Geological Quarterly, 2002, **46** (3): 255–266

# Ordovician through earliest Devonian development of the Holy Cross Mts. (Poland): constraints from subsidence analysis and thermal maturity data

Marek NARKIEWICZ

Narkiewicz M. (2002) — Ordovician through earliest Devonian development of the Holy Cross Mts. (Poland): constraints from subsidence analysis and thermal maturity data. Geol. Quart., **46** (3): 255–266. Warszawa.

The Łysogóry Block (ŁB) exposed in the northern Holy Cross Mts. (HCMts.) reveals subsidence and thermal development consistent with the pattern observed in adjoining East European Craton (EEC) areas. This evidence, in addition to previously reported similarities in sedimentation and deep crustal structure, contradicts the Pożaryski's hypothesis that the Łysogóry Block represents a terrane within the Caledonian orogen. This area is here interpreted as the part of a Late Silurian foredeep basin which developed on the Baltica margin in response to terminal phases of collision with Eastern Avalonia. The development of the continuous Late Silurian foredeep basin along the EEC margin from the Peri-Tornquist Basin in the north-west to the present northern HCMts. implies that the North German-Polish Caledonides orogen had its NE continuation near the present Holy Cross area. The southern HCMts. comprise the northern margin of the Małopolska Massif (MM). The Ordovician-Silurian subsidence development of this area, its thermal history and crustal structure point to a stable cratonic setting. Existing similarities in sedimentary succession (mostly Ordovician and Lower Silurian) as well as clearly Baltic palaeobiogeographic affinities indicate a close spatial connection between the MM and Baltica during the analysed time interval. The juxtaposition of the MM against the ŁB area can be explained assuming that the MM is a part of Baltica detached from its margin due to right-lateral strike-slip after late Ludlow and before Emsian time.

*Marek Narkiewicz, Polish Geological Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland; e-mail: mnar@pgi.waw.pl* *(received: April 17, 2002; accepted: May 7, 2002).*

Key words: Trans-European Suture Zone, Holy Cross Mountains, Early Palaeozoic, tectonic subsidence, thermal history, terranes.

## INTRODUCTION

The Palaeozoic deposits of the Holy Cross Mountains (HCMts.) in south-central Poland, although areally limited, are nevertheless important for the regional geology of Central Europe. These deposits record the evolution of a major tectonic zone — the Trans-European Suture Zone (TESZ — Berthelsen, 1993; Pharaoh *et al*., 1997; Pharaoh, 1999). In particular, they are a sensitive recorder of Early Palaeozoic phases of continental accretion along the present southwestern margin of the Baltica palaeocontinent (present East European Craton — EEC, Fig. 1). The course of accretion still raises much controversy as to the regional scale and detailed scenario of events (Pożaryski, 1990; Dadlez *et al*., 1994; Pharaoh, 1999; Belka *et al*., 2000).

The key problem in this context is an interpretation of geological structure, evolution and mutual relationship of several crustal blocks, two of which — the Łysogóry Block and Małopolska Massif — outcrop in the Holy Cross Mts. The objective of this paper is the Early Palaeozoic evolution of these units and their relationship to Baltica/EEC in the light of tectonic subsidence analysis of the Ordovician to Lower Devonian, and thermal maturity levels of the Lower Palaeozoic. One of the main aims of the study is to test if the possible terrane nature or collage pattern of crustal blocks is to any degree reflected in their subsidence patterns and thermal signatures.

## REGIONAL BACKGROUND

The Palaeozoic outcrops of the Holy Cross Mts. extend across the boundary between two major regional units (Fig. 1; i.a. Pożaryski, 1990; Dadlez *et al*., 1994; Belka *et al*., 2000). The northern part comprises a southern margin of the Łysogóry Block (ŁB) named after the Łysogóry Range in the HCMts. A northern part of the Małopolska Massif (MM) is exposed in the southern HCMts. These units are dissimilar in respect to their geophysical characteristics, including interpreted crustal thickness (see review in Dadlez, 2001), and also show differences in their Palaeozoic sedimentary development (see e.g. Szulczew-

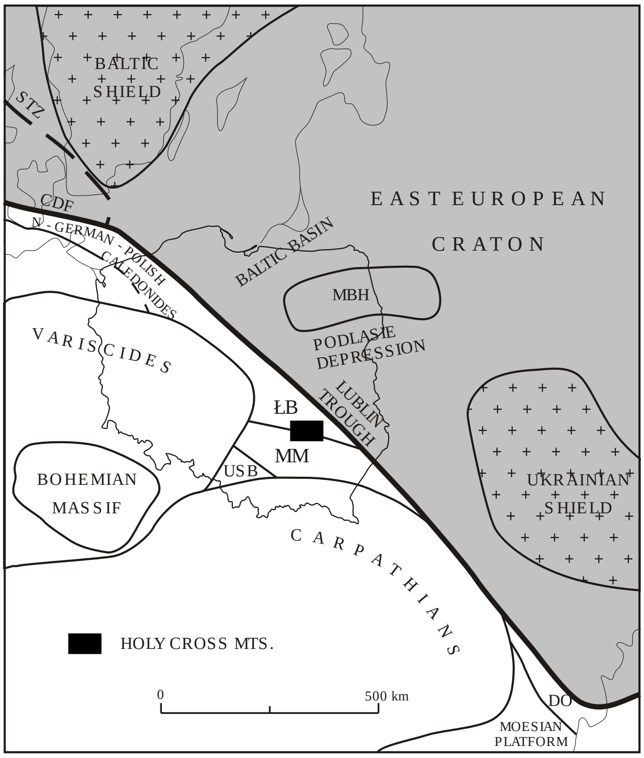


Fig. 1. Location of the study area against the simplified geology of central Europe (partly after Pharaoh *et al.*, 1997, fig. 1)

STZ — Sorgenfrei-Tornquist Zone, CDF — Caledonian Deformations Front, MBH — Mazury-Belarussian High, ŁB — Łysogóry Block, MM — Małopolska Massif, USB — Upper Silesian Block, DO — Dobrogea Orogen

ski, 1977, 1996; Belka *et al.*, 2000). The ŁB adjoins the north-eastern flank of the Late Devonian-Carboniferous Lublin Trough, which is located in the East European cratonic domain (Żelichowski and Kozłowski, 1983). The present boundary runs along the major Kazimierz-Ursynów Fault Zone (Pożaryski and Tomczyk, 1993; Dadlez, 2001) displaying a strong latest Carboniferous transpressional overprint. In turn, the Małopolska Massif is bordered by the Upper Silesian Block along the Kraków-Lubliniec Fault Zone in the south-west (Buła *et al.*, 1997). Most authors agree that the described pattern of particular blocks emerged generally during pre-Variscan times and has not undergone major rotations or translations since the Early Devonian (Pożaryski *et al.*, 1992; Dadlez *et al.*, 1994; Znosko, 1996) although opinions were also expressed on the dominant role of Variscan tectonics (Stupnicka, 1992; Lewandowski, 1993).

