Holy Cross Mountains in the Caledonian, Variscan and Alpine cycles — major problems, open questions

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Abstract. Composite tectonic structure of the Holy Cross Mountains originated as a result of multiple tectonic movements dating from Cambrian till Quaternary. The movements had different intensity in the northern (Łysogóry Block and southern (Kielce Block) parts of the area. The Caledonian and Variscan movements formed the fault-block structure with prevalent WNW–ESE directions, while the Alpine movements — disrupted the older units with transpressive slip translocations along already existing longitudinal faults. All the deformations occurred within an anorogenic area — a sinking, fragmented margin of the East European Platform.

Key words: *tectonics, age of tectonics movements, geotectonic evolution, Holy Cross Mountains*

The views on the palaeogeographic position and geotectonic evolution, and on the internal structure of the Palaeozoic Holy Cross Mountains (HCM), situated at the margin of the East European Platform (EEP) (Fig. 1) are quite diverse (Bednarczyk & Stupnicka, 2000; Brochwicz-Lewiński et al., 1981; Dadlez, 2001; Dadlez et al., 1994; Jaworowski & Sikorska, 2004; Kowalczewski, 1981, 2000; Mastella & Mizerski, 2002; Mizerski, 1979, 1988, 1991, 1992, 1994, 1995, 1996, 1998; Pożaryski, 1990, 1991; Pożaryski & Tomczyk, 1993; Pożaryski et al., 1992; Stupnicka, 1992; Znosko, 1984, 1994, 1996, 2000). Also the palaeomagnetic interpretation of the Palaeozoic situation of the HCM area relative to the Baltica craton differ (Lewandowski, 1993, 1994; Nawrocki, 1992, 1995). This is largely due to relatively poor outcrops in the key areas from the tectonic point of view, especially in the northern part of the HCM region.

The HCM are very important in the explanation of geotectonic problems of central Europe, since they are only area where Palaeozoic structures adjoining the EEP crop out (Fig. 1). The almost sole presence of marine sediments has enabled good establishment of the stratigraphic position of Palaeozoic units of the HCM. Nonetheless, disputes are still going on with respect to the types, genesis and the age of tectonic deformations of Palaeozoic rocks, as well as the geotectonic position of this region both now and in the geological past. Often in these disputes, the same facts are mentioned, yet differently interpreted. Occasionally, minor details lead to global reconstructions which are inconsistent with other geological data.

The author, carrying out geological field investigations in the HCM for over 30 years, has made an attempt to present a synthetic overview of the tectonics of the Palaeozoic rocks forming them, based on data gathered by himself and pointing out to the equivocal nature of some observations that served as the basis for global reconstructions.

The author believes that the existing outcrops are of primary importance for solving problems regarding the HCM Palaeozoic and that the interpretation of structural style and tectonic evolution of the area must be consistent with observations in the outcrops and with the borehole data.

The HCM are situated on two crustal blocks (Guterch et al., 1976) — the Łysogóry–Radom (northern) and the Małopolska (southern) Massifs. Both blocks differ not only in their crust thickness, but also in their different age of Palaeozoic tectonic deformations. This is reflected in their structural subdivisions into structural stages and structural complexes.

Structural stages and structural complexes

Research on the HCM Palaeozoic, with history dating back to late 1800s, allow to discern two major structural stages in the Palaeozoic strata of the Łysogóry–Radom Block: the Variscan (including strata from the Middle Cambrian to the Upper Devonian) and Laramide (Permian). The Variscan stage, because of the gaps occurring in the profile can be divided into two or three structural complexes: Early Caledonian (Cadomian?), Late Caledonian and Variscan. Within the Małopolska Block, the angular discontinuities in the section allow to discern as many as four structural stages: Early Caledonian or Cadomian (Cambrian), Late Caledonian (Ordovician and Silurian), Variscan (Devonian–Lower Carboniferous) and Alpine (Permian) — Fig. 2. Caledonide movements were attributed an important role in the Łysogóry–Radom Block by some researchers (Dadlez et al., 1994; Johnston et al., 1994; Znosko, 1974, 1984, 1994; Znosko & Kowalczewski, 1981), but this view is opposed by the results of detailed structural studies (Jurewicz & Mizerski, 1987; Mizerski, 1995, 1996, 1998).

