Polish, with English title.]

Birkenmajer, K., Gąsiorowski, S. M. & Wieser, T., 1960. Fragments of exotic rocks in the pelagic deposits of the Bathonian of the Niedzica Series (Pieniny Klippen Belt, Carpathians). *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 30: 29–57.

Birkenmajer, K. & Gedl, P., 2004. Dinocyst ages of some Jurassic strata, Grajcarek Unit at Sztolnia Creek, Pieniny Klippen Belt (Poland). *Studia Geologica Polonica*, 123: 245–277.

Birkenmajer, K. & Gedl, P., 2007. Age of some deep-water marine Jurassic strata at Mt Hulina, Małe Pieniny Range (Grajcarek Unit, Pieniny Klippen Belt, West Carpathians, Poland), as based on dinocysts. *Studia Geologica Polonica*, 127: 51–70.

Birkenmajer, K. & Gedl, P., 2012. Jurassic and Cretaceous strata in the Maruszyna IG-1 Deep Borehole (Pieniny Klippen Belt, Carpathians, Poland): lithostratigraphy, dinoflagellate cyst biostratigraphy, tectonics. *Studia Geologica Polonica*, 135: 7–54.

Birkenmajer, K., Gedl, P., Myczyński, R. & Tyszka, J., 2008. „Cretaceous black flysch" in the Pieniny Klippen Belt, West Carpathians: a case of geological misinterpretation. *Cretaceous Research*, 29: 535–549.

Birkenmajer, K & Geroch, S., 1961. On the age of Variegated Beds (Shales) in the Pieniny Klippen Belt, Carpathians. *Bulletin de l'Académie Polonaise des Sciences*, *Série des Sciences Géologiques et Géographiques*, 9: 213–219.

Birkenmajer, K. & Geroch, S., 1963. Du rapport des couches de Jarmuta avec les couches bigarrèes dans la zone des Klippes Piénines en Pologne. In: *Association Géologique Karpato-Balkanique, VI-ème Congrès, 2–16 Septembre 1963, Varsovie-Cracovie*, *Resumés des Communications*. Wydawnictwa Geologiczne, Warszawa-Kraków, pp. 28–29.

Birkenmajer, K. & Jednorowska, A., 1979. Paleocene foraminiferal assemblage from the Magura flysch at the contact with the Pieniny Klippen Belt at Jaworki, Carpathians, Poland. *Rocznik Polskiego Towarzystwa Geologicznego*, 49: 287–292. [In Polish, with English summary.]

Birkenmajer, K. & Jednorowska, A., 1987. Late Cretaceous foraminiferal biostratigraphy of the Pieniny Klippen Belt, Carpathians (Poland). *Studia Geologica Polonica*, 92: 7–28.

Birkenmajer, K. & Myczyński, R., 1977. Middle Jurassic deposits and fauna of the Magura Succession near Szlachtowa, Pieniny Klippen Belt (Carpathians). *Acta Geologica Polonica*, 27: 387–400.

Birkenmajer, K. & Myczyński, R., 1994. Pliensbachian (Early Jurassic) fauna from the Pieniny Klippen Belt, Carpathians, Poland: its stratigraphic and palaeogeographic position. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 42: 223–245.

Birkenmajer, K. & Myczyński, R., 2000. Bajocian age of the Podzamcze Limestone Formation at Stare Bystre, Pieniny Klippen Belt (Carpathians, Poland) based on its macrofauna. *Studia Geologica Polonica*, 117: 7–25.

Birkenmajer, K. & Oszczypko, N., 1988. New lithostratigraphic standard for the Palaeogene of the Magura Flysch Basin (southern part), Carpathians. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 36: 253–259.

Birkenmajer, K. & Oszczypko, N., 1989. Cretaceous and Palaeogene lithostratigraphic units of the Magura Nappe, Krynica Subunit, Carpathians. *Annales Societatis Geologorum Poloniae,* 59: 145–181.

Birkenmajer, K. & Pazdro, O., 1963a. Microfaunal reconnaissance of the Dogger of the Pieniny Klippen Belt (Carpathians). *Bulletin de l'Académie Polonaise des Sciences*, *Série des Sciences Géologiques et Géographiques*, 11: 127–132.

