General history of the PKB

(*Michał Krobicki*, *Jan Golonka*)

The Northern Carpathians are subdivided into an older range known as the Inner Carpathians and the younger one, known as the Outer or Flysch Carpathians. The PKB is situated at the boundary of these two ranges (Figs 2–4). The Inner Carpathians nappes contact along a Tertiary strike-slip boundary with PKB.

The relationship between PKB and the Magura Nappe changes along the PKB strike. In the Vah and Orava valleys these two units are divided by the Miocene sub-vertical strike-slip fault and both units are involved in the complex flower structure. Present day confines of the PKB are strictly tectonic. They may be characterized as a (sub)vertical faults and shear zones, along which a strong reduction of space of the original sedimentary basins took place. The NE-SW striking faults accompanying the PKB have the character of lateral slips. It is indicated by the presence of flower structures on the contact zone of the Magura Unit and the PKB, or by the structural asymmetry of the Inner Carpathian Paleogene Basin.

The tectonic character of the Polish section of PKB is mixed. Both the strike slip and thrust components occur here (e.g., Książkiewicz, 1977b; Golonka & Rączkowski, 1984; Birkenmajer, 1986; Ratschbacher *et al*., 1991; Jurewicz, 1994, 1997; Nemčok & Nemčok, 1994). In general the sub-vertically arranged Jurassic-Lower Cretaceous basinal facies display the tectonics of the diapir character originated in the strike-slip zone between two plates. The ridge facies are often uprooted and display thrust or even nappe character. The Niedzica Succession is thrust over the Czorsztyn Succession, while the Czorsztyn Succession is displaced and thrust over the Grajcarek Unit (e.g., Książkiewicz, 1977b; Golonka & Rączkowski, 1984; Jurewicz, 1997). The Grajcarek Unit is often thrust over the Krynica Sub-Unit of the Magura Nappe. The Upper Cretaceous–Paleogene flysch sequences of the Złatne Furrow (Golonka & Sikora, 1981) are often thrust over the various slope and ridge sequences. In the East Slovakian section of the PKB, the back-thrusts of the Magura Nappe onto PKB, as well as PKB onto the Central Carpathian Paleogene, are commonly accepted (see Nemčok, 1990; Lexa *et al*., 2000). The PKB tectonic components of different age, strike-slip, thrust as well as toe-thrusts and olistostromes mixed together, are giving the present-day melange character of the PKB, where individual tectonic units are hard to distinguish.

The PKB is composed of several successions of mainly deep and shallower-water limestones, covering a time span from the Early Jurassic to Late Cretaceous (Andrusov, 1938, 1959; Andrusov *et al*., 1973; Birkenmajer, 1958b, 1977, 1986, 1988; Mišík, 1994; Golonka & Krobicki, 2001, 2004). This strongly tectonized structure is about 600 km long and 1–20 km wide, stretching from Vienna to the West, to Romania to the East (Fig. 2).

During the Jurassic and Cretaceous within the Pieniny Klippen Basin the submarine Czorsztyn Ridge (= "pelagic swell" of Mišík, 1994, mainly so-called Czorsztyn Succession) and surrounding zones formed an elongated structure with domination of pelagic type of sedimentation (Birkenmajer, 1977, 1986; Mišík, 1994; Michalík & Reháková, 1995; Aubrecht *et al*., 1997; Plašienka, 1999; Wierzbowski *et al*., 1999; Golonka & Krobicki, 2001; 2004). The Pieniny Klippen Basin trends SW to NE (e.g., Aubrecht & Túnyi, 2001; see discussion in Golonka & Krobicki, 2001, 2004) (Fig. 7). Its deepest part shows the presence of deep water Jurassic-Early Cretaceous deposits (pelagic limestones and radiolarites) of Złatna Unit (Sikora, 1971; Golonka & Sikora, 1981; Golonka & Krobicki, 2002) later described also as Ultra-Pieniny Succession (Birkenmajer, 1988; Birkenmajer *et al*., 1990) or Vahicum (e.g., Plašienka, 1999). Somewhat shallower sedimentary zones known as the Pieniny, Branisko (Kysuca) successions have been located close to central furrow. Transitional slope sequences between basinal units and ridge units are known as Czertezik and Niedzica successions (Podbiel and Pruské successions in Slovakia) near the northern (Czorsztyn) Ridge, and Haligovce-Nižná successions near the southern so-called Exotic Andrusov Ridge (Birkenmajer, 1977, 1986, 1988; Aubrecht *et al*., 1997; Wierzbowski *et al*., 2004). The strongly condensed Jurassic-Early Cretaceous pelagic cherty limestones (Maiolica-type facies) and radiolarites of the Grajcarek Unit were also deposited in northwestern Magura Basin.