Structural evolution of the HCM area proceeded differently in both blocks until the Carboniferous, when the tectonic movements of the main phase of the Variscan orogeny (Sudetian? Erzgebirge phase?) occurred.

Łysogóry–Radom block

Early Caledonian (Cadomian?) Complex. Early Caledonian (Cadomian?) complex includes rocks of the Middle and Upper Cambrian and lowest Tremadocian. It has been discerned because of the gap ranging through the upper Tremadocian, Arenigian and Llanvirnian. The gap was regarded, also by the present author (Mizerski, 1995, 1998), as an effect of vertical uplifting movements; there is clearly no angular discordance between the Cambrian–lowest Tremadocian strata and the upper part of the Ordovician (Mizerski, 1995).

Radar image analysis revealed, however, a possibility of tectonic origin of the gap (Mastella & Mizerski, 2002). It could have originated as a result of "ironing" of lower Ordovician stages along a longitudinal dislocation at the boundary between the Cambrian–lowest Tremadocian strata and the upper part of the Ordovician. This interpretation

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is supported by numerous tectonic mirrors present at this boundary, found in borehole sections (Tomczyk, 1974).

Thus, discerning the Early Caledonian (Cadomian?) complex in the Łysogóry–Radom Block might not be substantiated. This is even more probable, as the Ordovician marine sedimentation began in the surrounding areas in the upper Tremadocian and lasted almost until the end of the period. The Ordovician palaeogeography of the area of Poland would be more coherent in this scheme.

Late Caledonian Complex. The Late Caledonian complex includes Llandeilo–lowest Devonian rocks. Tectonic movements at the Silurian-Devonian boundary resulted in shallowing of the sea, and appearance of lagoon and terrestrial facies of the lowest Devonian. The vertical movements were not accompanied by any folding deformations, and the rocks of the younger complex overlie conformably the older sediments, as confirmed by the structural analysis (Mizerski, 1995, 1998).

Variscan Complex. The Variscan complex includes Devonian rocks, the youngest strata of the Variscan zone. Presumably, Carboniferous (at least Lower Carboniferous) deposits belonged to the complex, but they were entirely eroded all over the uplifted part of the block in post-Variscan times.

The Variscan complex, together with older complexes, was folded during the Variscan movements, and the whole area was later eroded. The folded Cambrian–Devonian strata are covered with a strong angular discordance by almost horizontal Permian or Triassic deposits of the Laramide zone.

Małopolska Block

Early Caledonian (Cadomian?) Stage. The Early Caledonian Stage includes Lower and Middle Cambrian rocks. Recently, discovery of Upper Cambrian rocks in the Małopolska Block was reported (Szczepanik et al., 2004), but the data need confirmation.

The Cambrian strata are folded and overlain discordantly by transgressive deposits of the Upper Tremadocian (Czarnocki, 1939), beginning the Late Caledonide section. Traditionally, the folding is assumed to have occured during the Tremadocian Sandomierz phase.

Structural analysis of Cambrian strata outcropping in the eastern part of the HCM allowed to establish that during the folding of the Cambrian strata, a submeridional compression acted southwards (Mizerski, 1997; Mizerski & Skurek-Skurczyńska, 1999). With this compression are also associated (Mizerski, 1994, 1995, 1998) thrust surfaces of subparallel orientation and both folded and faulted underthrust structures, as well as overcast faults inclined to the south with accompanying folding structures, and mesofolds overturned to the north (Fig. 3).

The intensity and pattern of tectonic deformations during the Sandomierz phase depended mostly on lithology. Soft shales and sandy shales were mostly folded, while the harder sandstone-dominated complexes underwent faulting deformations.

Late Caledonian Stage. The Late Caledonian Stage includes Upper Tremadocian to Upper Silurian strata.

The tectonic involvement of Ordovician and Silurian rocks is much lesser than that of the Cambrian rocks. This indicates a minor role of Late Caledonide movenents as compared to the Early Caledonian ones (Mizerski, 1994, 1998; Orłowski & Mizerski, 1996, 1998).