Birkenmajer, K. & Pazdro, O., 1963b. On the age and geological position of the so-called „Sub-Flysch Beds" of the Pieniny Klippen Belt of Poland. *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 33: 415–456. [In Polish, with English summary.]

Birkenmajer, K. & Pazdro, O., 1968. On the so-called „Sztolnia beds" in the Pieniny Klippen Belt of Poland. *Acta Geologica Polonica*, 18: 325–365. [In Polish, with English summary.]

Birkenmajer, K. & Pécskay, Z., 1999. K-Ar dating of the Miocene andesite intrusions, Pieniny Mountains, West Carpathians, Poland. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 47: 155–169.

Birkenmajer, K. & Pécskay, Z., 2000. K-Ar dating of the Miocene andesite intrusions, Pieniny Mts, West Carpathians, Poland. A supplement. *Studia Geologica Polonica*, 117: 7–25.

Birkenmajer, K. & Turnau, E., 1962. Carboniferous microspores as secondary deposit in the Aalenian Flysch of the Pieniny Klippen Belt (Carpathians). *Bulletin de l'Académie Polonaise des Sciences*, *Série des Sciences Géologiques et Géographiques*, 10: 99–103.

Birkenmajer, K. & Tyszka, J., 1996. Palaeoenvironment and age of the Krzonowe Formation (marine Toarcian–Aalenian), Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 109: 7–42.

Birkenmajer, K. & Widz, D., 1995. Biostratigraphy of Upper Jurassic radiolarites in the Pieniny Klippen Belt, Carpathians. In: Baumgartner, P. O. *et al.* (eds), *Middle Jurassic to Lower Cretaceous radiolaria of Tethys: occurrence, systematics, biochronology*. *Mémoires de Géologie*, *Lausanne*, 23: 889–896.

Birkenmajer, K. & Wieser. T., 1956. Tuffites from variegated beds of the Pieniny Klippen-belt mantle, Central Carpathians. *Acta Geologica Polonica*, 6: 1–14. [In Polish, with English summary.]

Blaicher, J., 1973. *Opracowanie profili wzorcowych Karpat na podstawie badań biostratygraficznych. Jednostka magurska (dolna kreda)*. Archiwum CAG PIG-PIB, Oddział Karpacki, Kraków. [In Polish.]

Błaszyk, J., 1968. Ostracods from the Sztolnia Creek profile in the Pieniny Klippen Belt of Poland. *Acta Geologica Polonica*, 18: 367–373.

Davey, R. J., 1979. Marine Apto–Albian palynomorphs from Holes 400A and 402A, IPOD Leg 48, northern Bay of Biscay. In: Montadert, L. *et al.* (eds), *Deep Sea Drilling Project*, *Initial Reports*, 48: 547–577.

Dudziak, J., 1986. Calcareous nannoplankton from the Szlachtowa Formation, Jurassic, of Sztolnia Creek, Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 88: 135–141. [In Polish, with English summary.]

Gąsiorowski, S. M., 1962. Aptychi from the Dogger, Malm and Neocomian in the Western Carpathians, and their stratigraphical value. *Studia Geologica Polonica*, 10: 1–151.

Gedl, E., 2007. Lower Cretaceous dinocyst stratigraphy and palynofacies of the Grajcarek Unit, Pieniny Klippen Belt, West Carpathians, Poland. *Studia Geologica Polonica*, 127: 71–100.

Gedl, P., 2007a. Organic-walled Dinoflagellate cysts from some Jurassic and Cretaceous strata of the Grajcarek Unit at Hałuszowa, Pieniny Klippen Belt (West Carpathians, Poland). *Studia Geologica Polonica*, 127: 101–117.

Gedl. P., 2007b. Dinocysts from Upper Cretaceous deep-water marine variegated facies (Malinowa Shale Formation), Pieniny Klippen Belt, Poland: example from the Potok Trawne Creek. *Studia Geologica Polonica*, 127: 139–152.

Gedl, P., 2008a. Comments for discussion on biostratigraphy of the so-called „black flysch" of the Pieniny Klippen Belt in Poland. *Przegląd Geologiczny*, 56: 212–220. [In Polish, with English title.]