Palinspastic reconstruction of the PKB Basin indicates occurrence of submarine ridge during the whole Jurassic and Cretaceous times. This so-called Czorsztyn Ridge, an elongated structure, subdivided Pieniny and Magura basins within the Carpathian part of the northernmost Tethyan Ocean (Figs 5–7) (comp. Golonka, 2004, 2007a, 2007b with references cited therein). Its SW-NE orientation and location within the Tethyan Ocean is interpreted by means of palaeomagnetic data, relationship of sedimentary sequences and palaeoclimate (see discussion in Golonka & Krobicki, 2001, see also Aubrecht & Túnyi, 2001; Lewandowski *et al*., 2005; Grabowski *et al*., 2008). The basins divided by the Czorsztyn Ridge were dominated by a pelagic type of sedimentation. The deepest part of the PKB Basin is well documented by deep water Jurassic-Early Cretaceous deposits (radiolarites and pelagic *Maiolica*-type cherty limestones) (Birkenmajer, 1979, 1986; Golonka & Sikora, 1981; Golonka & Krobicki, 2004; Krobicki *et al*., 2006) of the so-called Branisko and Pieniny successions. The transitional, shallower sequences, which primary occupied slopes between deepest basinal units and the Czorsztyn Ridge are known as Czertezik and Niedzica successions, and the shallowest zone is Czorsztyn Succession which primary occupied SE slope of the Czorsztyn Ridge (Birkenmajer, 1986; Golonka & Krobicki, 2004; Krobicki & Golonka, 2006).

The **oldest Jurassic** rocks known only from the Ukrainian and Slovakian part of the PKB (Krobicki *et al*., 2003; Schlögl *et al*., 2004; Wierzbowski *et al*., 2012, 2021) consist of different type of *Gresten*-like clastic sediments with intercalations of *Gresten*-like dark/black fossiliferous limestones with brachiopods and grypheoids (?Hettangian-?Sinemurian) (Schlögl *et al*., 2004 with literature). However, Pliensbachian-Lower Bajocian *Bositra* ("*Posidonia*") black shales with spherosiderites (Skrzypny Shale Formation in local, formal nomenclature, see Birkenmajer, 1977) as well as dark marls and spotty limestones of widespread Tethyan *Fleckenkalk*/*Fleckenmergel* facies, indicate the oxygen-depleted conditions (Birkenmajer, 1986; Tyszka, 1994, 2001) (Fig. 9).