According to some authors the MM is in fact composed of several subordinate units of different geological development. E.g. Mizerski (1995) distinguished the northern Kielce Block and southern Miechów-Rzeszów Block, while Belka *et al.* (2000) define the eastern part of MM as the San Block, whereas their Łysogóry Block may be composed of smaller units, potentially separate terranes. Confirmation of these concepts, however, requires further studies enabling better geological and geophysical resolution.

The boundary between the MM and the ŁB is drawn along the Holy Cross Fault (HCF) generally corresponding to a crustal fracture zone (Guterch *et al.*, 1976, 1986; Pożaryski and Tomczyk, 1993; Dadlez, 2001). This fault shows a strong Variscan overprint related to transpression (Pożaryski *et al.*, 1992). While in the eastern Holy Cross Mts. the boundary between both blocks seems indeed to follow precisely the HCF, in its western part I consider that it runs farther to the south, along the northern limb of the Dyminy Anticline (Fig. 2). Such a course is suggested by the shift in strike of the Palaeozoic structures to nearly E–W in the southwestern HCMts. It is also reflected in a separate position of the Kielce area in the Devonian palaeogeographic pattern (the "Kostomłoty transitional zone" — Racki, 1993). The more southerly course of this boundary may be also expressed in the later (inherited) trend of the Włoszczowa-Rykoszyn-Karczówka Fault Zone mentioned by Pożaryski (1974, p. 338). The results of sedimentological studies by Malec (2001) indicate the Łysogóry provenance of clasts in greywackes and conglomerates from the top of the Silurian-lowermost Devonian sequence in the Kielce area, south of the HCF. In addition, the results of the present studies of the Lower Palaeozoic (see below) are in agreement with the corrected course of the MM/ŁB boundary in the western HCMts. as shown in Figure 2.

## PREVIOUS STUDIES

Until the 1980"s, discussion on the tectonics of the Holy Cross Mts. focused on whether Palaeozoic and/or Proterozoic orogens were present, in particular the Caledonian and Variscan ones, either in the entire region or only in its southern versus northern parts (see summaries in Tomczyk, 1974; Dadlez *et al.*, 1994). In the meantime, however, it became clear that the Palaeozoic successions of the Holy Cross Mts. lack attributes of a "typical" collisional orogenic belt, such as considerable crustal shortening and characteristic internal sedimenary-structural architectures. In particular, Szulczewski (1977) convincingly demonstrated the epicontinental character of the Palaeozoic deposition in the whole Holy Cross Mts. area. At present, the remaining proponents of the "orogenic approach" discuss mainly the relative importance of successive stages of tectonic deformation (*cf.* e.g. Stupnicka, 1992; Mizerski, 1995; Znosko, 1996).

The turning point in previous studies was the paper by Pożaryski (1990) who interpreted the Holy Cross Mts. as a fragment of the Caledonian strike-slip (left-lateral) orogen composed of terranes, including the Łysogóry terrane and the terrane of Małopolska Massif. This mobilistic concept was preceded by the hypothesis by Brochwicz *et al.* (1981) on a continental-scale, left-lateral translation along the SW-edge of the East European Platform during the Early Palaeozoic. In this context one should also mention the palaeomagnetic study by Lewandowski (1987) who interpreted large-scale displacement of the Małopolska Massif relative to EEC, in the Early Palaeozoic.

The terrane concept by Pożaryski (1990, see also Pożaryski *et al.*, 1992; Pożaryski and Tomczyk, 1993) was criticised by Dadlez *et al.* (1994). These authors raised methodological objections to the defining of exotic terranes by Pożaryski (1990) and cited stratigraphical, palaeomagnetic and palaeobiogeographical evidence questioning the validity of particular terranes, espe-

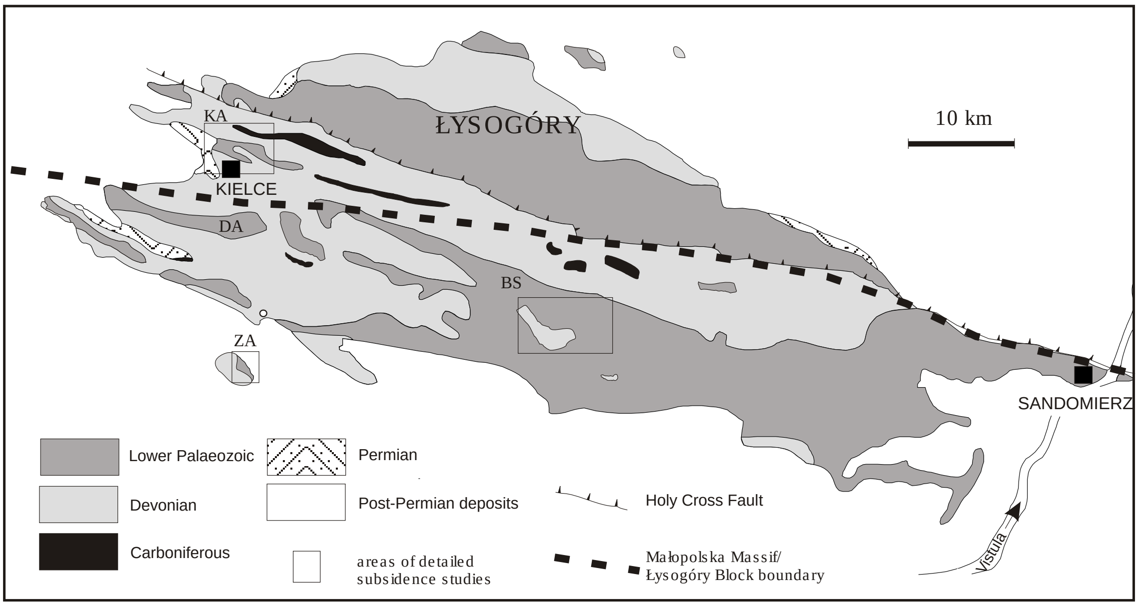


Fig. 2. Simplified geological map of the Holy Cross Mountains with a location of the areas/sections whose Ordovician-Early Devonian subsidence is analysed

ZA — Zbrza Anticline, BS — Bardo Syncline, DA — Dyminy Anticline, KA — Kielce area

cially the Łysogóry terrane. According to these authors the Łysogóry formed part of the passive margin of the EEC (miogeocline) whereas the Małopolska Block is merely a possible proximal terrane translated dextrally along the EEC (i.e. Baltica) margin not later than in the earliest Devonian.