The problem of the role of Late Caledonian movements in tectogenesis of the HCM area is still being debated. Znosko (2000) advocates their paramount importance. However, there are geological facts indicating mostly block nature of the Late Caledonian movements (Głazek, 1995; Głazek et al., 1981; Mizerski, 1995).

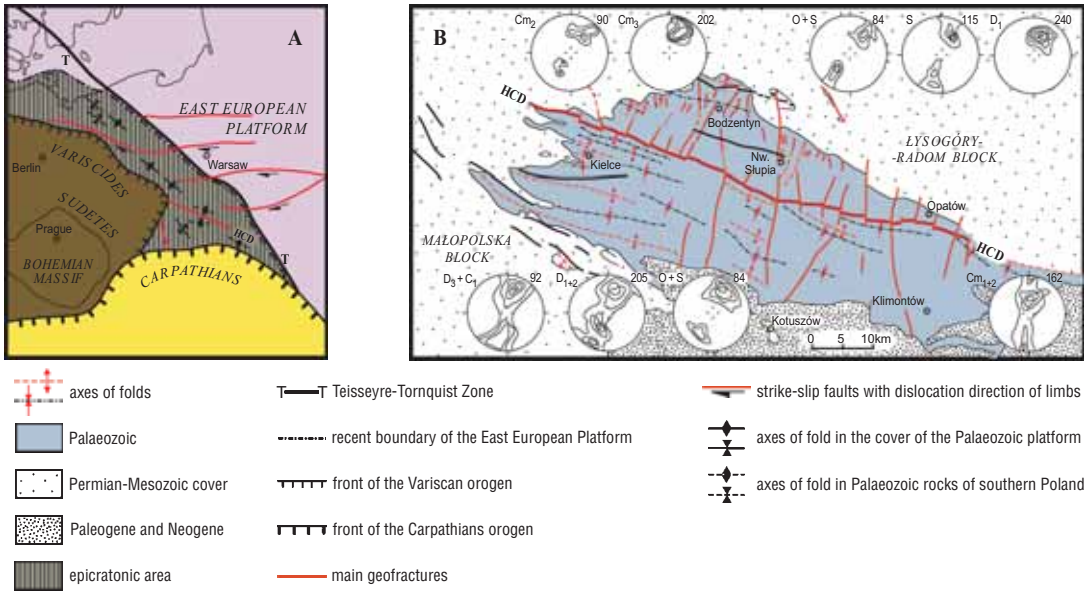

Fig. 1. Generalized geotectonic map of central Europe (A) and generalized tectonic map of the Palaeozoic cover on the Holy Cross Mts (B) and diagrams of the attitude of the strata in the Łysogóry–Radom block (at the top) and Małopolska block (at the bottom). On the upper-right hand side of each diagram — number of measurements (projection of normals onto the upper hemisphere; percent sarhithms: 2, 4, 6, 8, 10). On the upper-left hand side of each diagram — age of the strata: Cm_{1+2} — Lower and Middle Cambrian, Cm_2 — Middle Cambrian, Cm_3 — Upper Cambrian, O+S — Ordovician and Silurian, S – Silurian, D_1 — Lower Devonian, D_{1+2} — Lower and Middle Devonian, D_3+C_1 — Upper Devonian and Lower Carboniferous; H.C.D. — Holy Cross dislocation (after Mizerski, 1988, modified)

Statistical analysis of arrangement of the Cambrian and Ordovician–Silurian strata reveals a strong correlation of their dominants. However, detailed measurements in individual outcrops indicate differences between extensions of the Cambrian and Ordovician strata of about 20 degrees. This means that movements later than the Sandomierz phase remodelled the Cambrian deposits, adjusting their strikes to the axes of younger tectonic structures.

Variscan Stage. The Variscan Stage includes Emsian to Lower Carboniferous rocks. Rocks of this stage, together with the older beds, were heavily folded during the Variscan movements after the Early Carboniferous during the Sudetian or Erzgebirge phase. They are unconformably overlaid by the Permian or Triassic sediments of the Alpine Stage.