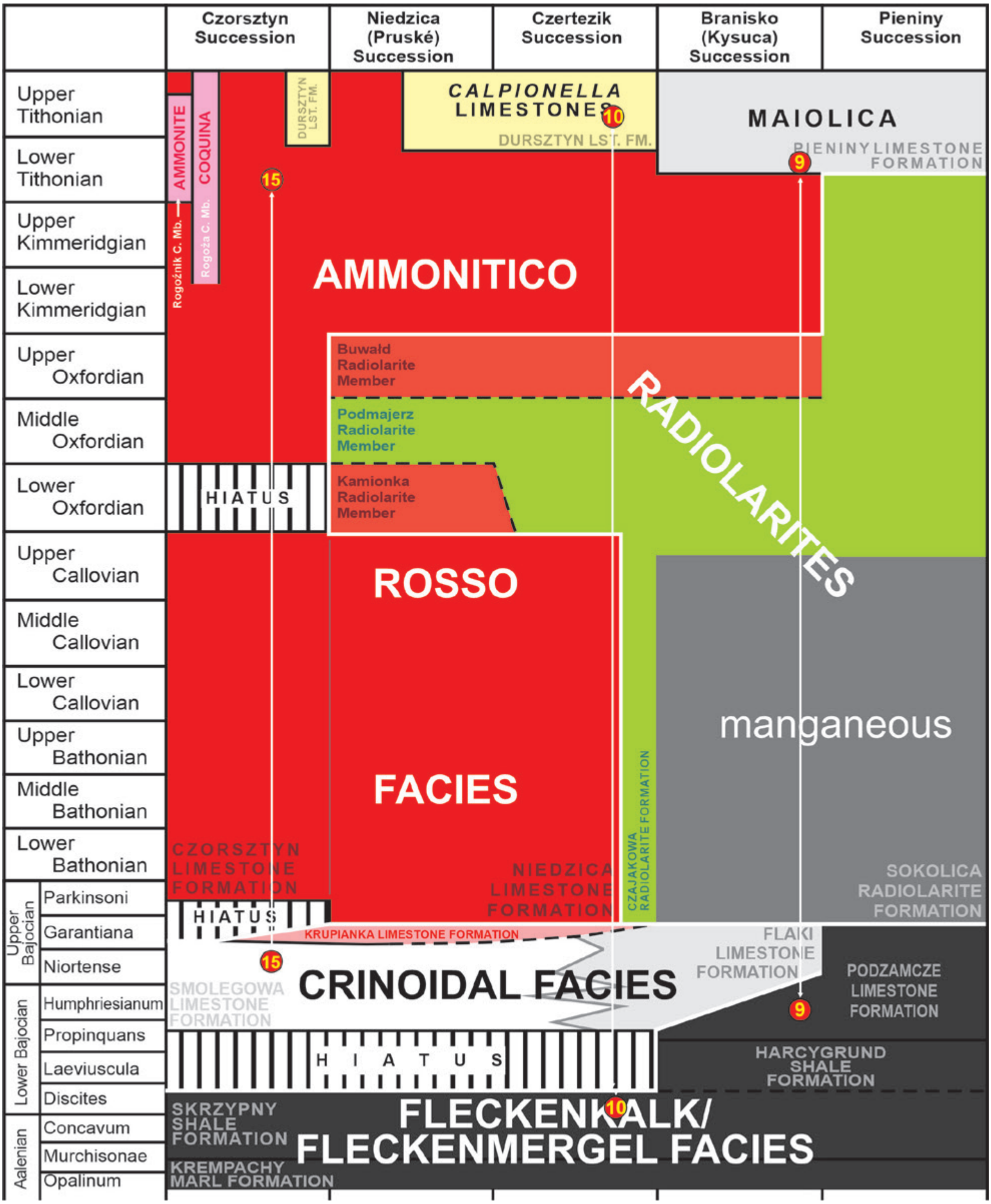

Fig. 9. Stratigraphical correlation between Jurassic lithofacies (lithostratigraphic units) of the Pieniny Klippen Belt successions (after Wierzbowski *et al*., 2004; supplemented by Krobicki & Wierzbowski, 2004)

One of the most rapidly change of sedimentation/palaeoenvironments within the PKB basins took place during late Early Bajocian when well-oxygenated multicoloured crinoidal limestones replaced dark and black sedimentation.

The origin of the above mentioned Czorsztyn Ridge was connected with this Bajocian postrift geotectonic reorganization (Golonka *et al.*, 2003; Krobicki, 2006, 2009).

One of the most important geotectonic element within Western Carpathians basins was the Czorsztyn Ridge (Swell), which originated during the Middle Jurassic (Early Bajocian) time. Palaeogeographicaly it has been the main object which separated, between the Middle Jurassic to the Late Cretaceous times, two large Carpathians basins, the Magura Basin on NW side and the Pieniny Basin on SE side. Therefore, the precise dating of its origin and first uplift is crucial for recognition of its geodynamic significance. Drastic change of sedimentation from dark/black shales of oxygen-poor environments (latest Pliensbachian–earliest Bajocian) to white/light grey crinoidal limestones of well oxygenated regimes, which presently directly overlie shales, were separated by significance stratigraphical hiatus (Fig. 10). It was biostratigraphicaly perfectly dated by ammonites collected from the basal part of crinoidal limestones in several outcrops of the Polish part of the PKB (Krobicki & Wierzbowski, 2004).