In spite of the criticism expressed by Dadlez *et al.* (1994) other authors followed Pożaryski's concepts by applying his model either directly (Franke, 1995; Unrug *et al.*, 1999) or with some modifications including a Gondwanan provenance of terranes and different times of their accretion (Valverde-Vaquero *et al.*, 2000; Belka *et al.*, 2000). The last two papers report new data on detrital material provenance based on zircons and muscovite dating, as well as provide a review and discussion of published biogeographical data on different fossil groups. In turn, new palaeomagnetic data was presented by Nawrocki (2000) according to whom "...tectonic movements and accretion of blocks along the SW edge of Baltica must have occurred before the latest Silurian..."and thus contrary to Lewandowski's (1993) concept of a right-lateral Late Palaeozoic translation of the MM.

In summary, the terrane hypothesis by Pożaryski (1990) appeared an important alternative for a "classical" collisional orogeny model in the area described. However, the potential terranes still lack convincing and comprehensive explanation and their boundaries are not precisely defined. There is also a lack of a consistent scenario explaining the mutual spatial and temporal relationship of blocks/terranes and the EEC as well as their stratigraphical, sedimentary, biogeographical, tectonic (subsidence development) and thermal attributes.

## SUBSIDENCE ANALYSIS

The present subsidence analysis was performed using a backstripping procedure which enables extraction of a tectonic component from total subsidence (e.g. Angevine *et al.*, 1990; Allen and Allen, 1990). The calculations were performed using the commercially available BasinMod 1-D software. Harland's *et al.* (1989) scale was used as a time reference and Sclater and Christie's (1980) algorithms were applied in decompaction procedures. In order to test the sensitivity of the result to different versions of the geological column the backstripping was recalculated using the more recent time scale (Gradstein and Ogg, 1996). However, the differences between the results appeared insignificant for the conclusions of this study.

## STRATIGRAPHY

The studied successions comprise Ordovician to Upper Silurian-lowermost Devonian deposits unconformably overlying various Cambrian rocks (Dzik and Pisera, 1994; Kowalczewski, 1994). In the south, the upper Tremadoc or Arenig deposits rest on the Lower to Middle Cambrian with a distinct angular disconformity. In the northern region the unconformity is less conspicuous and the stratigraphic gap encompasses probably only the upper part of the Tremadoc.

The sedimentary succession is generally similar in both the studied areas of the Holy Cross Mts., however it considerably differs in thickness, ranging from *ca*. 300 metres in the south to 1000–1500 metres or perhaps even 2000 metres in the north (Fig. 3). At its base it is developed as thin transgressive marine clastics (mostly Arenig) overlain by calcareous or shaly-calcareous deposits representing condensed Middle Ordovician (Llanvirn to Caradoc) carbonates (Dzik and Pisera, 1994). They are succeeded by dark graptolitic shales and/or mudstones comprising mostly the Upper Ordovician (Ashgill) to the middle part of the Silurian (lower Ludlow). In the south, the uppermost part (upper Ludlow) consists of various marine clastics, mostly siltstones and greywackes with a considerable

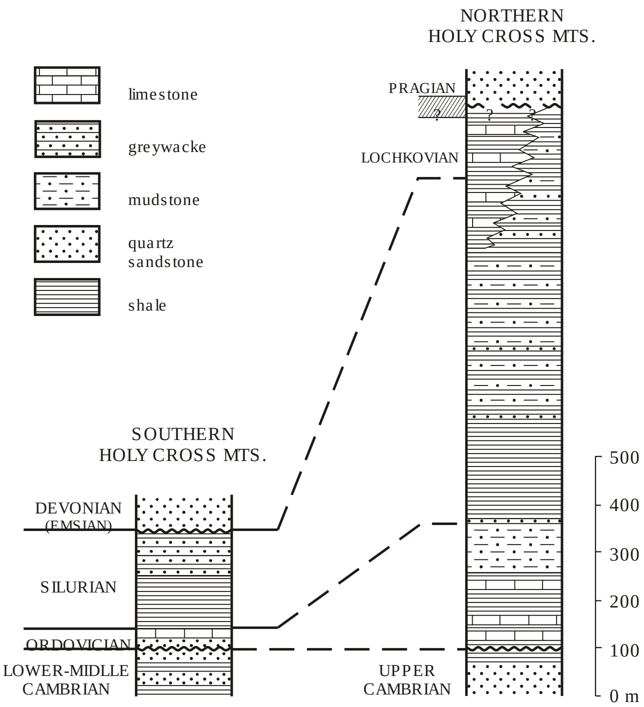


Fig. 3. Comparison of stratigraphy and general lithology of the southern and northern part of the Holy Cross Mts.; the sections are generalised using data compiled from various authors cited in the text

volcaniclastic component, passing upwards into sandstones and mudstones interpreted by Przybyłowicz and Stupnicka (1989) as shallow marine, probably nearshore facies.

Termination of the Ordovician-Silurian basin development is related to Late Caledonian tectonic movements (e.g. Pożaryski, 1990; Dadlez *et al*., 1994). In the southern region and over the entire MM area they were manifested in structural inversion and related compressional or transpressional deformations, uplift and strong erosion. Late Caledonian disconformity is overlain by terrigenous clastics ascribed generally to the Emsian (e.g. Szulczewski, 1995).