Gedl, P., 2008b. The age of the Szlachtowa Formation (the so-called „black flysch") and the Opaleniec Formation (Pieniny Klippen Belt, Poland) based on dinoflagellate cyst studies. *Przegląd Geologiczny*, 56: 245–252. [In Polish, with English abstract.]

Gedl, P., 2008c. One more time on the so-called „black flysch" of the Pieniny Klippen Belt in Poland. *Przegląd Geologiczny*, 56: 458–459. [In Polish, with English title.]

Gedl, P., 2008d. Organic-walled dinoflagellate cyst stratigraphy of dark Middle Jurassic marine deposits of the Pieniny Klippen Belt, West Carpathians. *Studia Geologica Polonica*, 131: 7–227.

Gedl, P., 2013. Dinoflagellate cysts from the Szlachtowa Formation (Jurassic) and adjacent deposits (Jurassic–Cretaceous) of the Grajcarek Unit at Szczawnica-Zabaniszcze (Pieniny Klippen Belt, Carpathians, Poland). *Geological Quarterly*, 57: 485–502.

Gedl, P. & Józsa, Š., 2015. Early?–Middle Jurassic dinoflagellate cysts and foraminifera from the dark shale of the Pieniny Klippen Belt between Jarabina and Litmanová (Slovakia): age and palaeoenvironment. *Annales Societatis Geologorum Poloniae*, 85: 91–122.

Gedl, P., Plašienka, D., Schlögl, J., Józsa, Š. & Madzin, J., 2012. New occurrences of the Szlachtowa Formation in the surroundings of Jarabina village (Pieniny Klippen Belt, Eastern Slovakia). In: Józsa, Š., Reháková, D. & Vojtko, R. (eds), *Environmental, Structural and Stratigraphical Evolution of the Western Carpathians, 8th Conference, December 6th–7th 2012, Bratislava, Abstract Book*. Comenius University, Bratislava, p. 9.

Głuchowski, E. A., 1987. Jurassic and Early Cretaceous articulate Crinoidea from the Pieniny Klippen Belt and the Tatra Mts, Poland. *Studia Geologica Polonica*, 94: 1–102.

Głuchowski, E. A., Krawczyk, A. J. & Słomka, T., 1983. Isocrinida from the Szlachtowa Formation (Jurassic) of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica*, 77: 83–88.

Golonka, J. & Sikora, W., 1981. Microfacies of the Jurassic and Lower Cretaceous sedimentarily thinned deposits of the Pieniny Klippen Belt in Poland. *Biuletyn Instytutu Geologicznego*, 331: 7–37. [In Polish, with English summary.]

Gradstein, F. M., Ogg, J. G. & Hilgen, F. J., 2012. On the geological time scale. *Newsletters on Stratigraphy*, 45: 171–188.

Horwitz, L., 1932. Compte-rendu des recherches géologiques effectuées en 1931 pour la révision des feuilles Nowy-Targ et Szczawnica. *Posiedzenia Naukowe Państwowego Instytutu Geologicznego* (*Comptes-Rendus des Séances du Service Géologique de Pologne*), 33: 61–63. [In Polish, with French title.]

Horwitz, L., 1935a. Contributions ŕ la stratigraphie des Karpates. *Posiedzenia Naukowe Państwowego Instytutu Geologicznego (Comptes-Rendus des Séances du Service Géologique de Pologne)*, 42: 39–46.

Horwitz, L., 1935b. Nouvelle coupe schématique de la Zone Piénine des Klippes (Karpates Polonaises). *Sprawozdania Polskiego Instytytu Geologicznego* (*Bulletin du Service Géologique de Pologne*), 8: 79–133.

Horwitz, L., 1963. Geological structure of the Pieniny Mts, Carpathians (posthumous paper with comments by K. Birkenmajer). *Prace Instytutu Geologicznego*, 38: 152 pp. [In Polish, with English summary.]

Jednorowska, A., 1980. Microfauna and age of the Malinowa Shale Formation (Upper Cretaceous) in the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 67: 7–21. [In Polish, with English summary.]

