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Łysogóry Unit (Central Poland) versus East European Craton — application of sedimentological data from Cambrian siliciclastic association

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The Middle and Late Cambrian deposits of the Łysogóry Unit and the Early and Middle Cambrian deposits of the East European Craton form part of an extensive siliciclastic sedimentary prism that was deposited on a tide and storm influenced continental shelf. In SE Poland, the proximal part of the Cambrian passive margin sedimentary prism of the East European Craton (Baltica) corresponds to the Łysogóry Unit whereas the NE part of the Małopolska Massif is thought to represent its distal part. Based on sedimentological criteria, the Cambrian siliciclastic association appears to indicate that the Łysogóry Unit and Małopolska Massif were not detached from Baltica during the breakup of the Precambrian Rodinia supercontinent, thus casting serious doubt on the exotic terrane nature of the Holy Cross Mts. Neither the Łysogóry Unit nor the Małopolska Massif are terranes in so far as they were not subject to lateral translations along the margin of Baltica. The Cambrian phases of Caledonian deformations in the Holy Cross Mts. may be explained in terms of rotational block movements controlled by large-scale listric normal faults dipping off the craton.

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INTRODUCTION

The Łysogóry Unit (Fig. 1) covers the Łysogóry region of the Holy Cross Mts. (*sensu* Czarnocki, 1950) (Fig. 2) and the area that extends further to the north-east (Radom-Kraśnik High *sensu* Żelichowski, 1972) as far as the Kazimierz Fault that is interpreted either as forming part of the Teisseyre-Tornquist Line or as a shallow fault at the front of Caledonian thrusts (*cf*. Guterch *et al*., 1996; Dadlez, 2001). The Łysogóry Unit is bounded to the NW by the Grójec Fault, and to the SW by the Holy Cross Fault (Figs. 1 and 2). The latter separates the Łysogóry Unit from the Kielce region of the Holy Cross Mts. The Kielce region is considered as forming part of the Małopolska Massif (Pożaryski *et al*., 1992). The origin of tectonic units occurring between the Variscan Deformation Front and the East European Craton has been interpreted in different ways. The Łysogóry Unit is considered to represent either part of a Caledonian thrust-and-fold belt (Znosko, 1962, 1996, 1998) developed on the passive margin of the East European Craton (Dadlez *et al*., 1994; Kowalczewski, 2000), or as an exotic terrane involved in a Caledonian strike-slip orogen (Pożaryski, 1990, 1991; Pożaryski *et al*., 1992). According to the latter interpretation, the Małopolska Massif, including the Kielce region (Figs. 1 and 2), is thought to form a separate terrane. Further to the south-west, the Upper Silesian Massif corresponds to another terrane (Pożaryski *et al*., 1992; Nawrocki and Poprawa, 2006).

The Łysogóry Unit was interpreted as a Gondwana-derived terrane on the base of the Cadomian K/Ar age of detrital muscovite contained in its Middle and Late Cambrian clastic sediments (Belka *et al*., 1997). This interpretation was maintained during later research on detrital muscovite from Middle Cambrian deposits of the marginal part of the East European Craton (borehole sections: Okuniew IG 1 and Łopiennik IG 1). According to Belka *et al*. (2000), the Łysogóry Unit and the Małopolska and Upper Silesian massifs are crustal fragments that were derived from the marginal parts of Gondwana and not from the East European Craton. However, U-Pb age determinations of zircon grains extracted from Cambrian deposits of the Łysogóry Unit and from drill cores of the Okuniew IG 1 borehole (Middle Cambrian and crystalline basement), show that Late Proterozoic zircon ages are not restricted to Cadomian Gondwana sources (Valverde-Vaquero *et al*., 2000). The Łysogóry Unit contains detrital zircons that may have been derived from the East Euro-

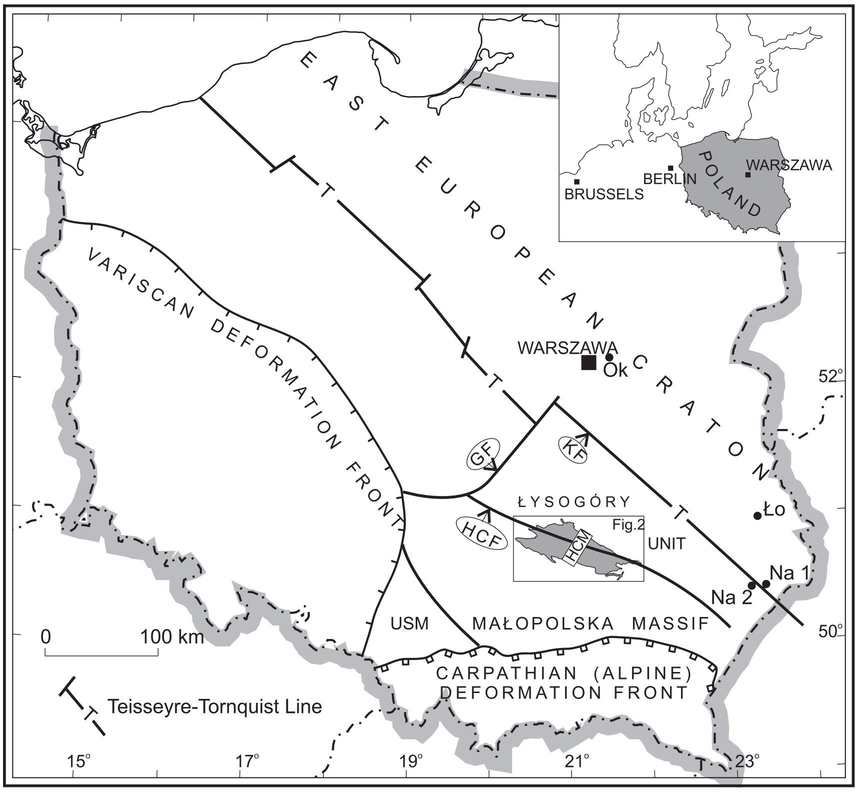

Fig. 1. Location of the study area in the framework of the main tectonic units of Poland (modified after Guterch *et al.*, 1996)

HCM — Holy Cross Mts., HCF — Holy Cross Fault, GF — Grójec Fault, KF — Kazimierz Fault, USM — Upper Silesia Massif; borehole sections studied in the area outside of the Holy Cross Mts.: Na 1 — Narol IG 1, Na 2 — Narol PIG 2, Ło — Łopiennik IG 1, Ok — Okuniew IG 1