The upper part of the Silurian in the northern region is considerably thicker and more complete, comprising the uppermost part of the system (Přidoli) with a transition to the lowermost Devonian deposits. Although its detailed stratigraphy is still debatable, a general sedimentary succession seems to be established (*cf*. Malec, 1993*b*, 2001; Kowalczewski *et al*., 1998). Graptolitic shales are overlain by rhythmically bedded shales and graded beds of graywacke siltstones and sandstones belonging most probably to the upper Ludlow. These sediments are interpreted by Malec (1993*a*, 2001) as deeper-water flysch deposits. Based on preliminary studies of current mark directions Malec interprets source areas for the clastics as being located in the south-west or west, outside the Małopolska Massif area (Malec, 2001).

The graywackes pass upwards into more shaly deposits with subordinate sandy and/or limy interbeds and with an open marine fauna, also interpreted as a deeper-water flysch. The uppermost part of the succession is composed, in a clearly shallowing-upwards fashion, of coarser-grained, sandy to conglomeratic deposits. Kowalczewski *et al*. (1998) interpret the latter as braid delta, braid plain to alluvial fan facies, apparently reflecting regression in the basin prior to the uplift. The age of these deposits is disputable although recent palynostratigraphic investigations point to the latest Přidoli-earliest Lochkovian (Turnau in: Kowalczewski *et al*., 1998). It is, however, probable that they may be diachronous, ranging higher into the Lochkovian (*cf*. Malec, 1993*b*; Szulczewski, 1995). They are overlain — conformably or with a small angular unconformity — by thick alluvial clastics starting a new basinal cycle and ascribed to the Siegenian (Pragian)-Emsian.

The backstripping analysis embraced four synthetic stratigraphic sections: two from the southern region (Zbrza Anticline and Bardo Syncline) and two from the northern one (north-west of Kielce, and the Łysogóry area directly to the north of the HCF; Fig. 2). The Zbrza section was compiled from Deczkowski and Tomczyk (1969). The Bardo section is based on descriptions by Bednarczyk (1981), Tomczykowa and Tomczyk (1981), Dzik and Pisera (1994) and Kowalczewski (1994). Two variants of the backstripping results reflect different estimates of the thickness and stratigraphy of the Upper Silurian greywackes by Romanek and Rup (1989, variant A in Fig. 3) and Stupnicka *et al*. (1991, variant B).

The lower part of the Kielce section was compiled using data from Dzik and Pisera (1994) and Kowalczewski (1994). Again, two variants represent different thickness estimates of the Upper Silurian, those according to Malec (1993*b*, variant A) and those of Stupnicka (1995, variant B). The latter variant also assumed that the Late Silurian flysch sedimentation ended before the Přidoli whereas in the former it was ascribed to the late Ludlow and Přidoli. The Łysogóry sequence is based on several sections described by Bednarczyk (1981), Dzik and Pisera (1994) and Kowalczewski (1994). Variants A and B reflect different thickness estimates of the greywacke and clayey deposits of the Upper Silurian and lowermost Devonian by Tomczykowa and Tomczyk (1981) and Kowalczewski (1994) *versus* Jurewicz and Mizerski (1987).

It should be stressed that the stratigraphic data used for the present study are of variable quality, partly due to poor exposures and fragmentary borehole sections. Locally (Fig. 4) it was necessary to extrapolate data from neighbouring sections/areas. Moreover, the chronostratigraphy was partly based on local subdivisions, and the correlation with the standard epochs or stages is arbitrary and may be imprecise. This refers mainly to the Upper Ordovician and Upper Silurian units. Although the poorly-constrained stratigraphic data is considered to be the main source of error in backstripping calculations it is nevertheless assumed here that the results do reflect general subsidence patterns on a regional scale. Further refinements in stratigraphy will most probably change the details of the tectonic subsidence development but the overall trends should remain.

## PALAEOBATHYMETRY AND EUSTASY

There are only scarce published interpretations of the absolute palaeowaterdepths of analysed deposits. In most cases interpretations are purely qualitative and refer mainly to nearshore marine or continental deposits of the lowermost and uppermost parts of the studied succession (as described above). Obviously, in the latter cases palaeobathymetric corrections are not important for results of the analysis. The main problem in that respect is the palaeobathymetry of graptolitic shales (Ordovician to lower part of Silurian) and siliciclastic deposits of the upper part of the Silurian. The widely accepted epicontinental character of sedimentation of these deposits (Szulczewski, 1977; Dadlez *et al*., 1994) would constrain the maximum waterdepths in the Ordovician to Early Silurian to a few hundreds of metres. The minimum palaeobathymetry of the dark anoxic shales can be estimated at *ca*. 100 meters corresponding to the commonly assumed depth to oxygen-minimum layer in epicontinental basins (Byers, 1977; Stoakes, 1980). The upper part of the greywackes in the Kielce section is interpreted by Malec (2001) as a deeper-water flysch facies which would place it in waterdepths of the order of at least several hundred metres. The overlying deposits represent a shallowing-upward sequence with waterdepths decreasing most probably to shallow subtidal, passing to nearshore coarser clastic facies. According to Przybyłowicz and Stupnicka (1989) the uppermost Silurian in the southern HCMts. was deposited in a shallow-water nearshore marine environment.

The impact of eustatic changes on the sedimentation of these deposits was considered only occasionally (e.g. Dzik and Pisera, 1994). For the purposes of the present paper only a qualitative scenario of possible global sealevel changes will be briefly discussed, based on the recent interpretations by Barnes *et al.* (1996) for the Ordovician and Kaljo *et al.* (1996) for the Silurian.

According to these papers, the onset of the Ordovician is marked by a global highstand terminated by a eustatic sealevel drop in the late Arenig followed by a lowstand in the Llanvirn. The latter events are probably responsible for the occurrence of a considerable sedimentary gap at the Arenig/Llanvirn boundary in the Mójcza section (Dzik and Pisera, 1994), and, probably, also for the general presence of gaps questionably attributed by Tomczyk (1974) to the tectonic “Łysogóry phase”. The Late Ordovician highstand, estimated by Barnes *et al.* (1996) to be among the highest sealevels in the Phanerozoic, was punctuated by a short-term eustatic minimum related to the latest Ordovician (Hirnantian) glaciation (see also Dzik and Pisera, 1994, for the discussion of this event in the context of the Mójcza section). The latter event is most probably responsible for the origin of the widespread Ordovician/Silurian boundary gap regarded by Tomczyk (1974) as evidence of the “Taconian phase”. According to Kaljo *et al.* (1996), the global sealevel had been systematically rising since the earliest Silurian with the eustatic maximum attained in the late Llandovery and early Wenlock. Sealevel started to drop in the late Wenlock and the maximum lowstand is placed near the Gorstian/Ludfordian boundary (Ludlow) and in the Přidoli.