Krawczyk, A. J., Krobicki, M. & Słomka, T., 1992. Belemnites from the Szlachtowa Formation (Middle Jurassic), Pieniny Klippen Belt, Carpathians. *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 40: 1–7.

Krawczyk, A., Muszyński, M. & Słomka, T., 1987. Exotic rock fragments from psammitic rocks of the Szlachtowa Formation, Jurassic flysch, Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 92: 75–86. [In Polish, with English summary.]

Krawczyk, A. & Słomka, T., 1986. Development and sedimentation of the Szlachtowa Formation, Jurassic flysch, east of Szczawnica: Grajcarek Unit, Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 88: 129–134. [In Polish, with English summary.]

Krawczyk, A. & Słomka, T., 1987. Exotic rocks from the Szlachtowa Formation, Jurassic flysch, of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 92: 69–72. [In Polish, with English summary.]

Lukeneder, A., Halásová, E., Kroh, A., Mayrhofer, S., Pruner, P., Reháková, D., Schnabl, P., Sprovieri, M. & Wagreich, M., 2010. High resolution stratigraphy of the Jurassic–Cretaceous boundary interval in the Gresten Klippenbelt (Austria). *Geologica Carpathica*, 61: 365–381.

Michalík, J., 1994. Notes on the paleogeography and paleotectonics of the Western Carpathian area during the Mesozoic. *Mitteilungen der Österreichischen Geologischen Gesellschaft*, 86: 101–110.

Mišík, M., 1978. Some paleogeographical problems concerning Klippen Belt. In: Vozár, J., Mišík, M. & Nemčok, J. (eds), *Paleogeographical Evolution of the West Carpathians*. Geological Institute of D. Štúr, Bratislava, pp. 147–159. [In Slovak, with English summary.]

Mišík, M., 1997: The Slovak part of the Pieniny Klippen Belt after the pioneering works of D. Andrusov. *Geologica Carpathica*, 48: 209–220.

Myczyński, R., 1973. Middle Jurassic stratigraphy of the Branisko Succession in the vicinity of Czorsztyn, Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 42: 1–122. [In Polish, with English summary.]

Myczyński, R., 2004. Toarcian, Aalenian and Early Bajocian (Jurassic) ammonite faunas and biostratigraphy in the Pieniny Klippen Belt and the Tatra Mts, West Carpathians. *Studia Geologica Polonica*, 123: 7–131.

Nowak, W., 1968. Stomiosphaerids of the Cieszyn Beds (Kimmeridgian–Hauterivian) in the Polish Cieszyn Silesia and their stratigraphical value. *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 38: 275–327. [In Polish, with English summary.]

Nowak, W., 1971. Wyniki badań mikrofacjalnych profilu Szczawnica-Zabaniszcze. In: *Przewodnik XLIII Zjazdu Polskiego Towarzystwa Geoloogicznego, Kraków 12–14 września 1971*. Wydawnictwa Geologiczne, Warszawa, pp. 215–218.

Nowak, W., 1973. Znaczenie *Parastomiosphaera malmica* (Borza) dla korelacji utworów dolnego tytonu w Karpatach. *Kwartalnik Geologiczny*, 17: 648–650. [In Polish.]

Nowak, W., 1976. *Parastomiosphaera malmica* (Borza) from the Polish Carpathians and its stratigraphical value for Lower Tithonian deposits. *Rocznik Polskiego Towarzystwa Geologicznego* (*Annales de la Société Géologique de Pologne*), 46: 89–134.

Obermajer, M., 1986. Microfacies and age of the Pieniny Limestone Formation (Tithonian–Barremian) of the Grajcarek Unit, eastern part of the Pieniny Klippen Belt, Carpathians. *Przegląd Geologiczny*, 34: 317–323. [In Polish, with English summary.]

Obermajer, M., 1987a. Preliminary micropalaeontological study of the Pieniny Limestone Formation (Tithonian–Barremian) in the Pieniny Klippen Belt (Carpathians, Poland). *Studia Geologica Polonica*, 92: 41–54. [In Polish, with English summary.]