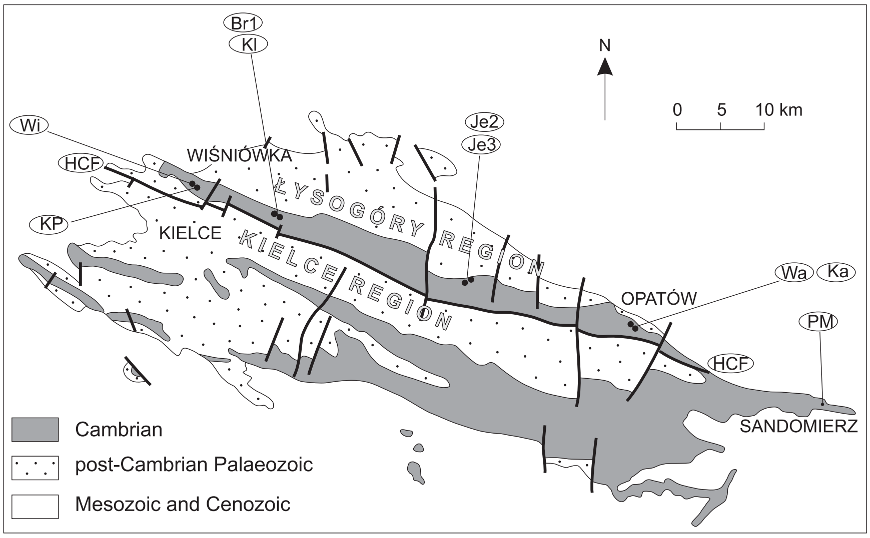

Fig. 2. Location of outcrop and borehole sections studied in the Łysogóry region, Holy Cross Mts.

HCF — Holy Cross Fault; outcrops: KP — Kamecznica Podmąchocicka, Wi — Wiśniówka, Kl — Klonówka, Wa — Wąworków, Ka — Karwów, PM — Pieprzowe Mts., boreholes: Br1 — Brzezinki IG 1, Je2 — Jeleniów IG 2, Je3 — Jeleniów IG 3

pean Craton (Baltica) (Valverde-Vaquero *et al*., 1999). Therefore, results of geochronologic studies on detrital muscovites and zircons prove neither the Gondwana provenance of the Łysogóry Unit nor its origin as an allochthonous terrane. Some authors claimed that the Cambrian fauna of the Łysogóry Unit reflects a Gondwana rather than a Baltica affiliation (Belka *et al*., 2000; Valverde-Vaquero *et al*., 2000). There is no doubt that the lower part of the Late Cambrian deposits of the Łysogóry Unit contains mostly Avalonian (peri-Gondwanan) trilobites. However, this does not belie the fact that Late Cambrian trilobite assemblages are dominated by a Baltica-type fauna, and that the Late Cambrian biozonation of the Łysogóry region is identical with that of the Baltica palaeobiogeographical province (Żylińska, 2002). Palaeomagnetic investigations lead to divergent opinions on the timing and direction of strike-slip movements of the supposed terranes contained in the Caledonian suture zone of Poland and failed to explain the position of the Łysogóry Unit during the Cambrian (Lewandowski, 1993; Nawrocki, 2000). This is not surprising as there are divergent opinions on the Cambrian position of Baltica (East European Craton) with respect to Gondwana (Torsvik and Rehnström, 2001; Popov *et al*., 2002; *cf*. Nawrocki, 2003; Nawrocki and Poprawa, 2006).

The results of previous research on the Cambrian siliciclastic association, including isotopic age determination of detrital grains, palaeobiogeography and palaeomagnetic studies, have provided no evidence supporting an unambiguous determination of the geotectonic position of the Łysogóry Unit and its relation with the East European Craton. This paper aims at shedding some light on this problem based on sedimentological data.

DATA

ŁYSOGÓRY UNIT

In the Łysogóry Unit, the Cambrian clastic succession shows considerable lateral facies changes. Based on lithostratigraphic criteria, the following formations are recognized that are discussed in detail below (Fig. 3).

PIEPRZOWE MTS. FORMATION

The Pieprzowe Mts. Shale Formation, which was defined by Orłowski (1975), deserves special attention as it appears to occur on both sides of the Holy Cross Fault in the Łysogóry Unit and Małopolska Massif (Fig. 1). According to Szczepanik (2001), thermal alteration of acritarchs from the