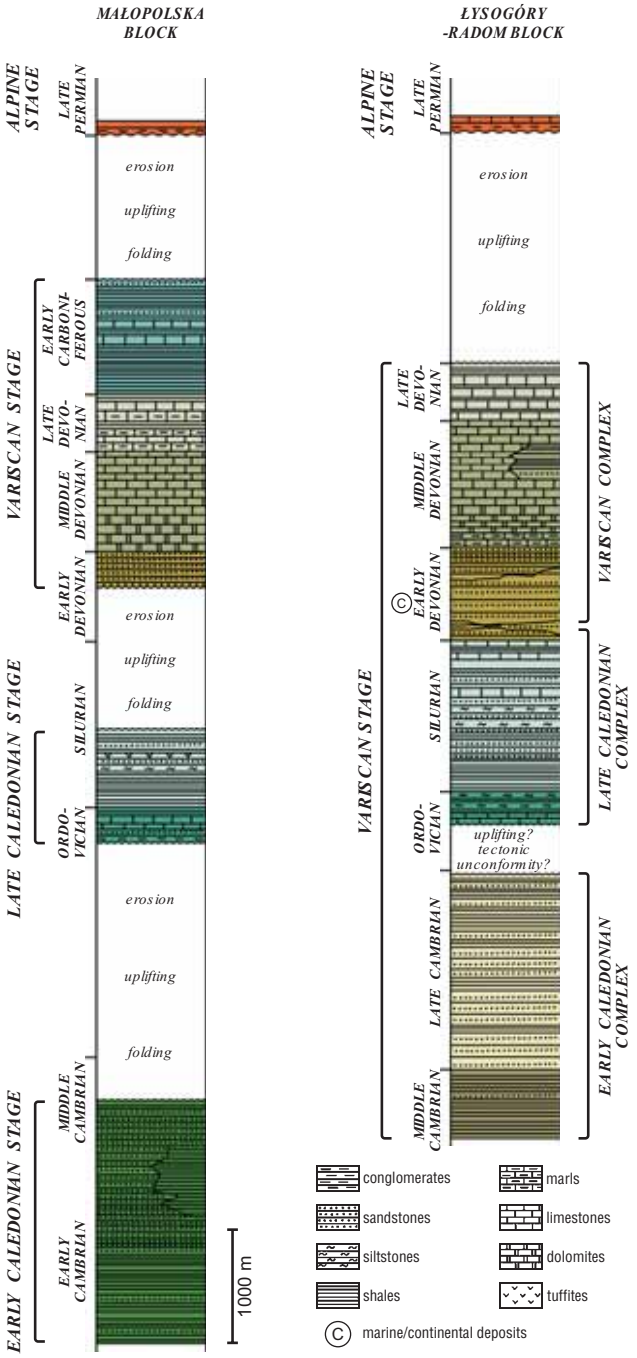

Fig. 2. Generalized lithostratigraphic and structural sections of the Palaeozoic rocks of the Małopolska and Łysogóry–Radom blocks

The role of Caledonian and Variscan movements in the tectogenesis of the Holy Cross Mountains Palaeozoic

The debates on the relative role of Caledonide and Variscan movements in the tectogenesis of the HCM Palaeozoic continue, but the most geological facts indicate that the Variscan movements played a major role in formation of the HCM Palaeozoic. The evidence includes:

- ❏ analogous (Fig. 1) regional extent of the Lower and Upper Palaeozoic strata (Mizerski, 1996, 1998);
- ❏ the same inventory of small tectonic fault and fold structures found in the Lower and Upper Palaeozoic rocks, except for thrusts and associated fold structures indicating pressure from the south (Mizerski, 1998; Mizerski & Skurek-Skurczyńska, 1999);
- ❏ major fold structures, encompassing both Lower and Upper Palaeozoic strata, have axes oriented parallel to the subordinate fold structures occurring within the Lower and the Upper Palaeozoic rocks;
- ❏ in rocks of all the geologic systems there occur identical assemblages and systems of joints and cleavage (Mizerski, 1995).

The inventory of small tectonic structures occurring within all the geologic systems of the Małopolska Block is analogous to that of the Łysogóry–Radom Block. The only exception is the lack of northward thrusts in the Cambrian rocks of the Łysogóry–Radom Block. This is obvious, because the Early Caledonian movements, even if active within that massif, involved only uplifting there.