## RESULTS AND INTERPRETATION

Figure 4 illustrates considerable differences in the course and magnitude of tectonic subsidence in the two investigated areas of the HCMts. Both sections representing the Łysogóry Block reveal convex curves with an initial stage of minor Ordovician to earliest Silurian subsidence followed by an acceleration starting in the Wenlock (Łysogóry) or mid-Llandovery (Kielce). In both sections a period of particularly accelerated subsidence comprises the late Ludlow, i.e. the time when deeper-water flysch facies developed (Fig. 4). Such a scenario is typical for foredeep settings in front of a thrust belt causing flexural bending of a lithospheric plate margin (e.g. Angevine *et al*., 1990). A similar interpretation was adopted for comparable Early Palaeozoic subsidence histories of the Welsh Basin and Lake District Basin (King, 1994), Brabant Massif (Van Grootel *et al*., 1997), and the Peri-Tornquist Basin in northern Poland (Poprawa *et al*., 1999).

The inclusion of palaeobathymetric corrections may even strengthen the above interpretation since the Late Silurian flysch deposition may have occurred in waterdepths exceeding the range of 100–400 metres typical of an outer continental shelf. The latter setting may be ascribed to the underlying graptolitic shales. It should be stressed that the depositional systems interpreted for the Upper Silurian flysch sediments (Malec, 2000, 2001) are compatible with the foredeep basin model. In the example described the hypothetical orogenic load could have been situated south-west of the present ŁB. This is indicated by both general regional context (see below — Discussion) and the data on sediment-transport directions in the flysch succession (Malec, 2000, 2001).

In contrast to above described sections, both the sections representative for the northern margin of the Małopolska Massif display clearly lower and more uniform rates of tectonic subsidence. In the case of the Bardo section, variant A calculations give results qualitatively similar to the Łysogóry sections. If this variant is indeed more realistic than variant B, it may be easily explained in terms of changing palaeowater-depth history, assuming rather conservative palaeobathymetry corrections (Fig. 5). The low and relatively uniform rates of tectonic subsidence are typical of stable cratonic settings (e.g. Angevine *et al*., 1990; Einsele, 1992). In the MM area, the onset of coarser clastic deposition may be related to an eustatic fall in the late Wenlock (Kaljo *et al*., 1996).

## REGIONAL PATTERN OF THERMAL MATURITY

The data analysed include thermal maturity indices for 12 localities (Fig. 6). Most of the data (9 localities) were initially TAI values determined for the Cambrian by Szczepanik (1997) and for the Silurian (section near Kielce) by Malec (2000 and pers. comm.). Both values for the Ordovician were based on conodont CAI indices (Mójcza — Belka, 1990; Pobroszyn — Katarzyna Narkiewicz, pers. comm.). In addition, a single $T_{max}$ (Rock Eval) measurement was obtained for the Silurian from Prągowiec near Bardo. All the data are expressed in conodont CAI units for the purpose of comparison (Fig. 6).

Although the analysed database is limited it is nevertheless possible to draw some general conclusions regarding regional trends in maturity distribution. Figure 6 shows a distinct pattern of a low organic maturity in the south, with the CAI 1–2 corresponding to immature rocks and the oil window (Epstein *et al*., 1977). The data for the northern MM margin contrasts with the values of CAI 3–5 indicating overmature rocks in the southern part of the Łysogóry Block. This pattern is independent of the age of the respective samples and thus reflects a different overall thermal maturity of both regions. Moreover, it seems signifi-