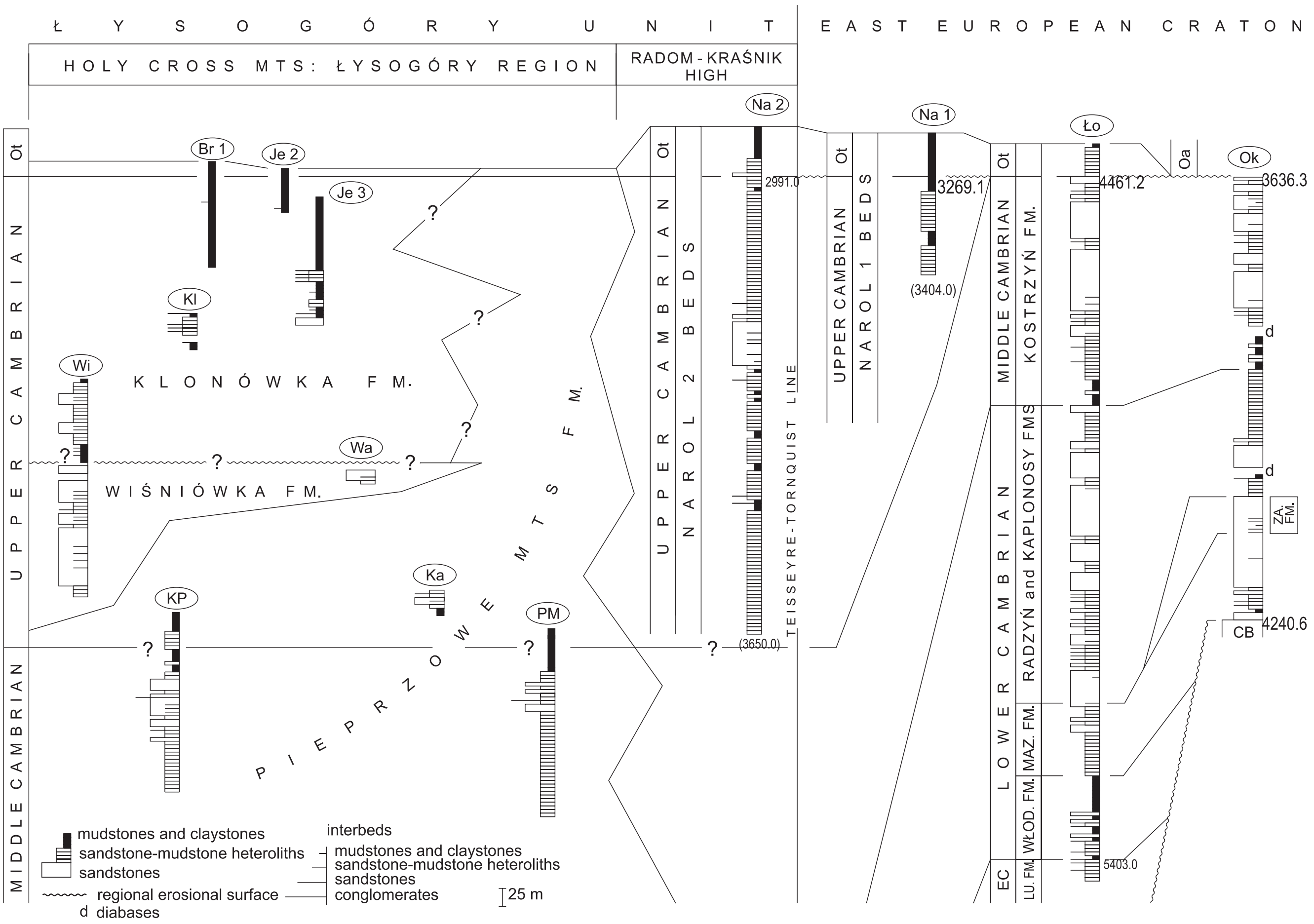

Fig. 3. Correlation of the sections studied

CB — crystalline basement of the East European Craton, EC — Ediacaran, Ot — Ordovician (Tremadocian), Oa — Ordovician (Arenigian), LU. FM. — Lublin Formation, WŁOD. FM. — Włodawa Formation, MAZ. FM. — Mazowsze Formation, ZA. FM. — Zawiszyn Formation; remaining abbreviations as in Figures 1 and 2

Pieprzowe Mts. Fm. suggests that this formation and its stratotype area (i.e. Pieprzowe Mts.) should be referred to the Łysogóry Unit. The total thickness of the Pieprzowe Mts. Fm. was estimated at 400 m (Orłowski, 1975, 1992, 1997; Orłowski and Mizerski, 1995), though some authors claim that it may be 600 m or even twice as thick (Kowalczewski, 1990; Kowalczewski and Lendzion, 1996). The main reason for these differences are difficulties in a reliable identification of the formation boundaries and the complicated tectonic structure of the Holy Cross Mts. Orłowski (1975, 1992, 1997) attributed the Pieprzowe Mts. Fm. to the Middle Cambrian. However, according to Kowalczewski (1995, 2000), it may extend from the Early Cambrian into the early Tremadocian. This formation contains indeed Middle and Late Cambrian and early Tremadocian acritarch assemblages (Szczepanik, 2001; Żylińska and Szczepanik, 2002).

The Pieprzowe Mts. Fm. consists of mudstones, claystones and sandstone-mudstone heteroliths, in places alternating with sandstones (Fig. 3). Przewłocki (2000) gave a sedimentological description of these deposits. Sandstone-mudstone heteroliths show lower flow regime horizontal laminations, lenticular, wavy and flaser bedding and small-scale cross bedding. Sandstone beds exhibit upper flow regime horizontal lamination, hummocky cross-stratification, convolute bedding and graded bedding (*cf.* Bielikowski, 1960). Erosional channels can be observed in some of outcrops. The top surfaces of sandstones are usually distinct and marked by current ripple marks. Sole surfaces reveal current marks, mainly tool marks. These are, among others prod marks that occasionally suggest bipolar flow directions (Jaworowski, 2001). Load casts, synaeresis cracks, crawling traces of trilobites (*Cruziana*) and feeding burrows were also observed. The Pieprzowe Mts. Fm. also contains conglomerates such as the Komorna Conglomerate Bed in the vicinity of Sandomierz (Samsonowicz, 1920; Orłowski, 1975; Kowalczewski, 1995) that was deposited by a dense turbidity current representing a transformed debris flow (Jaworowski, 2001). Other conglomerate beds of the Pieprzowe Mts. Fm. were deposited by debris-and-grain flows (Jaworowski, 2001).

Przewłocki (2000) interpreted the Pieprzowe Mts. Fm. as a shelf deposit that accumulated between the fairweather and storm wave base and/or below the storm wave base. Transport direction analyses indicates that the shoreline of the basin was located somewhere to the NE of the outcrops and extended in a NW–SE direction. It should be noted, that according to

Przewłocki (2000), the deposits of the Pieprzowe Mts. Fm. are "genetically related" to rocks occurring on the Polish part of the East European Craton. In our views, the sandstones represent shelf sands that are associated with tidal sand ridges and/or tidal sand waves, as well as with storm layers and the fills of storm-cut channels (Fig. 4). The heteroliths are composed of alternating thin storm sand layers and mudstones and claystones that were deposited from suspension. The heteroliths were deposited in the transition zone between shelf sands and shelf muds. The latter are represented by mudstones and claystones. This interpretation is not contradicted by the occurrence of conglomerate beds that were deposited by debris flows transformed into dense turbidity currents, which spread over a very gently sloping sea-floor.

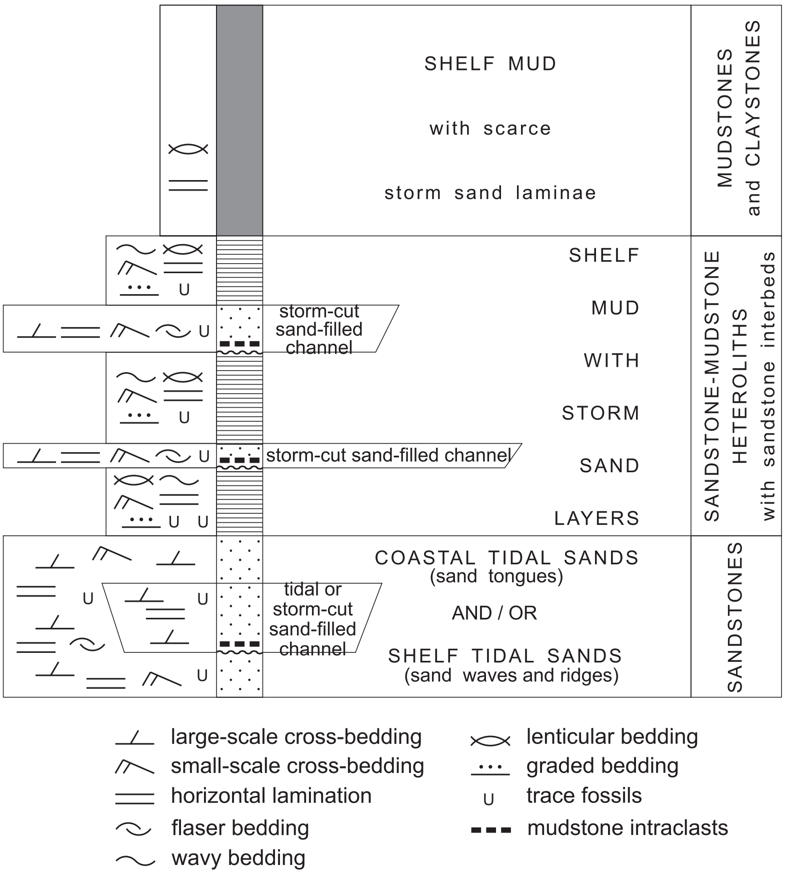

Fig. 4. Facies model for Cambrian sediments of the East European Craton and Łysogóry Unit (partly after Jaworowski, 1997, modified)