All the above facts indicate that the structural style of the Palaeozoic strata of the HCM was basically shaped under the influence of the Variscan movements, after the Early Carboniferous, and the pattern of deformation was mainly controlled by the local lithology of particular rock units.

The role of the Caledonian movements varied. Within the Łysogóry–Radom Block they were only vertical movements not associated with any tectonic deformations. The movements were also present in the Małopolska Block, but their intensity was different.

A comparison of lithologically similar Cambrian and Silurian rocks of the Małopolska Block reveals that the Cambrian rocks exhibit much stronger tectonic involvement than the Silurian ones. Also the angular unconformities between the Cambrian and the Ordovician markedly exceed those between the Silurian and the Devonian. This could suggest that the Early Caledonian movements were stronger that the Late Caledonian ones.

The author does not doubt the presence of Late Caledonian fold structures (see Znosko, 1994, 2000). Their existence, however, can be easily explained with differential block movements. The author, like Głazek et al. (1981), believes that the Late Caledonian movements are mainly reflected in discontinuous deformations and continuous wide-radius structures.

The structural analysis of the Palaeozoic strata of the HCM points to the predominant role of the Variscan movements in formation of their structure (Mizerski, 1995, 1996, 1998). This analysis does not sufficiently support a key role attributed to the Late Caledonian movements by some researchers.

Geotectonic position of the Palaeozoic of the Holy Cross Mts

Previous results of geological and geophysical (palaeomagnetic) studies seemed to indicate that during the Early Palaeozoic the Łysogóry–Radom Block was a stable crustal element, while the Małopolska Block could have been a terrane, moving in SE–NW direction along the passive margin of Baltica. Recent petrographic results (Jaworowski & Sikorska, 2004), however, show that this view needs revising.

In 1988, the author presented a hypothesis that during the Palaeozoic the HCM area was situated in a broken, depressed margin of the EEP (Fig. 4). This was indicated by similarities in sedimentation within areas presently located west and east of the T-T zone (TESZ). Such a geotectonic position of the area was the reason why the Palaeozoic tectonic structures of the HCM could not be of orogenic type, neither during the Caledonian, nor the Variscan movements, that were regarded by the author as the most important during the HCM tectogenesis. This view was criticized (Jaroszewski, 1988, 1989; Znosko, 1988, 1989).

Since then, there appeared new data on the HCM geology, concerning lithology, tectonics, biostratigraphy, palaeobiogeography, and palaeomagnetic position of the area.

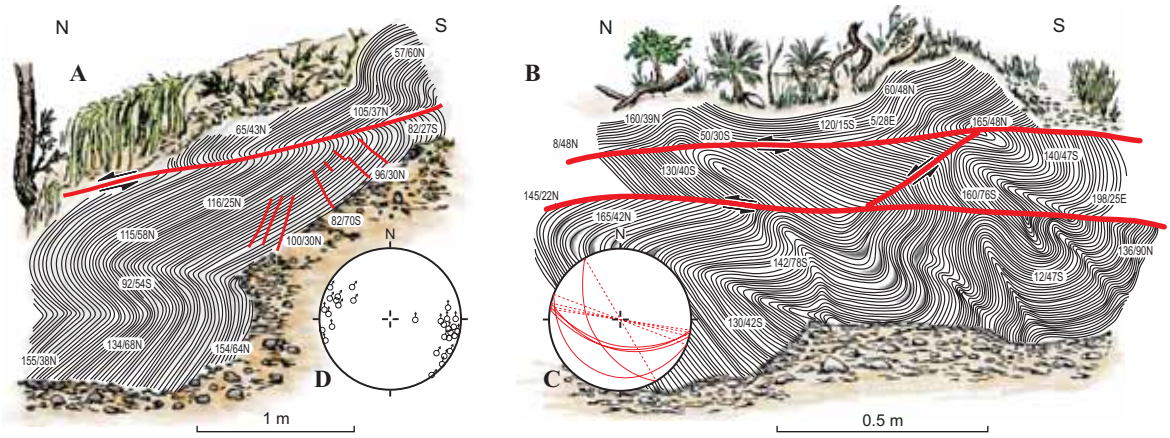

Fig. 3. Overthrusts and drag folds in the Cambrian rocks in the western part of the Małopolska block. A — overthrust accompanying drag folds (arrows — movement directions), B — example of overthrusts and folds, connected with tectonic transport to the north, C — diagram of selected overthrust surfaces (projection on the upper hemisphere), D — diagram of the axes of the drag folds; projection on the upper hemisphere (arrows — vergency of the drag folds)