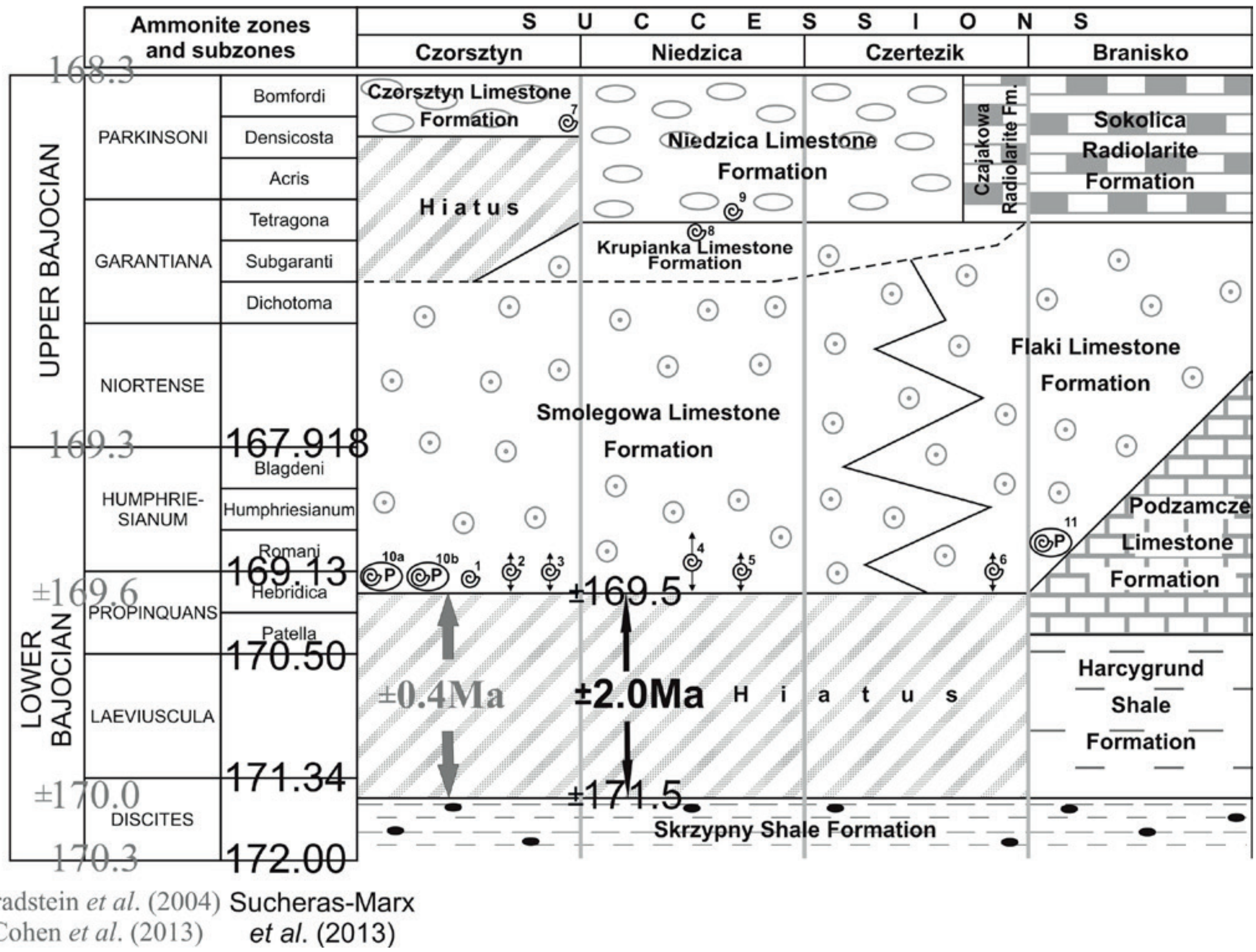

Fig. 10. Lithostratigraphical scheme of the klippen successions of the Pieniny Klippen Belt (after Krobicki & Wierzbowski, 2004, slightly modified; lithostratigraphical units after Birkenmajer, 1977) with data of duration of the Early Bajocian. Numeration indicates outcrops with ammonites (described in Krobicki & Wierzbowski, 2004): 1, 2, 7 – Czorsztyn-Sobótka; 3 – Krupianka; 4, 8, 9 – Niedzica-Podmajerz; 5 – Czajakowa Skała; 6 – Wysokie Skałki; ammonites in phosphatic concretions: 10a – Falsztyn; 10b – Czorsztyn-Sobótka; 11 – Flaki. Lithology of lithostratigraphical units: Skrzypny Shale Formation – black shales with spherosiderites; Harcygrund Shale Formation – dark spotty shales; Podzamcze Limestone Formation – dark spotty limestones; Smolegowa Limestone Formation – white crinoidal limestones; Flaki Limestone Formation – grey crinoidal limestones; Krupianka Limestone Formation – red crinoidal limestones; Czorsztyn and Niedzica Limestone formations – red nodular limestones; Czajakowa Radiolarite Formation – green radiolarites; Sokolica Radiolarite Formation – black manganeous radiolarites. Chronostratigraphic data: grey Times New Roman – Gradstein *et al*. (2004) and Cohen *et al*. (2013); black arial – Sucheras-Marx *et al*. (2013)