WIŚNIÓWKA FORMATION

The Wiśniówka Sandstone Formation (Orłowski, 1975) conformably overlies the Pieprzowe Mts. Fm. and crops out in the Łysogóry region of the Holy Cross Mts. This formation consists of the lower Łysogóry Quartzites (Czarnocki, 1950) and the upper Wąworków Sandstones (*sensu* Kowalczewski, 1995, 2000). In quarries near Wiśniówka (Figs. 2 and 3), the Łysogóry Quartzites are separated from the overlying Klonówka Formation (Orłowski, 1975) by a tectonic breccia (Studencki, 1994). Assuming a complex thrust-and-fold structure for the Łysogóry region, the thickness of the Łysogóry Quartzites is estimated at 80–200 m (Kowalczewski *et al*., 1986), whereas the thickness of the Wąworków Sandstones is about 300 m (Kowalczewski and Lendzion, 1996). Assuming a monoclinal structure for this region, the thickness of the whole Wiśniówka Fm. is estimated at 1400 m (Mizerski, 1979; Orłowski and Mizerski, 1995). According to Orłowski (1992, 1997), the Wiśniówka Fm. represents the uppermost Middle Cambrian and lowermost Late Cambrian. Kowalczewski (1995, 1997) claimed that the Łysogóry Quartzites represent both the Middle and Late Cambrian, whereas the Wąworków Sandstones as a whole should be attributed to the Late Cambrian. Acritarch and trilobite-based studies conducted by Szczepanik (2002), Żylińska (2002) and Żylińska and Szczepanik (2002) indicate a Late Cambrian age for the entire Wiśniówka Fm.

The Łysogóry Quartzites consist of quartzites and quartzitic sandstones (Sikorska, 2000), commonly fine-grained but also medium-, coarse- or vari-grained, that contain interbeds of sandstone-mudstone heteroliths. The bed thickness of sandstones is variable. Thinly and medium bedded sandstones commonly exhibit small-scale cross bedding and upper flow regime horizontal lamination showing primary current lineation (Dżułyński and Żak, 1960). The dominant thick-bedded sandstones (generally *ca*. 1 m thick, occasionally up to 3 m thick) are usually structureless but contain concentrations of horizontally oriented mudstone intraclasts. Hummocky cross-stratification was observed in some sandstone beds (Studencki, 1994). Interbeds of heteroliths show lenticular and small-scale cross bedding. Ripple marks are frequent on top surfaces of the sandstone beds (Radwański and Roniewicz, 1960). Irregular crests interpreted as antidunes (Dżułyński and Żak, 1960) were observed on top surfaces of thick beds. Some of the sandstone beds are disturbed by slumps. A characteristic feature of the Łysogóry Quartzites is the presence of large-scale wash-outs and erosional channels (Dżułyński and Żak, 1960; Studencki, 1994). Graded bedding (Radwański and Roniewicz, 1960; Bielikowski, 1960), locally inverse (Orłowski, 1968), was also observed in the Wiśniówka Fm., especially in heterolithic interbeds. Current marks — predominantly tool marks (groove and prod marks) — are found on the sole surface of sandstone beds. Synaeresis cracks and gas bubble impressions (Radwański and Roniewicz, 1960), as well as problematic raindrop impressions (Orłowski, 1968), are also worth mentioning. Trace fossils, represented mainly by crawling and resting traces of trilobites and occasionally other organisms are very abundant. Dwelling burrows, e.g. of *Bergaueria* (Radwański and Roniewicz, 1963), and feeding burrows resembling *Paleodictyon* (Orłowski, 1968) are also present, however, they are scarce.

There is general agreement that the Łysogóry Quartzites, which crop out near Wiśniówka, were deposited in a shallow-marine environment, with Dżułyński and Żak (1960) estimating water depths being in the range of several to a dozen or so metres, while Radwański and Roniewicz (1960) suggest water depth between ten to a few tens of metres. Although Dżułyński and Żak (1960) postulated for the Łysogóry Quartzites a very shallow-water environment, they clearly negated a beach environment. According to those authors, the Łysogóry Quartzites represent deposits of strong tidal and storm currents, i.e. tidalites and tempestites. This interpretation is not at odds with the occurrence of slumps, which, according to Dżułyński and Żak (1960), developed in response to spontaneous liquefaction of rapidly deposited, loosely packed sands that spread over an almost flat sea-floor. Current directions observed in the Łysogóry Quartzites from Wiśniówka are very variable, with S→N and SW→NE directions being the dominant ones. Correspondingly Dżułyński and Żak (1960) concluded that the source area of these Cambrian clastics was located somewhere to the south of their present outcrops in the Łysogóry Unit.

Czarnocki (1927, 1950) and Samsonowicz (1920, 1956) suggested that the Holy Cross Cambrian deposits represent flysch or flysch-like sediments. Czermiński (1959) and Malec (2003) also pointed out the similarity between the Wiśniówka deposits and flysch. Nevertheless, Dżułyński and Żak (1960) and Radwański and Roniewicz (1960) clearly established that the Wiśniówka Fm. is not a flysch succession.

To summarize, the Łysogóry Quartzites consist of shelf sands deposited as tidal sand ridges and/or tidal sand waves affected by storms (Fig. 4). The presence of *Bergaueria* dwelling burrows indicates an inundated shoal, located below ebb-tide level. Problematic raindrop impressions may point to periods of emergence. Most of the depositional structures developed as a result of abrupt depositional events. Sandstone-mudstone heteroliths represent a transitional environment to shelf muds. In heteroliths, sandstone intercalations displaying graded bedding represent storm layers. The thus defined sedimentary environment of the Łysogóry Quartzites correspond to the general facies model (option II) developed by Jaworowski (1997) for the Early and Middle Cambrian sandstones of the marginal zone of the East European Craton. The Łysogóry Quartzites are the rocks from which Belka *et al.* (1997, 2000) and Valverde-Vaquero *et al.* (2000) had collected samples to determine the age of detrital muscovite and zircon.