Obermajer, M., 1987b. Lower Cretaceous sedimentary break in the Niedzica Succession near Niedzica, Pieniny Klippen Belt, Carpathians (Poland). *Studia Geologica Polonica*, 92: 55–68. [In Polish, with English summary.]

Oszczypko, N., Malata, E., Švabenická, L., Golonka, J. & Marko, F., 2004. Jurassic–Cretaceous controversies in the Western Carpathian Flysch: the „black-flysch" case study. *Cretaceous Research*, 25: 89–113.

Oszczypko, N., Olszewska, B. & Malata, E., 2012. Cretaceous (Aptian/Albian–?Cenomanian) age of „black flysch" and adjacent deposits of the Grajcarek thrust-sheets in the Małe Pieniny Mts (Pieniny Klippen Belt, Polish Outer Carpathians). *Geological Quarterly*, 56: 411–440.

Oszczypko, N., Ślączka, A., Oszczypko-Clowes, M. & Olszewska, B., 2015. Where was the Magura ocean? *Acta Geologica Polonica*, 65: 319–344.

Pazdro, O., 1979. Microfauna from the Opaleniec Formation, Middle Jurassic, Pieniny Klippen Belt of Poland, Carpathians. *Studia Geologica Polonica*, 61: 105–128. [In Polish, with English summary.]

Pécskay, Z., Gméling, K., Molnár, F. & Benkó, Z., 2015. Neogene calc-alkaline intrusive magmatism of post-collisional origin along the Outer Carpathians: a comparative study of the Pieniny Mountains and adjacent areas. *Annales Societatis Geologorum Poloniae*, 85: 77–89.

Picha, F. J., 1996. Exploring for hydrocarbons under thrust belts a challenging new frontier in the Carpathians and elsewhere. *AAPG Bulletin*, 89: 1547–1564.

Picha, F. J., Stráník, Z. & Krejčí, O., 2006. Geology and hydrocarbon resources of the Outer Western Carpathians and their foreland, Czech Republic. In: Golonka, J. & Picha, F. J. (eds), The Carpathians and their foreland: geology and hydrocarbon resources. *AAPG Memoir*, 84: 49–175.

Plašienka, D., 2012. Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians – an overview. *Geological Quarterly*, 56: 601–628.

Plašienka, D. & Mikuš, M., 2010. Geological structure of the Pieniny and Šariš sectors of the Klippen Belt between the Litmanová and Drienica villages in Eastern Slovakia. *Mineralia Slovaca*, 42: 155–178.

Plašienka, D. & Soták, J., 2015. Evolution of Late Cretaceous–Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): tectonic controls over a growing orogenic wedge. *Annales Societatis Geologorum Poloniae*, 85: 43–76.

Plašienka, D., Soták, J., Jamrichová, M., Halásová, E., Józsa, Š., Madzin, J. & Mikuš, V., 2012. Structure and evolution of the Pieniny Klippen Belt demonstrated along a section between Jarabina and Litmanová villages in Eastern Slovakia. *Mineralia Slovaca*, 44: 17–38.

Popa, M. E., 2005. Aspects of Romanian Palaeozoic palaeobotany and palynology. Part II: Overview of the Upper Carboniferous formations in the South Carpathians. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, 156: 415–430.

Pszczółkowski, A., 2015. Aptian age of the „spotted limestone" (Pieniny Limestone Formation) in the Grajcarek Stream (Pieniny Klippen Belt, Poland). *Annales Societatis Geologorum Poloniae*, 85: 21–42.

Pszczółkowski, A. & Myczyński, R., 2004. Ammonite-supported microfossil and nannoconid stratigraphy of the Tithonian–Hauterivian limestones in selected sections of the Branisko Succession, Pieniny Klippen Belt (Poland). *Studia Geologica Polonica*, 123: 133–197.

Pugaczewska, H., 1971. Aalenian Gryphaeinae from the Pieniny Klippen Belt of Poland. *Acta Palaeontologica Polonica*, 16: 389–399. [In Polish, with English summary.]

Reháková, D., 2000. Calcareous dinoflagellate and calpionellid bioevents versus sea-level fluctuations recorded in the West-Carpathian (Late Jurassic/Early Cretaceous) pelagic environments. *Geologica Carpathica*, 51: 229–243.