When we try to estimate absolute time of this uplift event (= origin of the Czorsztyn Ridge) we can use two proposed scales of duration of the Early Bajocian. First one is described and illustrated by Gradstein *et al*. (2004) and Cohen *et al*. (2013), which suggest 2 Ma for the whole Bajocian, and by this reason the hiatus has about 0.4 Ma only. Second idea is based on estimation of the duration of this sub-stage, based on a cyclostratigraphic analysis of the carbonate content from the Chaudon–Norante section (Subalpine Basin, France) (Sucheras-Marx *et al*., 2013), which indicates that the Early Bajocian only lasted c. 4.082 Ma. Using these authors calibration of duration of the Early Bajocian ammonite zones (the Discites zone lasted 0.66 Ma, the Laeviuscula zone 0.84 Ma, the Propinquans zone 1.37 Ma, and the Humphriesianum zone 1.22 Ma) we can conclude that the hiatus, which corresponds with time necessary for origin/uplift of the Czorsztyn Ridge, is about 2 Ma. From geotectonical processes point of view such calculation is more probably (Krobicki, 2018) (Fig. 10).

The central Atlantic (Withjack *et al*., 1998) and Alpine Tethys went into a drifting stage during the **Middle Jurassic**. The oldest oceanic crust in the Ligurian-Piemont Ocean was dated as late as the Middle Jurassic in the southern Apennines and in the Western Alps (see Ricou, 1996 and literature cited therein). Bajocian oceanic spreading of the Alpine Tethys documented by isotopic methods (Bill *et al*., 2001) fit well with the Pieniny data (Winkler & Ślączka, 1994), which well correspond to the supposed opening of the Ligurian-Penninic Ocean. Crinoidal limestones were developed in more elevated parts of the Pieniny Klippen Basin (Czorsztyn, Niedzica and Czertezik successions), and were redistributed to deeper-water Branisko Succession as the grey crinoidal cherty limestones. Sedimentation of still younger (since latest Bajocian) red nodular *Ammonitico Rosso*-type limestones was effect of Meso-Cimmerian vertical movements which subsided Czorsztyn Ridge and produced tectonically differentiated blocks as well as accompanied by the formation of neptunian dykes and scarp-breccias (e.g., Birkenmajer, 1986; Aubrecht *et al*., 1997; Wierzbowski *et al*., 1999; Aubrecht, 2001; Aubrecht & Túnyi, 2001; Krobicki, 2006; Krobicki & Golonka, 2006).

The **Late Jurassic** (Oxfordian-Kimmeridgian) history of the PKB reflects strongest facial differentiation within sedimentary basin where mixed siliceous-carbonate sedimentation took place. The formation of limestones of the *Ammonitico-rosso* type was mostly related with existence of elevated part of sea bottom (Czorsztyn Ridge and its slopes), whereas deposition of radiolarites (Birkenmajer, 1977, 1986; Mišík, 1999) took place in deeper parts of the bordering basins. The main phase of this facial differentiation took place later, mainly during Oxfordian times when the greatest deepening effect is indicated by widespread Oxfordian radiolarites which occur in the all basinal successions, whereas the shallowest zone (Czorsztyn Succession) is completely devoid of siliceous intercalations at that time. Oxfordian radiolarites are typical for transitional (Niedzica and Czertezik) successions and strictly basinal parts of the basin (Branisko and Pieniny successions). Similar compositions of facies are well known in several European Alpine regions (e.g., Betic Cordillera, Southern Alps, Apennine, Karavanke, and Ionian Zone). These regions, together with PKB basins formed the so-called Alpine Tethys (Golonka, 2004).