The Wąworków Sandstones, forming the upper part of the Wiśniówka Fm. (Kowalczewski, 1995, 2000; Kowalczewski and Lendzion, 1996), consist of vari-coloured, frequently red, quartzitic sandstones with abundant iron compounds, alternating with variegated mud- and claystones and with sandstone-mudstone heteroliths containing interbeds of pyroclastic rocks (Kowalczewski *et al.*, 1976; Chlebowski 1978). According to Radwański and Roniewicz (1962), these deposits accumulated in an environment identical to that of the Łysogóry Quartzites from Wiśniówka. These authors underlined that, despite previous interpretations by Samsonowicz (1920, 1956), the Wąworków Sandstones are neither beach nor near-shore deposits. In the basal part of sandstones, quartz gravel concentrations and conglomerates up to 20 cm thick, occur as beds or lenses, filling erosional furrows (Orłowski, 1968). As in the case of the Łysogóry Quartzites, these represent storm-cut channel fills. Similar to the Łysogóry Quartzites, the clastic material of the Wąworków Sandstones, was derived from southern sources. We interpret the Wąworków Sandstones, just as the Łysogóry Quartzites, as shelf sands (tidal sand ridges and/or tidal sand waves) with interbeds of heteroliths characteristic for a transitional environment to shelf muds (Fig. 4).

KLONÓWKA FORMATION

The Klonówka Shale Formation, established by Orłowski (1975), occurs in the Łysogóry region of the Holy Cross Mts. above the Wiśniówka Fm. (Figs. 2 and 3). The lower part of the Klonówka Fm. is best exposed in the Wiśniówka Duża quarry where it is separated from the Łysogóry Quartzites of the Wiśniówka Fm. by a fault zone marked by a tectonic breccia, a dozen or so metres thick (Studencki, 1994). The middle part of the Klonówka Fm. is well known from outcrops located to the ESE of the Wiśniówka area (Figs. 2 and 3), whilst its upper parts are only known from boreholes described in the classical work of Tomczykowa (1968). Orłowski (1975, 1992, 1997) estimated the maximum thickness of the Klonówka Fm. at 400 m. Orłowski (1975, 1997) attributed the Klonówka Formation to the latest Late Cambrian and early Tremadocian. This is compatible with the interpretations by Tomczykowa (1968) and Kowalczewski (1995) and has been confirmed by the results of recent investigations on Late Cambrian trilobites and acritarchs from the Holy Cross Mts. (Żylińska, 2002; Żylińska and Szczepanik, 2002).

The lower part of the Klonówka Fm. consists of sandstone-mudstone heteroliths with sandstones intercalations formed by thin quartzitic sandstones, ferruginous sandstones and wackes (Czarnocki, 1927; Tomczykowa, 1968; Orłowski, 1968; Kowalczewski, 2000). In its upper parts, the number of sandstone intercalations decreases: heteroliths pass upward into mud- and claystones. Orłowski (1975) emphasised the reddish colouration of the heteroliths of the Klonówka Fm. Sedimentological logs compiled for this formation in the Wiśniówka area (Studencki, 1994) show that it is composed mainly of sandstone-mudstone heteroliths with interbeds of sandstones, mudstones and claystones. The heteroliths exhibit lenticular bedding and small-scale cross bedding. Sandstone interbeds show trace fossils represented by dwelling and feeding burrows as well as by resting traces of trilobites. Orłowski (1975) established in the Klonówka Fm. a formal lithostratigraphic unit, referred to as the Chabowe Doły Sandstone Bed. This unit consists of a fine-grained sandstone layer occurring as lens (up to 60 cm thick) that contains abundant fossils, mostly trilobite fragments.

All available data (Czarnocki, 1927; Tomczykowa, 1968; Orłowski, 1968, 1975; Studencki, 1994; Kowalczewski, 2000; Żylińska, 2002) indicate that the Klonówka Fm. is a shelf deposit. Heteroliths of this formation accumulated in the transition zone from shelf sands to shelf muds, with the latter being formed by mudstones and claystones (Fig. 4). Sandstone interbeds in heteroliths represent storm layers and in part the fill of storm-cut channels. According to the interpretation presented here, the Chabowe Doły Sandstone Bed is the fill of a large storm-cut cross-shelf channel that was incised into mud-clay deposits (*cf.* Duke *et al.*, 1991). This is compatible with its content of mixed trilobite fragments typical for two different subzones (Żylińska, 2002; Żylińska and Szczepanik, 2002).

There is a striking similarity in the lithology and depositional environment of the Klonówka and Pieprzowe Mts. formations. The Klonówka Fm. represents, however, a shelf environment more distant from the shoreline than Pieprzowe Mts. Fm. and lacks tidal sand ridges and tidal sand waves. It is difficult to identify the location of source areas that supplied clastics to the Klonówka Fm. As according to our interpretation it interfingers with the Pieprzowe Mts. and the Wiśniówka formations (Fig. 3), clastic transport directions were presumably NE→SW and S/SW→N/NE.

Near Wiśniówka, the contact between the Wiśniówka and Klonówka formations is tectonically strongly disturbed. Although no sections have as yet been found to establish depositional continuity between these formations, it is likely that an erosional gap occurs between them in the western part of the Łysogóry region (Fig. 3).

NAROL 2 BEDS

These beds are represented by the Late Cambrian to early Tremadocian sediments that were penetrated by the Narol PIG 2 borehole, drilled in south-east Poland, SW of the Kazimierz Fault, in the extreme peripheral, southeastern part of the Łysogóry Unit (Fig. 1). The name “Narol 2 Beds” is tentative and has been introduced for purpose of this report. These deposits occur at depths between 2991 and 3650 m. Their real thickness (Fig. 3) is about 630 m (after correction for stratal dips ranging from 10 to 15°). The Narol 2 Beds (Fig. 3) represent almost the whole Late Cambrian succession from the *Homagnostus obesus* Zone upwards (Lendzion 1992/93, written com.) and grade into Tremadocian deposits documented by graptolitic faunas (Modliński, 1992, written com.). In other words, the Narol 2 Beds are age equivalent to the Klonówka and Wiśniówka formations, as well as probably to the upper part of the Pieprzowe Mts. Fm. Szczepanik (2002) stressed the identity of acritarch assemblages from the Wiśniówka Fm. and those found in the Narol 2 Beds.

The Narol 2 Beds mainly consist of sandstone-mudstone heteroliths, mudstones and claystones (Fig. 3). Medium- and locally thick-bedded fine-grained quartzitic sandstones, occurring in the middle portion of the drilled section, are subordinate. The heteroliths show lenticular, wavy and flaser bedding, small-scale cross bedding, low angle and horizontal laminations, and graded bedding. The latter was noted in thin sandstone beds with sharply marked sole and top surfaces. Concentrations of mudstone intraclasts are frequent in thin sandstone interbeds. Current marks (mostly groove marks) or load casts were observed on sole surfaces of sandstone beds. Trace fossils, mainly feeding burrows and escape burrows, are also quite common. Feeding burrows were encountered in mudstones and claystones. In drill cores a large slump, about 40 m thick, was found in heteroliths of the upper portion of the Narol 2 Beds. A further slump, a dozen or so metres thick, is evident in heteroliths from the lower part of the Narol 2 Beds. The medium- and thick-bedded sandstones show horizontal lamination, small-scale cross bedding and low angle lamination. Amalgamation of beds is locally visible. Concentrations of mudstone intraclasts are frequent. In sandstones rare feeding burrows are the only trace fossils.