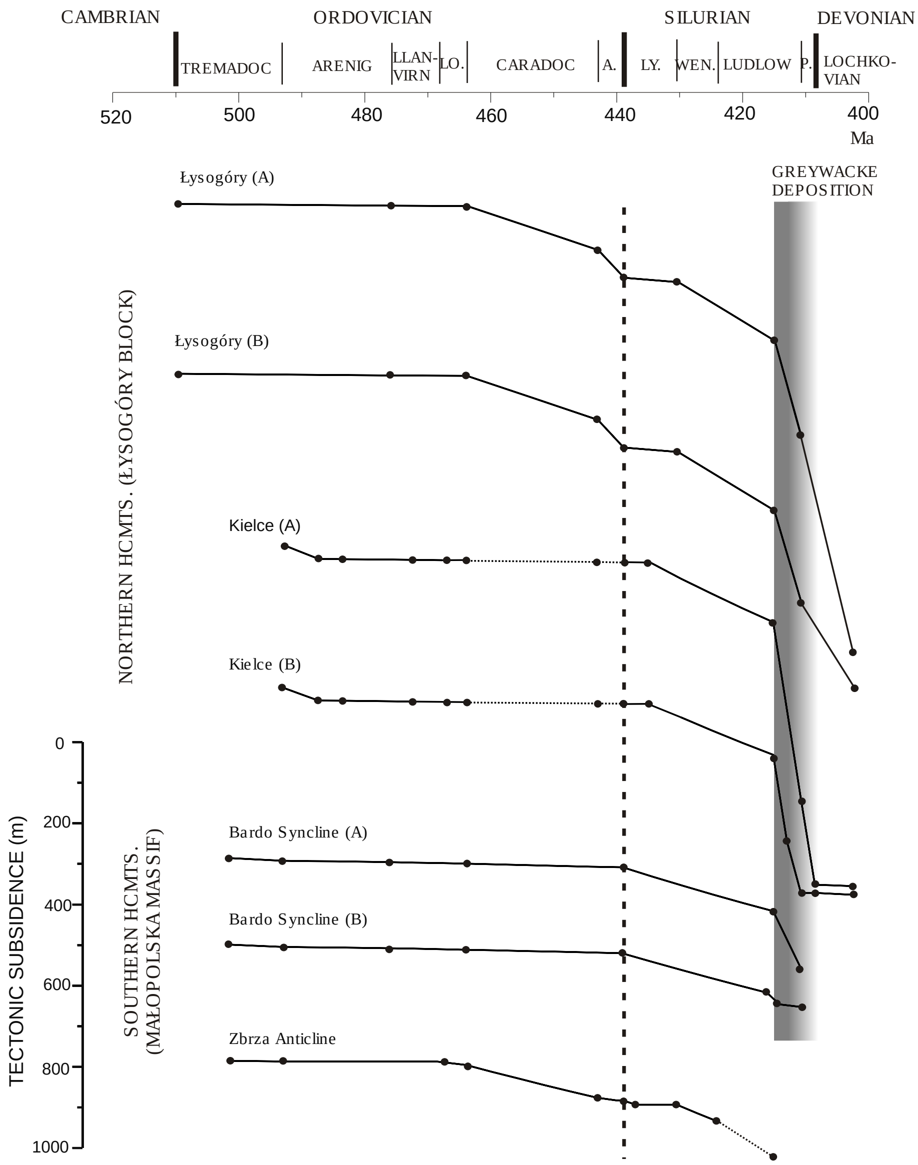


Fig. 4. Tectonic subsidence curves of analysed successions

LO. — Llandeilo, A. — Ashgill, LY. — Llandovery, WEN. — Wenlock, P. — Přidoli; stratigraphic scale after Harland *et al.* (1990); broken lines in subsidence curves represent intervals with poor stratigraphic control

cant that closely situated localities on opposite sides of the boundary between the Małopolska Massif and the Łysogóry Block display contrasting maturity values (Fig. 6).

In general, the low maturity level in the Lower Palaeozoic of the southern HCMts. corresponds to a low maturity of the Devonian and Carboniferous rocks in that region (Belka, 1990). According to that author the present maturity was attained probably during the Late Carboniferous (*op. cit.*). Marynowski (1999) demonstrated that a zone of increased maturity in the Devonian correlates with the western part of the HCF and may be attributed to an increased heat flow along this tectonic line. On the other hand, the Lower Palaeozoic data does not reveal any marked tendency to increased values towards the MM/ŁB boundary. Also, it does not show any decreasing regional trend towards east. Therefore, it is here concluded that the distribution of maturity values in the Lower Palaeozoic strata is related to the pre-Variscan thermal history. It is assumed that it reflects first-order differences in the Early Palaeozoic thermal regime of the northern part of the MM *versus* the ŁB.

The low thermal regime in the MM part of the HCMts. implies that the regional thermal field in this area was not affected by Early Palaeozoic tectonic and/or magmatic events, neither near the Cambrian/Ordovician boundary nor in the Late Silurian-Early Devonian.

## REGIONAL SIGNIFICANCE OF THE RESULTS — A DISCUSSION

The results given here demonstrate contrasting patterns of the Ordovician to earliest Devonian tectonic subsidence in southern *versus* northern parts of the Holy Cross Mts. These

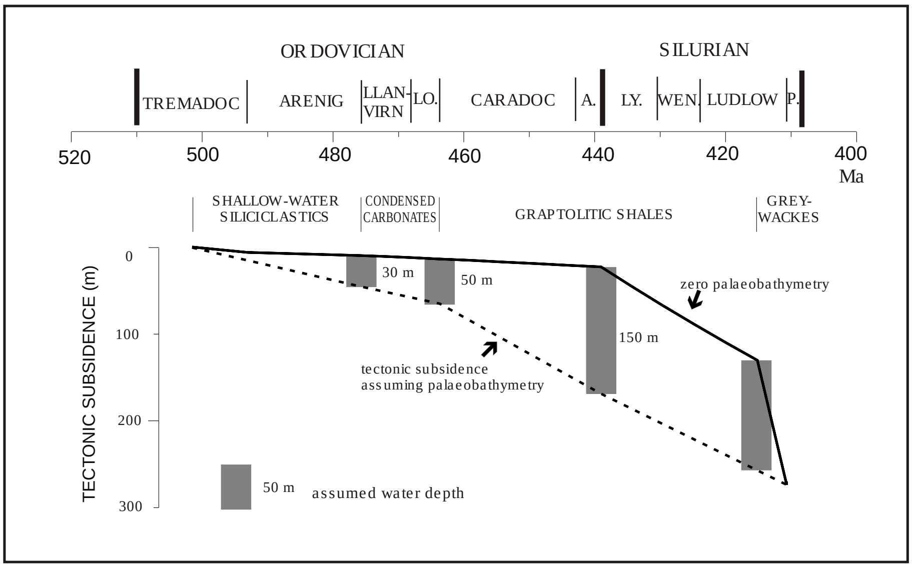


Fig. 5. Modelling of the tectonic subsidence of the Bardo Syncline section (variant A) assuming palaeobathymetric corrections

Explanations as in Fig. 4

differences can be attributed to contrasting structural settings: a stable cratonic basin in the south and a foredeep settting in the north. This implies that both areas are fragments of larger regional units which had been juxtaposed due to some later tectonic processes. Therefore, the present discussion will focus on a wider regional context of the study area in order to explain its present structural configuration.

There are merely scarce data on the Lower Palaeozoic north of the HCMts. documenting only its uppermost part in a few boreholes in the Radom area (Miłaczewski *et al*., 1983). These observations evidence that the development and thickness of the uppermost Silurian to lowermost Devonian are very similar to those of the northern HCMts. It is remarkable that highly comparable deposits were encountered also in the Lublin Trough area. For example, the lowermost Devonian Sycyna Formation developed as marine shales several hundreds metres thick extends both in the Łysogóry Block area (near Radom) as well as in the Lublin area (Miłaczewski, 1981).

The well data from the MM area south of the HCMts. (Jurkiewicz, 1975; Moryc, 1985) are too scarce to enable reliable backstripping calculations. However, they do demonstrate similar facies and sediment thicknesses, suggesting patterns of tectonic subsidence comparable to the southern HCMts. In particular, the Ordovician development displays remarkable similarity in the MM area between the HCMts. and the Carpathians (Tomczyk, 2000; Tomczykowa and Tomczyk, 2000). It is