During the **latest Jurassic–Early Cretaceous** (Tithonian-Berriasian), the Czorsztyn Succession included hemipelagic to pelagic organogenic carbonate deposits of medium depth, for example white and creamy *Calpionella*-bearing limestones. Several tectonic horsts and grabens were formed, rejuvenating some older, Eo- and Meso-Cimmerian faults (Birkenmajer, 1986; Krobicki, 1996a). Such features resulted from the intensive Neo-Cimmerian tectonic movements and are documented by facies diversification, hardgrounds and condensed beds with ferromanganese-rich crusts and/or nodules, sedimentary-stratigraphic hiatuses, sedimentary breccias and/or neptunian dykes (Birkenmajer, 1958a, 1975, 1986; Michalík & Reháková, 1995; Krobicki, 1996a; Aubrecht *et al*., 1997; Krobicki & Słomka, 1999; Golonka & Krobicki, 2002; Plašienka, 2002; Golonka *et al*., 2003; Krobicki *et al*., 2006). In the same time within deeper successions (mainly Branisko and Pieniny ones) cherty limestone of *Maiolica*-type (=*Biancone*) facies deposited. It is one of the famous, widespread Tethyan facies well known both from the Alpine and the Apennine regions (Pszczółkowski, 1987; Wieczorek, 1988). In whole western Tethys this facies originated mainly in deep basins (above CCD but above ACD levels) but also on submarine elevations or drowned platforms and around the Jurassic/Cretaceous boundary reflects the greatest facies unification in this ocean (e.g., Winterer & Bosellini, 1981; Wieczorek, 1988).

Late Cretaceous pelagic deposits with the youngest part developed as *Scaglia Rossa* pelagic, foraminiferal, multicoloured green/variegated/red marl deposits (= *Couches Rouge* = *Capas Rojas*) deposited during the latest, third episode of evolution of the Pieniny Klippen Basin (Birkenmajer, 1986, 1988; Bąk K., 2000), when unification of sedimentary facies took place within all successions (Albian-Coniacian). Still younger are flysch and/or flyschoidal facies (Santonian-Campanian) (i.a. Birkenmajer, 1986; Mišík, 1994; Aubrecht *et al*., 1997; Birkenmajer & Jednorowska, 1983a, 1984, 1987a, 1987b; Gasiński, 1991; Birkenmajer & Gasiński, 1992; Bąk, K., 1998; Bąk M., 1999). During this syn-orogenic stage of the development of the PKB Basin these flyschoidal deposits developed as submarine turbiditic wedges, fans and canyon fills (Rawdański, 1978; Birkenmajer, 1986) with several episodes of debris flows with numerous exotic pebbles took place (Late Albian-Early Campanian) (Fig. 11).