The Narol 2 Beds were deposited in a marine environment on a shelf influenced by tides and storms. The presence of benthic fauna, escape burrows and the probable occurrence of hummocky cross-stratification are indicative of a shallow-water environment between fair-weather and storm wave base. Identification of hummocky cross-stratification, presumably represented by structures here referred to as low angle laminations, is however hampered by the small diameter of the drill cores. Sandstones, subordinate in the Narol 2 Beds, represent shelf sands deposited in the form of tidal ridges and/or sand waves influenced by storms. Heteroliths, the dominant element of the Narol 2 Beds, represent mostly storm deposits (storm sand layers, fill of storm-cut channels). Mud- and claystones correspond to shelf muds deposited basin-ward from the tidal sands and the heteroliths (Fig. 4). The Narol 2 Beds represent the same sedimentary environment as the Late Cambrian and early Tremadocian deposits of the Łysogóry region of the Holy Cross Mts. The clear dominance of heteroliths suggests that the Narol 2 Beds ought to be considered as facies equivalents of the Klonówka Fm. and/or the Pieprzowe Mts. Fm. Although it is difficult to determine the transport direction of the Narol 2 Bed clastics, it is likely that they were derived from northeastern sources, as is the case for the Pieprzowe Mts. Fm.

EAST EUROPEAN CRATON

Cambrian deposits on the East European Craton of southeast Poland are known only from borehole sections. In order to compare these with those of the Łysogóry Unit, the boreholes Narol IG 1, Łopiennik IG 1 and Okuniew IG 1 were investigated (Figs. 1 and 3). The Narol IG 1 borehole is located on the very margin of the East European Craton adjacent to the Kazimierz Fault and at a distance of 10 km from the Narol IG 2 well. The Łopiennik IG 1 and Okuniew IG 1 borehole sections were chosen because they were exactly those from which Belka *et al*. (1997, 2000) and Valverde-Vaquero *et al*. (2000) collected samples for K-Ar age dating of detrital muscovite and U-Pb dating of detrital zircon (see introduction). All Cambrian lithostratigraphic units distinguished on the East European Craton of SE Poland (Lendzion, 1983; Mens *et al*., 1990; Lendzion and Jankauskas, 1994) consist of alternating quartzitic sandstones, sandstone-mudstone heteroliths, as well as of mudstones and claystones. However, they differ in the proportion of these deposits.

NAROL 1 BEDS

The Narol IG 1 borehole penetrated the Late Cambrian and early Tremadocian Narol 1 Beds (Figs. 1 and 3). According to Lendzion (1988), their Cambrian part occurs in the depth interval of 3269.1 to 3404 m and includes the Late Cambrian *Parabolina spinulosa–Acerocare* zones, with a gap comprising the *Leptoblastus–Peltura minor* zones. An erosional surface separates the Cambrian deposits from the overlying Tremadocian claystones and mudstones that contain graptolites. The presence of this erosional hiatus differentiates the Narol 1 Beds from the Narol 2 Beds in which this gap is not observed. The Narol 1 Beds consist of claystones, mudstones and sandstone-mudstone heteroliths that are identical to those observed in the Narol 2 Beds, apart from the lack of slumps. Similar to the Narol 2 Beds, the Narol 1 Beds were deposited in a marine shelf environment that was influenced by tides and storms (Fig. 4). Clastics were probably transported in a NE→SW direction, as in the case of the Narol 2 Beds.

WŁODAWA FORMATION

The Włodawa Formation, that corresponds to the Włodawa Subformation of Mens *et al*. (1990) who consider it as the lower part of the Mazowsze Formation (see below), occurs in the Łopiennik IG 1 borehole in the depth interval of 5294.0–5403.0 m (Fig. 3). It consists of mudstones and claystones and sandstone-mudstone heteroliths with sandstone interbeds, and contains small phosphatic concretions and feldspar grains. In south-east Poland, its maximum thickness is in excess of 100 m. According to Mens *et al*. (1990), the Włodawa Fm. embraces the *Sabellidites cambriensis–Platysolenites antiquissimus* zones of the earliest Cambrian. As deposits containing *Sabellidites* are Ediacaran in age (*cf.* Moczydłowska and Vidal, 1986), this formation straddles the Ediacaran/Cambrian boundary. At its base, the Włodawa Fm. grades without interruption into the irregularly laminated heteroliths of the Lublin Fm. that contains a Late Ediacaran *Vendotaenia* flora.

MAZOWSZE FORMATION

This formation occurs in the Łopiennik IG 1 borehole at depths between 5192.0–5294.0 m, and in the Okuniew IG 1 borehole at depths between 4125.6–4240.6 m. It consists of sandstones containing glauconite and phosphatic concretions and sandstone-mudstone heteroliths. In the Łopiennik IG 1 section the Mazowsze Fm. consists mainly of heteroliths, whereas in the Okuniew IG 1 section sandstones dominate particularly in its upper parts. The Mazowsze Fm. conformably overlies the Włodawa Fm. in the Łopiennik IG 1 section, but rests in Okuniew IG 1 on the Lower Proterozoic crystalline basement of the East European Craton. The Mazowsze Fm. attains a maximum thickness of 160 m and spans according to Mens *et al*. (1990) mainly the Early Cambrian *Platysolenites antiquissimus* Zone.

ZAWISZYN FORMATION

This formation occurs in the Okuniew IG 1 borehole at the depths between 4077.8–4125.6 m. It consists of 50 m of glauconitic sandstones with rare interbeds of sandstone-mudstone heteroliths, mudstones and claystones. Its absence in the Łopiennik IG 1 section is attributed to lateral facies changes, rather than to an erosional hiatus (Jaworowski, 1978; Moczydłowska and Vidal, 1986). The contact between the Zawiszyn Fm. and the overlying and underlying deposits is gradational. According to Mens *et al*. (1990), the Zawiszyn Fm. spans the Early Cambrian *Mobergella* and *Schmidtiellus mickwitzi* Zone.

KAPLONOSY AND RADZYŃ FORMATIONS

These formations, which occur in the Łopiennik IG 1 borehole in the depth interval of 4778.0–5192.0 m, and in the Okuniew IG 1 borehole in the depth interval of 3894.0–4077.8 m, consist of alternating sandstones and sandstone-mudstone heteroliths. As in both borehole sections the transition between the Kaplonosy and Radzyń formations is very gradual their common boundary can hardly be defined. Data presented by Mens *et al*. (1990) indicate that the Kaplonosy Fm. includes variegated sandstones and interbeds of reddish-brown heteroliths, whereas the sandstones of the Radzyń Fm. contain glauconite and rare phosphatic concretions. The combined Kaplonosy and Radzyń formations attain a maximum thickness of about 500 m, and span, according to Mens *et al*. (1990) the upper and top-most parts of the Early Cambrian, commencing at the *Holmia* Zone.