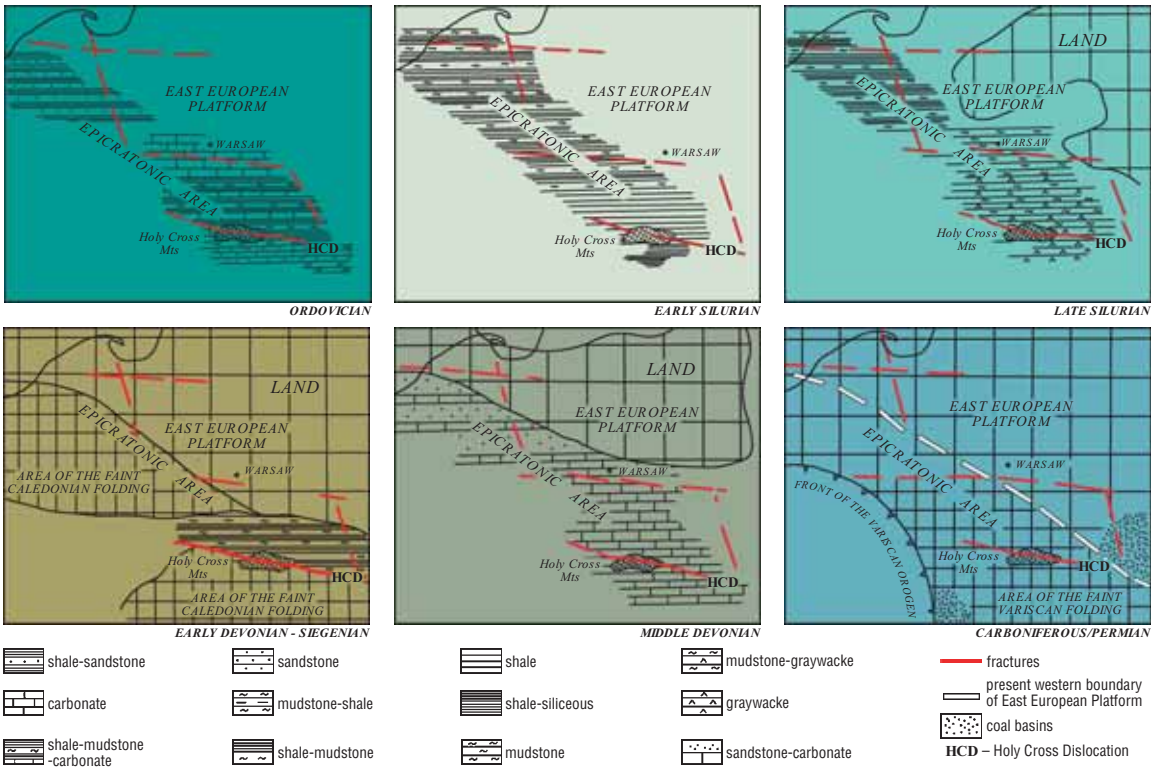

Fig. 4. Scheme of the inferred history of the development of western foreland of the East European Platform in Poland in the Palaeozoic (after Mizerski, 1988, modified)

Recent sedimentological-petrographical studies (Jaworowski & Sikorska, 2004) fully confirm the former view of the author. Their results clearly indicate that in the Cambrian the HCM was situated at the passive margin of Baltica. This means that the hypothesis of a terrane origin of the Łysogóry–Radom and Małopolska blocks should be rejected.

Thus, it should be assumed that the present SW border of the EEP is not the boundary of Baltica, and that this craton reached farther westwards, extending at least to the zone of frontal thrust of the European Variscides. The HCM area was situated in the mobile, marginal zone of the craton, named an epicratonic zone in the literature. Such zones are characterized by their mobility and appearance of tectonic deformations during their historical development. This allows to explain the presence of complex tectonic deformations, both the Caledonian and the Variscan ones, occurring far at the periphery of the orogens.