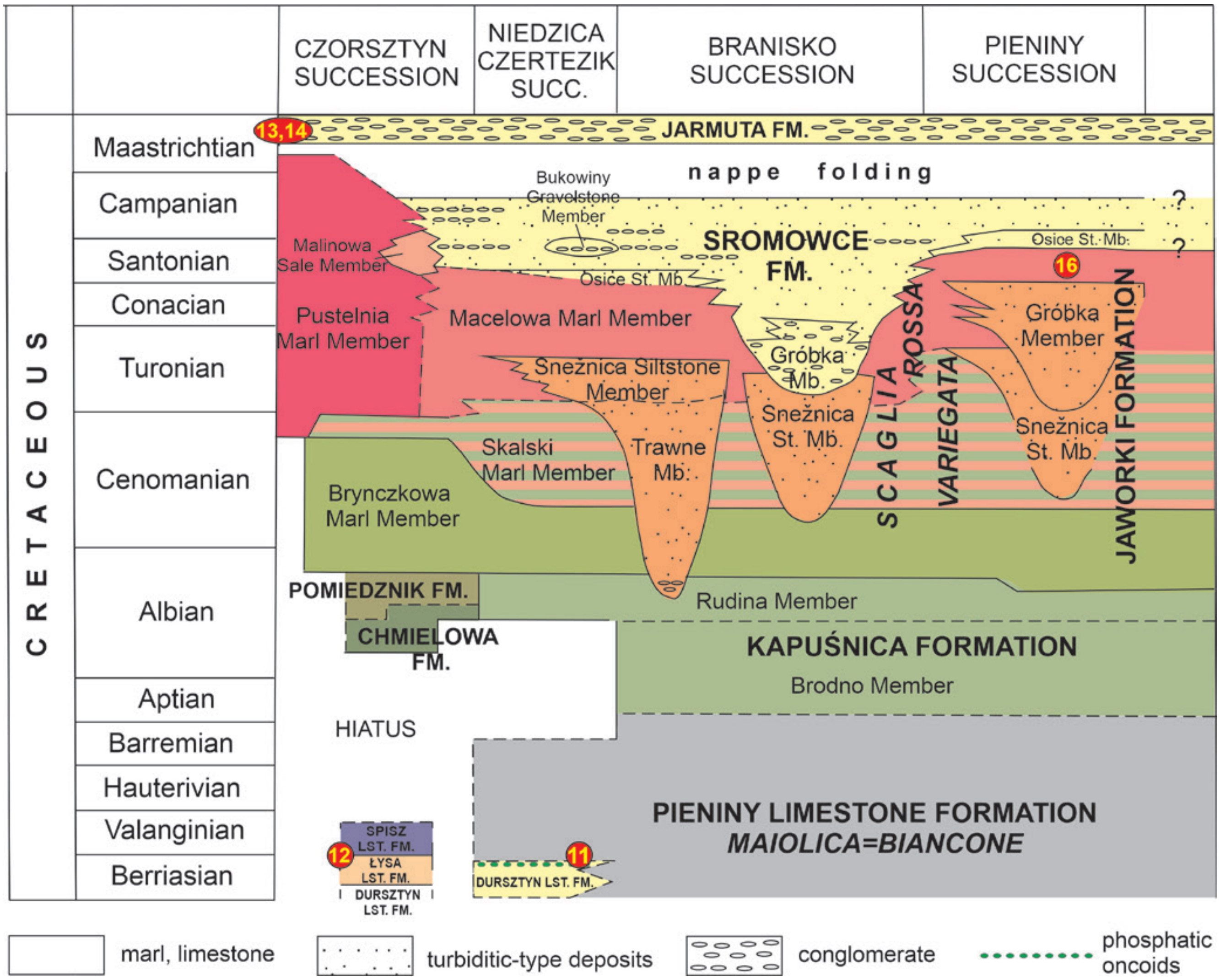

Fig. 11. Detailed stratigraphic table of the Cretaceous rocks of the Czorsztyn, Niedzica (Pruské), Czertezik, Branisko (Kysuca) and Pieniny successions in the Pieniny Klippen Belt in Poland (from Birkenmajer & Jednorowska, 1987, simplified) with locations of field trip stops

The Pieniny Klippen Basin was closed at the **Cretaceous/Paleocene** transition, as effect of strong Late Cretaceous (Subhercynian and Laramian) thrust-folding (Birkenmajer, 1977, 1986, 1988). From south to north folding of the successive nappes, built by Jurassic-Cretaceous deposits of early mentioned sedimentary successions, took place. Simultaneously with this Laramian nappe folding the uppermost Cretaceous (Maastrichtian) fresh-water and marine molasse with exotic material was deposited and Paleocene flysch was continuation of this sedimentary event. They covered with unconformity several klippen nappes folded earlier and this so-called Klippen Mantle was refolded together with them somewhat later.

The second tectonic episode was connected with strong Savian and Styrian (**Early** and **Middle Miocene** respectively) compression, when the Cretaceous nappes, the Klippen Mantle and the new Paleogene deposits were refolded together (Birkenmajer, 1986) and originated system of transverse strike-slip faults. Good visible effect of several tectonic phases of folding and deformations within PKB is geomorphologic view of tectonically isolated klippes of Jurassic and Cretaceous hard rocks surrounding by softer shales, marls and flysch deposits.

The last important event in the PKB was **Middle Miocene (Sarmatian)** volcanism represented by calc-alkaline andesite dykes and sills which cut mainly Paleogene flysch rocks of the Outer Carpathians (Magura nappe) (Małkowski, 1958; Birkenmajer, 1979, 1986, 1988) recently precise dating radiometrically (Birkenmajer & Pécskay, 1999, 2000). They formed so-called Pieniny Andesitic Line (PAL) (Fig. 12).