Reháková, D. & Michalík, J., 1997. Evolution and distribution of calpionellids – the most characteristic constituents of Lower Cretaceous Tethyan microplankton. *Cretaceous Research*, 18: 493–504.

Scheibner, E., 1968. The Klippen Belt of the Carpathians. In: Maheľ, M., Buday, T. *et al.* (eds), *Regional Geology of Czechoslovakia. II. The West Carpathians*. Geological Survey of Czechoslovakia, Academia, Praha, pp. 304–371.

Segit, T., Matyja, B. A. & Wierzbowski, A., 2015. The Middle Jurassic succession in the central sector of the Pieniny Klippen Belt (Sprzycne Creek): implications for the timing of the Czorsztyn Ridge development. *Geologica Carpathica*, 66: 285–302.

Sikora, W., 1971. Wycieczka D-2. Trasa: Zakopane-Szczawnica-Jaworki-Czorsztyn-Kapuśnica-Złatne-Dursztyn. Punkt 1 – Szczawnica-rzeźnia. In: *Przewodnik XLIII Zjazdu Polskiego Towarzystwa Geoloogicznego, Kraków 12–14 września 1971*. Wydawnictwa Geologiczne, Warszawa, pp. 212–215, 218–224.

Skompski, S., 1982. The nature and systematic position of the microfossils *Globochaete alpina* Lombard, 1945. *Acta Geologica Polonica*, 32: 47–56.

Ślączka, A., Krugłov, S., Golonka, J., Oszczypko, N. & Popadyuk, I., 2006. Geology and hydrocarbon resources of the Outer Carpathians, Poland, Slovakia, and Ukraine: general geology. In: Golonka, J. & Picha, F. J. (eds), *The Carpathians and their foreland: geology and hydrocarbon resources*. *AAPG Memoir*, 84: 221–258.

Topchishvili, M., Lominadze, T. & Tsereteli, L., 1998. Ammonite associations and biostratigraphy of the Middle Jurassic sediments of Georgia. *Cuadernos de Geología Ibérica*, 24: 293–309.

Tyszka, J., 1994. Palaeoenvironmental implications from ichnological and microfaunal analyses of Bajocian spotty carbonates, Pieniny Klippen Belt, Polish Carpathians. *Palaios*, 9: 175–187.

Tyszka, J., 1995. *Mid-Jurassic palaeoenvironment and benthic* *communities in the Pieniny Klippen Belt and the Magura basins, Pieniny Klippen Belt, Poland.* Unpublished PhD thesis, Institute of Geological Sciences, Polish Academy of Sciences, Kraków, 192 pp.

Tyszka, J., 1999. Foraminiferal biozonation of the Early and Middle Jurassic in the Pieniny Klippen Belt (Carpathians). *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 47: 27–45.

Uhlig, V., 1885. Reiseberichte aus der penninischen Klippenzone. I und II. *Verhandlungen der K. K. Geologischen Reichsanstalt, Wien*, I: 10: 252–254; II: 11: 282–283.

Uhlig, V., 1890. Ergebnisse geologischer Aufnahmen in den westgalizischen Karpathen. II. Der pieninische Klippenzug. *Jahrbuch der K. K. Geologischen Reichsanstalt*, 40: 559–824.

Widz, D., 1991. Les radiolaires du Jurassique supérieur des radiolarites de la zone des Klippes de Pieniny (Carpathes Occidentales, Pologne). *Revue de Micropaléontologie, Paris*, 34: 231–260.

Widz, D., 1992. Datation par les radiolaires des radiolarites jurassique de l'Unite de Grajcarek (Zone des Klippes de Pieniny, Carpathes occidentales, Pologne). *Bulletin of the Polish Academy of Sciences*, *Earth Sciences*, 40: 115–124.

Widz, D. & De Wever, P., 1993. Nouveaux Nassellaires (Radiolaria) des radiolarites jurassiques de la coupe de Szeligowy Potok (Zone des Klippes de Pieniny, Carpathes occidentales, Pologne). *Revue de Micropaléontologie, Paris*, 36: 77–90.