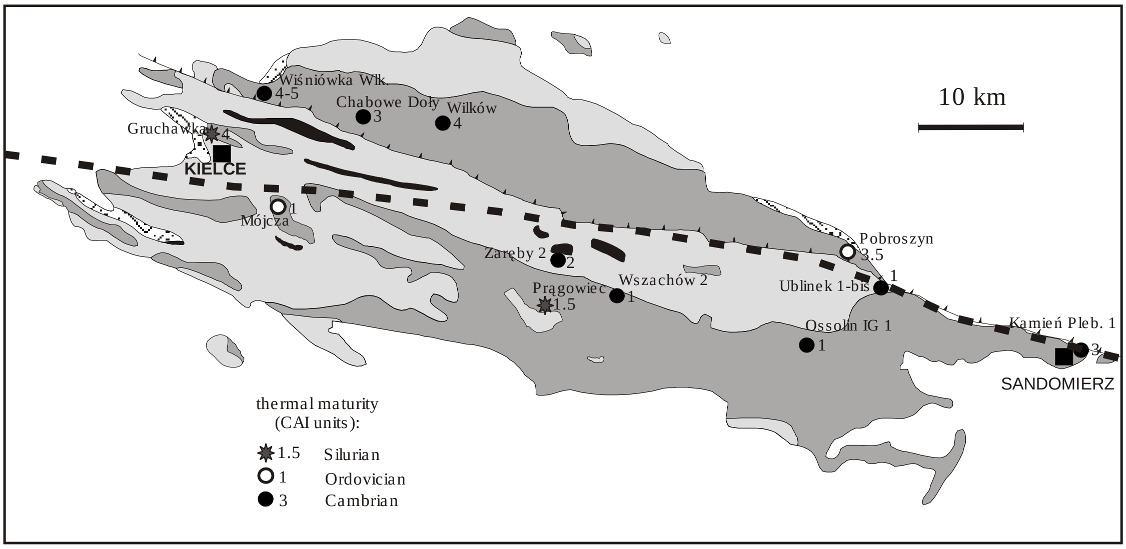


Fig. 6. Thermal maturity of the Lower Palaeozoic deposits in the Holy Cross Mountains; see the text for sources of maturity data

Explanations as in Fig. 2

worth stressing that Upper Silurian coarse-grained clastics of considerable thickness (typical of the northern HCMts.) have not been encountered over most of the MM area except for its south-western margin. The low and relatively constant subsidence rates seem therefore typical for the Małopolska Massif, distinguishing this area from the Łysogóry Block.

Complete Lower Palaeozoic sections are documented in the Podlasie Depression and in the basement of the Lublin Trough, both units clearly within the EEC (Baltica) area (Fig. 1). There, the sedimentary development is similar to that of the ŁB as stressed by Dadlez *et al*. (1994). Moreover, backstripping calculations by Poprawa and Pacześna (2002) demonstrate that the tectonic subsidence pattern is also similar, displaying characteristic acceleration during Ludlow and Přidoli. This evidence was used by the present author (Narkiewicz, 2000) to interpret the presence of a continuous Late Silurian foredeep basin extending from the ŁB area to the east and north including the EEC (Baltica) margin towards the Peri-Tornquist Basin in northern Poland (Poprawa *et al*., 1999).

Poprawa and Pacześna (2002) report that the total magnitude of the Late Silurian tectonic subsidence generally increases towards the southwestern EEC margin attaining values of more than 1100 metres in the Warsaw area (Okuniew IG 1 well). Such magnitude exceeds by almost 500 metres the maximum value obtained by the present author for the Łysogóry (A) variant (Fig. 4). According to Poprawa and Pacześna (2002) the apparent lack of a trend of increasing subsidence between the Lublin-Podlasie area and the Łysogóry Block seems to contradict the interpretation of a continuous Late Silurian foredeep basin extending east and north of the present MM/ŁB boundary (Narkiewicz, 2000).

However, the observed irregular pattern of Late Silurian tectonic subsidence in the area discussed may be reconciled with the concept of a continuous foredeep basin for the following reasons:

1. The SW-margin of the Lublin Trough is a fault zone with a complex history of syn-Variscan (Late Carboniferous) and probably also later (syn-Alpine) strike-slip movements with dextral sense. Although the total displacement may have been on the order of several tens rather than hundreds of kilometres, it may have affected to a certain degree the primary pattern of the Lower Palaeozoic basin. The results of Poprawa and Pacześna (2002) show the decrease in subsidence from NW to SE and in this direction the data seem to be more consistent with the ŁB data (compare e.g. the Łopiennik IG 1 well in the cited paper).

2. A progressive trend of gradually increasing subsidence towards the orogen edge would be expected only in a case of homogeneous lithospheric plate underlying the foredeep basin. Assuming that the ŁB is a distinct crustal unit bounded by deeply-rooted discontinuities, it seems not surprising that it responded individually to an orogenic load.

The data on the thermal maturity of the Lower Palaeozoic north-east of the HCMts. were reported from the EEC as far as 100 km from the studied area (Nehring-Lefeld *et al*., 1997). They indicate levels of maturity increasing towards the south-west and reaching up to CAI 4–5, i.e. values comparable to those observed in the northern HCMts. Data from the area south of the HCMts. are scarce and located mostly in the western part of MM (Belka and Siewniak-Madej, 1996). These results reveal a lack of any distinct thermal events in the Ordovician to Devonian. It may be therefore assumed that the existing data, although limited, point to a consistent pattern of thermal maturity within both analysed regional units, and a clear contrast between them.

In summary, the presented results suggest that the Ordovician to earliest Devonian depositional and subsidence evolution of the Łysogóry Block generally followed the scenario known from the undisputable EEC — the Podlasie Depression and Lublin Trough. It is here interpreted that the above-named regional units were all parts of the same foredeep basinal system extending from southeastern Poland towards the north-west, i.e. along the Baltica margin. The present results are thus not compatible with the concept of the late Early Palaeozoic accretion of the ŁB as a separate terrane (Pożaryski, 1990, see also Pożaryski *et al*., 1992; Franke, 1995; Unrug *et al*., 1999).

On the other hand, the Małopolska Massif displayed a different subsidence pattern and a contrasting thermal history in the Early Palaeozoic. The MM can be interpreted as a part of the Ordovician to Silurian stable cold cratonic area being apparently "not in place" within the present regional configuration of the Lower Palaeozoic. It can be safely assumed that this unit was placed in its approximately present position relative to the ŁB before the onset of the uniform Emsian marginal marine to continental clastic deposition which developed in both regions of the Holy Cross Mts. (e.g. Szulczewski, 1995; see also data on detrital muscovite ages in the Emsian in Belka *et al*., 2000). The hypothetical displacement of the MM may explain the apparent lack of an orogenic wedge south and west of the presumed foredeep in the ŁB area. In order to determine the direction of this translation and the provenance of the MM crust it is necessary to discuss the general biogeographic affinities of the Lower Palaeozoic in the MM area, as well as its palaeomagnetic and sediment-provenance constraints.