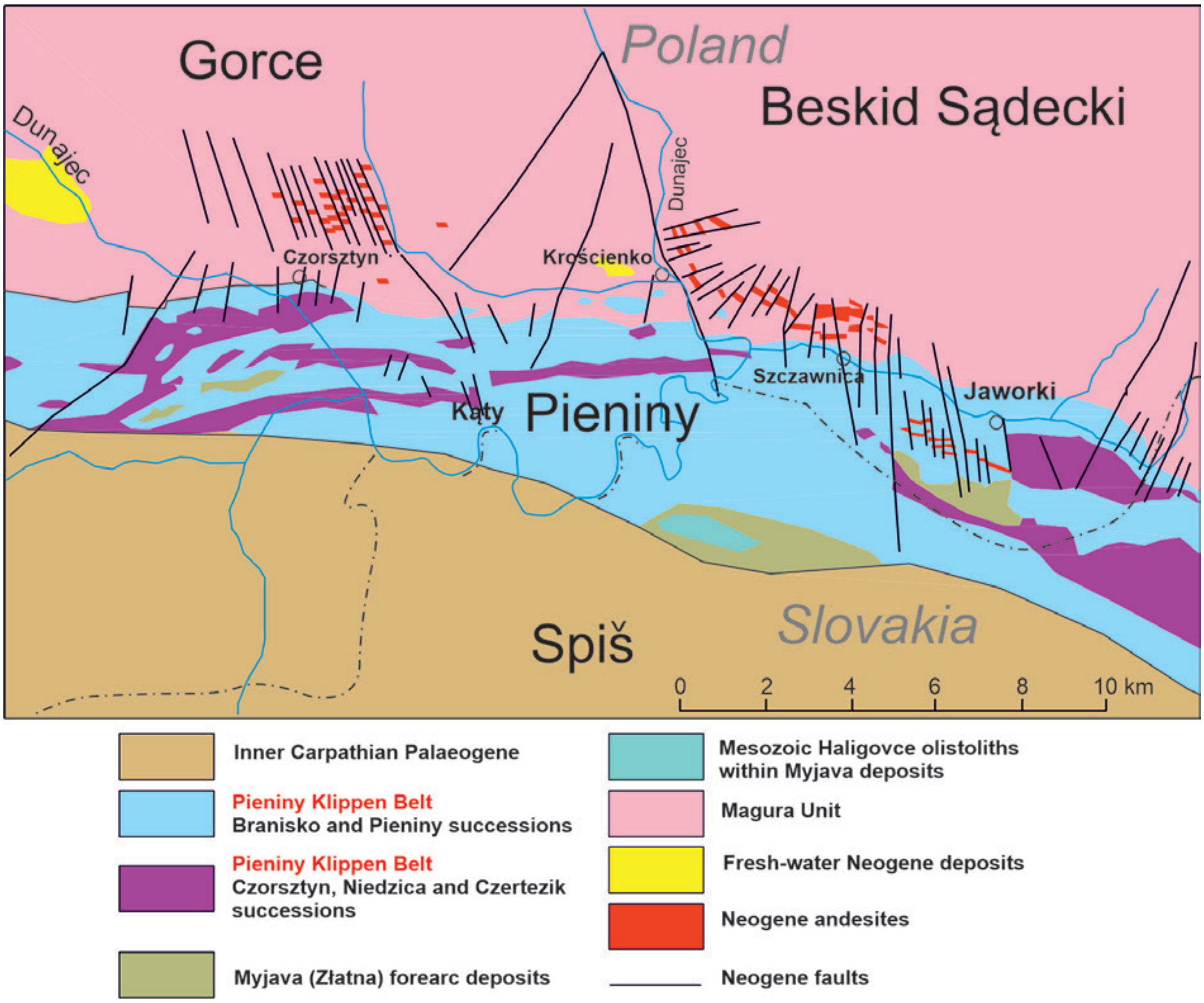

Fig. 12. Geological sketch of the Pieniny Klippen Belt (Polish sector) and surrounding regions (after Birkenmajer, 1979 – simplified)

DESCRIPTION OF THE TRIP

Passage: Kraków – Rzyki – Leszna Górna – Wisła – Szczawnica

(*Jan Golonka*, *Michał Krobicki*)

The field trip starts in AGH University of Krakow parking lot and leads southward to the Carpathians. In Krakow and its vicinity the Mesozoic rocks of the North European Plate are exposed. The platform is dissected by numerous faults into several horsts and grabens. The grabens are filled with the Miocene Molasse deposits, while horsts elevate the Upper Jurassic rocks. These rocks are represented mainly by Oxfordian cyanobacterial-sponge buildups with associated nodular, chalky and micritic limestones (Matyszkiewicz, 1997). Passing the bridge on Wisła River we can observe the hill of Wawel with the Polish Royal Castle on the top. The Royal Castle was built in 10th century and remodeled several times. The most important remodeling was done by Queen Bona and her team of Italian architects in 16th century giving the castle its Renaissance character. The Wawel hill is built by the white-weathering Upper Oxfordian massive limestones. These limestones are horst elevated and shaped by karst phenomena. Following southwards the road crosses the Carpathian Foredeep filled with Miocene molasse deposits. Springs of hydrosulphuric mineral waters are connected with the Miocene deposits (Cieszkowski & Ślączka, 2001). These mineral waters are being utilized at spas Mateczny and Swoszowice located within Krakow City limits. After a few kilometers the route passes over the frontal thrust-faults of the Outer Carpathian flysch belt.