KOSTRZYŃ FORMATION

In the Łopiennik IG 1 borehole the Kostrzyń Fm. occupies the depth interval of 4461.2–4778.0 m and in the Okuniew IG 1 borehole the depth interval of 3636.6–3894.0 m. This formation is composed mainly of sandstones with intercalations of sandstone-mudstone heteroliths that, along with mudstones and claystones, predominate in its upper parts. In the Łopiennik IG 1 and Okuniew IG 1 borehole sections, a distinct erosional hiatus occurs between the top of the Kostrzyń Fm. and the overlying Ordovician deposits. The age of the latter is Tremadocian in the Łopiennik IG 1 section, and Arenigian in the Okuniew IG 1 section. The Kostrzyń Fm. attains maximum thicknesses of about 250 m, and spans, according to Mens *et al.* (1990), the Middle Cambrian *Baltoparadoxides oelandicus* Zone. Samples taken by Belka *et al*. (2000) for the age determination of detrital muscovite in Cambrian sediments of the East European Craton come from the Kostrzyń Fm. of the Łopiennik IG 1 and Okuniew IG 1 sections. The samples collected by Valverde-Vaquero *et al.* (2000) for age determination of detrital zircon come from the Kostrzyń Formation of the Okuniew IG 1 section.

DEPOSITIONAL ENVIRONMENT

The quartzitic sandstones of all Cambrian formations of the Polish part of the East European Craton are commonly fine-grained and only rarely medium- and coarse-grained. Very coarse-grained sandstones were found only in the lower part of the Mazowsze Fm. of the Okuniew IG 1 section. The sandstones show sedimentary structures such as small- and large-scale cross bedding, low-angle laminations, upper and lower flow regime horizontal laminations. Thick concentrations of mudstone intraclasts are common, with some of them being undoubtedly related to amalgamation of sandstone beds. Cross bedding is locally of the herringbone type. Trace fossils include mostly feeding and dwelling burrows, with the latter occurring particularly, but not exclusively in coarse-grained sandstones.

The sandstone-mudstone heteroliths of all the formations display lenticular, wavy and flaser bedding, horizontal lamination, small-scale cross bedding, graded bedding, synaeresis cracks and small slumps. The dominant trace fossils are feeding burrows. Dwelling burrows are rare. The original structure of heteroliths is commonly disturbed by complete bioturbation. The mudstones and claystones contain infrequent thin lenses and laminae of fine-grained sandstones.

The Cambrian successions of the Polish part of the East European Craton have since long been interpreted as having been deposited in a shallow marine environment on a shelf influenced by tides and storms (Jaworowski, 1978, 1982, 1997). The Cambrian sandstones were interpreted as representing (1) coastal tidal sands developed as sand tongues (shoals) and (2) shelf sands deposited as tidal sand ridges and fills of storm-cut channels eroded into muds and clays. In our views, these interpretations require modification in so far as the Cambrian shelf sands were probably deposited not only as tidal sand ridges but also as tidal sand waves (Fig. 4). Heteroliths were deposited in transitional areas between tidal coastal sands or tidal shelf sands to shelf muds and clays and show repeated reworking during storms. The Cambrian clastics of the East European Craton were derived from its emerging areas, as evidenced, among others, by petrographic investigations (Sikorska, 1998). Clastic material found in the Łopiennik IG 1 and Okuniew IG 1 sections was transported in a NE→SW direction (Jaworowski, 1982, 1997).

DISCUSSION

The Middle and Late Cambrian deposits of the Łysogóry Unit, as well as the Early and Middle Cambrian deposits of the East European Craton represent a siliciclastic association that was deposited on a vast shelf influenced by tides and storms. This association includes three main facies, namely (1) quartzitic sandstones, (2) sandstone-mudstone heteroliths and (3) mudstones and claystones. Pre-Arenigian erosion removed the Late Cambrian and Tremadocian deposits on the Polish part of the East European Craton. These deposits are only preserved along the margin of this craton immediately to the NE of the Łysogóry Unit, as evidenced by the Narol 1 Beds.

Sedimentary conditions of the Cambrian deposits of the Łysogóry Unit and of the East European Craton can be characterized by one and the same facies model (Fig. 4). Sedimentological and lithological affinities between the Cambrian deposits of the Łysogóry Unit and the East European Craton support the concepts of Dadlez *et al.* (1994) and Kowalczewski (2000) according to which a vast Early Palaeozoic sedimentary prism developed on the passive margin of Baltica. The passive nature of the continental Polish Baltica margin on which these Cambrian sediments were deposited was confirmed by geochemical studies (Przewłocki, 2000; Jaworowski and Sikorska, 2005). The Cambrian (and partly Ordovician) development of this passive continental margin is confirmed by quantitative subsidence analysis on the Lublin–Podlasie Slope of the East European Craton (Poprawa and Pacześna, 2002).

The Cambrian succession of the Kielce region is not dealt with in this paper. Nevertheless, it appears that in the Kielce region Cambrian depositional conditions were identical with those attributed to the Łysogóry Unit. This suggestion is based on the present authors' own fragmentary observations and on a literature study (*cf.* Studencki, 1988; Mizerski *et al.*, 1999; Kowalczewski, 2000; Orłowski and Żylińska, 2002). In our views, the Cambrian deposits of the Kielce region of the Holy Cross Mts., i.e. from the NE part of the Małopolska Massif, accumulated in a distal part of the passive Baltica margin, the proximal part of which corresponded to the Łysogóry Unit. This interpretation is compatible with the concept that all of the Early Palaeozoic sediments of the Holy Cross Mts. were deposited on a "labile platform" (Szulczewski, 1977).

The conclusion that the Cambrian sediments of both the Łysogóry Unit and Małopolska Massif form part of the sedimentary prism that was deposited on the passive margin of the East European Craton (Baltica) finds justification in the presence of the Late Cambrian siliciclastic association in the Kielce region (Kowalczewski, 2000; Szczepanik *et al.*, 2004). In this respect, the Cambrian palaeogeographic maps of the Holy Cross Mts. given by Kowalczewski (2000) are of great importance. These maps show relatively narrow zones of sand deposition and intervening zones of sandstone-mudstone heteroliths and mudstones and claystones. These zones trend in a WNW–ESE direction that approximately parallels the Holy Cross Fault and the Teisseyre-Tornquist Line. According to our interpretation, these sand were deposited along and on the elevated crests of tilted fault blocks (Fig. 5) that formed part of the passive margin of the East European Craton. These blocks were controlled by large-scale listric normal faults, as seen on many modern rifted continental margins and in intra-continental rifts (e.g. Lister *et al.*, 1986; Osmundsen *et al.*, 2002). It is difficult to ascertain whether these faults dipped towards the craton, as in the case during the Ediacaran (Vendian)–Lower Cambrian sedimentation in Northern Poland (Jaworowski and Sikorska, 2003), or were dipping off the craton. We give preference to the latter possibility (Fig. 6), as it explains much better the significant thickness of the Narol 2 Beds. A transfer fault separating the northern and southern segments of the Polish part of the Baltica passive margin, characterized by opposite dipping detachment surfaces, may coincide with the deep-rooted present-day Grójec Fault (Figs. 1 and 6).