The formation of Variscan tectonic structures of the HCM area can be associated, by analogy with collisional development of the Alpine-Carpathian tectogene (Ziegler et al., 1995; Cymerman, 1998), with tensions caused by the development of the Sudetic orogen, transmitted onto its foreland. Deformations due to such tensions might occur even at a 1000 km distance from the front of an orogen (Zoback, 1992; Ziegler et al., 1995). Given the fact, that the HCM Palaeozoic is situated in a close neighbourhood of the Variscan orogen front, such a conclusion seems very plausible.

Tectonics deformations of the Paleozoic rocks in the Alpine Cycle

After the Variscan tectonic movements, the HCM area was levelled and covered with a multikilometre-thick layer of Permian-Mesozoic marine and terrestrial deposits formed in an extensive Germanic-Polish Basin (Kutek & Głazek, 1972). Tectonic movements at the Cretaceous–Paleogene boundary, associated with the formation of Laramide units in the rocks of the platform cover, caused a tectonic inversion, and subsequent erosion exposed the Palaeozoic strata.

Tectonic movements of the Laramide phase resulted in formation of numerous fold structures in the SW Mesozoic margin of the HCM (Stupnicka, 1972). In the N and NE margins of the HCM, the Permian–Mesosoic beds lie almost horizontally on the Variscan strata. It is commonly assumed that the Laramian movements did not rearrange structurally the HCM Palaeozoic, even though they might have left a mark in Palaeozoic rocks in some regions (Lamarche et al., 1999), especially in the SW part of the Palaeozoic core of the HCM (Dębowska, 2004). The cartographic representation of the Łysogóry–Radom Block indicated instead that the Laramide movements left no influence there.

However, a detailed analysis of radar images of the Cambrian strata within the Łysogóry–Radom Block revealed multiple overlaps resulting from dextrous transpressive translocations (Mastella & Mizerski, 2002), due to horizontal compression perpendicular to the Holy Cross dislocation. Such interpretation is corroborated by recent studies on the Cambrian of the W part of the Łysogóry–Radom Block (Szczepanik et. al., 2004), where cartographic methods revealed several faults reaching stepwise the HCM dislocation.

By analogy with the deformations occurring in the SW Mesozoic slope of the HCM (Konon & Mastella, 2001; Mastella & Konon, 2002), the transpressive strike slip movements and associated deformations should be attributed to post-Cretaceous movements — Laramian or later.

Thus is cannot be excluded that the folds occurring in the Cambrian strata, with axes parallel to the lines of regional dips of rock beds (Mizerski, 1991, 1995), are also related to these translocation movements.

Conclusions

Despite the existing disagreements about the relative role of the Caledonian, Variscan and Alpine tectonic movements in the tectogenesis of the HCM area, and about its geotectonic position, all data reviewed by the author allow to reach the following conclusions:

- ❏ During the Palaeozoic, the HCM area was situated at a mobile passive margin of Baltica; the mobility of the area, associated with the presence of oblique faults, caused not only differentiation of sedimentation in that zone, but also resulted in fold tectonic deformations forming during the periods of tectonic activation of these zones. Such periods probably coincided with orogenic processes occurring in the marginal zones of the continent;
- ❏ The oldest tectonic movements, affecting only the Małopolska block, occurred at the Cambrian–Ordovician boundary. They are associated with thrust surfaces and accompanying folds formed by meridional pressures directed northwards;
- ❏ Late Caledonian movements within the Łysogóry–Radom Block caused only the shallowing of the marine basin and appearance of lagoon facies, while in the Małopolska Block these were movements leading to wide-radius deformations associated with faulting movements;
- ❏ Most important role in the tectogenesis of the HCM Palaeozoic was played by the Variscan movements after the Early Carboniferous. They led to the origin of major tectonic units, both in the Małopolska, and the Łysogóry–Radom blocks;
- ❏ After the Cretaceous, perhaps during the Laramian phase or later, transpression caused strike-slip translocations along longitudinal dislocations, accompanied by disruption of Palaeozoic strata into overlapping scales;
- ❏ The HCM are not an orogen, but a massif built of Palaeozoic rocks folded at the passive margin of Baltica.

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