In general, the clastics of the Cambrian siliciclastic association of the Łysogóry Unit transported from NE were derived from the East European Craton. The elevated crests of tilted intra-basinal blocks of the passive margin acted as local clastic sources. Material derived from these crests may have been transported both in NE→SW and S/SW→N/NE directions.

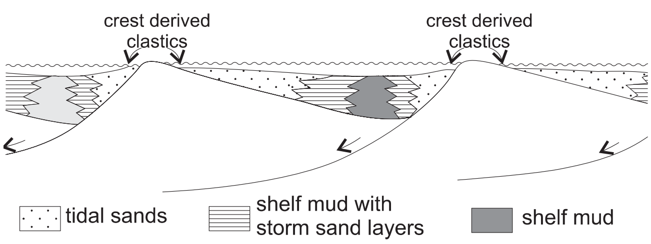

Fig. 5. A model for Cambrian sedimentation in the Holy Cross Mts.: shallow-water siliciclastic association in a tilted block regime

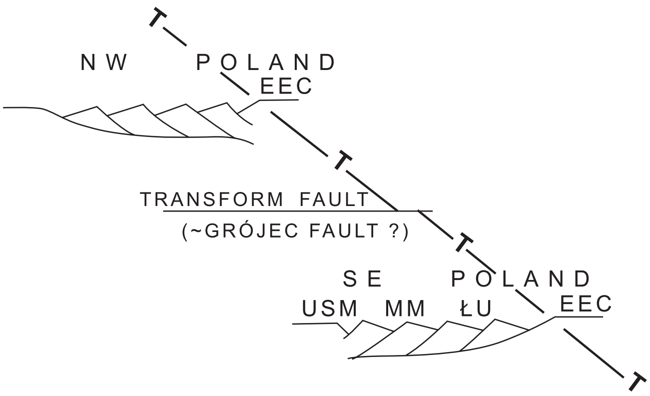

Fig. 6. Conceptual model for extensional detachment faulting along the Polish segment of the rifted passive Baltica margin (not to scale)

EEC — East European Craton, T-T — Teisseyre-Tornquist Line, USM — Upper Silesia Massif, MM — Małopolska Massif, ŁU — Łysogóry Unit

This interpretation explains the duality of transport directions of clastics, inferred from sedimentological data (Fig. 5). Moreover, the crests of these tilted tectonic blocks were areas of syn-sedimentary erosion. This process may have led to the development of the stratigraphic gap between the Wiśniówka and Klonówka formations in the western part of the Łysogóry region (Fig. 3), and of the gaps known from the Cambrian succession of the Kielce region.

The results of our study indirectly confirm the notion of Nawrocki (2003) that claims that the Małopolska Massif was not derived from Gondwana. Analyses of sedimentological data presented here require neither an allochthonous origin for the Łysogóry Unit and the Małopolska Massif, nor that they were translated over substantial distances along the margin of Baltica. They rather suggest that both the Łysogóry Unit and Małopolska Massif form integral parts of Baltica (East European Craton) and that they occupied approximately their present position already long before the Cambrian. In other words, we suggest that the Łysogóry Unit and Małopolska Block were not detached from Baltica during the breakup of the Precambrian Rodinia supercontinent, although they represent major fault blocks of the rifted Baltica margin. This notion is close to Żelaźniewicz's concept (1998) according to which the Małopolska Massif took in its present-day position at the SW margin of Baltica already during its Cadomian (and earlier) evolution. Our interpretation is consistent with the results of the CELEBRATION 2000 seismic experiment profile CEL02 (Malinowski *et al*., 2005).

Development of rifted passive margin, involving asymmetric simple-shear extension of the continental lithosphere (Ziegler and Cloetingh, 2004), can explain the extremely complicated structural style and architecture of the Palaeozoic succession of the Holy Cross Mts. (Znosko, 1962, 1984, 1996, 2001; Kowalczewski and Rubinowski in Żak, 1962; Kowalczewski *et al.*, 1986; Stupnicka, 1992; Pożaryski and Tomczyk, 1993; Mizerski, 1995, 2004; Kowalczewski, 2000; Bednarczyk and Stupnicka, 2000). Activity along listric normal faults in response to on going stretching of the continental crust can result in strong gravitational displacement of crustal blocks (*cf.* Wernicke, 1981). In the Holy Cross Mts., the Cambrian phases of Caledonian deformation can be explained by the rotational displacement of crustal blocks along large-scale listric normal faults dipping off the craton.

CONCLUSIONS

1. The Middle and Late Cambrian deposits of the Łysogóry Unit and the Early and Middle Cambrian deposits of the East European Craton form part of a siliciclastic passive margin prism that developed on a vast shelf influenced by tides and storms.

2. The Łysogóry Unit corresponds to the proximal part of the Cambrian passive margin of the East European Craton (Baltica), the distal part of which includes the Cambrian deposits of the Kielce region of the Holy Cross Mts., corresponding to the NE part of the Małopolska Massif.

3. The Cambrian passive margin succession of Poland was supplied with clastics from NE sources located on the East European Craton, whilst the crests of major tilted fault blocks acted as secondary clastic sources.

4. The Cambrian palaeogeography of the Holy Cross Mts. was characterized by narrow zones of sand deposition that were separated by zones in which sandstone-mudstone heteroliths, mudstones and claystones prevailed. The zones of sand deposition corresponded to shoals on the elevated leading edges of tilted fault blocks that are carried by large-scale listric normal faults. These faults were active mainly during the break-up of the pre-Cambrian Rodinia supercontinent.

5. The listric normal faults of the Łysogóry Unit and the Małopolska Massif probably dipped off the craton, that is in the opposite direction than the craton-ward dipping faults that were active in Northern Poland during Ediacaran (Vendian)–Early Cambrian times. The transfer fault that separated the northern and southern segments of the Polish passive Baltica margin probably coincided with deep-seated present-day Grójec Fault.

6. Cambrian successions, based on sedimentological data and their facies and thickness development, appear to indicate that the Łysogóry Unit and Małopolska Massif were not detached from Baltica during the break-up of the Precambrian Rodinia supercontinent, but formed integral parts of the Baltic passive margin. This casts serious doubts on the applicability of the terrane concept to the Holy Cross Mts. It is proposed that neither the Łysogóry Unit nor the Małopolska Massif are allochthonous terranes and that they were not translated over considerable distances along the margin of the East European Craton (Baltica).

7. The Cambrian phases of Caledonian deformations in the Holy Cross Mts. may be related to rotational block movements along large-scale listric normal faults.

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