Most of the biogeographic data from the studied area refer to the Ordovician, mainly in the southern HCMts. (MM). The interpretations based on brachiopods (recently e.g. Cocks, 2000), conodonts, ostracods and trilobites (*cf*. review by Dzik, 1999) unanimously point to generally Baltic affinities. This is in agreement with the data on acritarchs (Servais and Fatka, 1997) although these are not referred to any specific exposures and thus their affiliation to MM *versus* ŁB is not clear. The data characterising directly the northern Holy Cross Mts. (ŁB) are few. Conodonts from a single exposure in Pobroszyn include not only Baltic but also Bohemian and North American forms (Dzik, 1999).

Palaeomagnetic data, obtained exclusively from the southern Holy Cross Mts., provided a basis for contradictory interpretations of the movement of the Małopolska Massif relative to Baltica (EEC). Lewandowski (1993) assumed right-lateral translation of the MM along the Baltica margin after the Early Devonian and before the Middle Carboniferous. On the other hand, Nawrocki (2000) argued that MM did not undergo any considerable post-Caledonian right-lateral translation. He claimed that his recent Bardo diabase study indicated the accretion of the MM already before the latest Silurian. A careful analysis of his stratigraphical data (particularly those on the uncertain age of intrusion and tectonic deformations — compare also Migaszewski, 2002) suggests however that the time of accretion could equally extend into the earliest Devonian (Lochkovian).

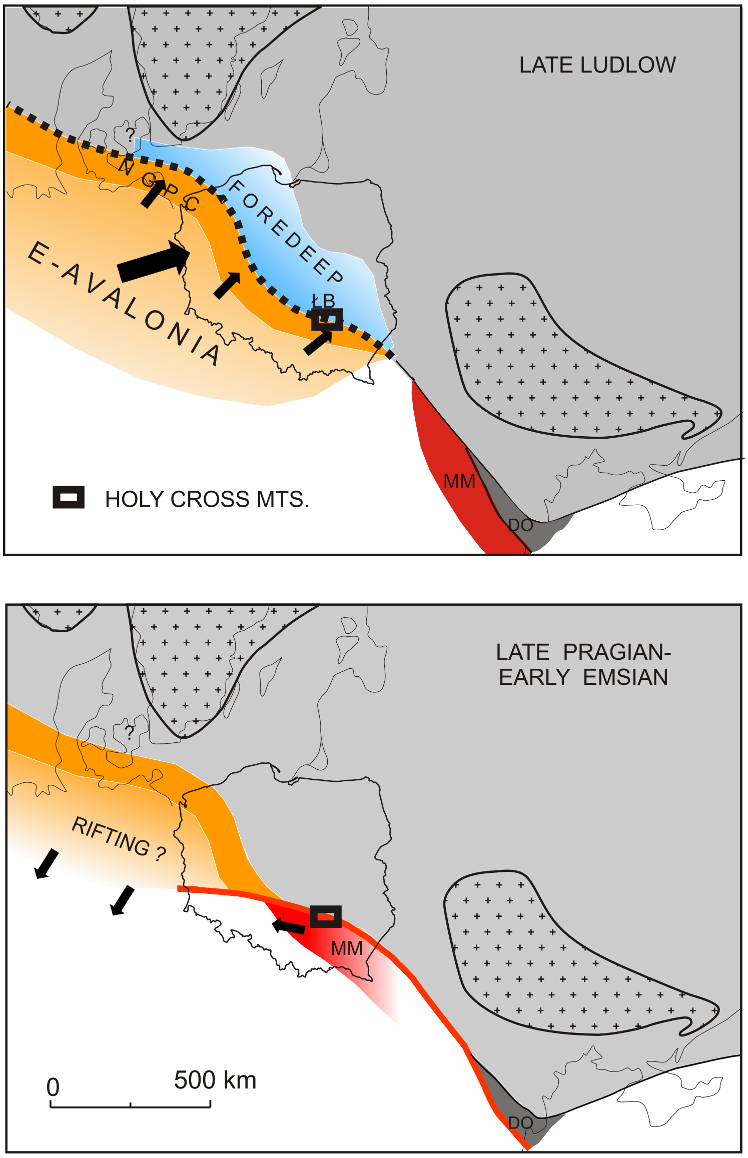


Fig. 7. Hypothetical Late Silurian to Early Devonian development of the TESZ in Central Europe, consistent with the data analysed in the present paper

NGPC — North German-Polish Caledonides; other explanations as in Fig. 1

The studies of detrital material provenance were based on zircons (Valverde-Vaquero *et al*., 2000) and muscovite (Belka *et al*., 2000) from the Cambrian and Lower Devonian. The muscovite data from the MM area point to Cadomian detrital ages in the Lower Cambrian and thus, according to the cited authors, prove the Gondwana affinity of the massif. However, this may appear a premature conclusion in the light of observations by Valverde-Vaquero *et al*. (2000) who found zircons of that age — attributed to Vendian volcanics — in the EEC (Baltica) area near Warsaw. Belka *et al*. (2000) argued that their data on muscovite ages and the compilation of palaeobiogeographic data collectively indicate that the MM has been a part of Baltica since the Middle Cambrian ("first Gondwana-derived microplate that accreted to the margin of Baltica"). According to these authors, the Łysogóry Block probably had been also situated very close (or even attached) to the Fennoscandian segment of Baltica since Late Cambrian time. However, the authors do not attempt to interpret the mutual spatial-temporal relationships of the MM, ŁB and EEC during accretion.

The data discussed, in particular those on the biogeography of the Lower Palaeozoic in the MM area, strongly suggest that the MM was a part of Baltica during the Ordovician to Silurian interval. Having in mind the general palaeogeographic-structural configuration in the TESZ area during the Late Silurian, i.e. in the time when possible MM translation occurred, it seems most probable that the MM was displaced due to right-lateral strike-slip movement along the present SW margin of Baltica (=EEC). The opposite sense of translation seems improbable as there was Eastern Avalonia crust accreted to the (present) NW of the study area, i.e. in the area of the North German-Polish Caledonides (Pharaoh, 1999; Dadlez, 2000; Fig. 1). Also in the light of the present knowledge of contemporary plate kinematics (Torsvik *et al*., 1996) the most probable direction of translation would be right-lateral consistent with the sinistral rotation of Baltica (Dadlez, 2000).

Figure 7 shows a possible scenario including, first, a development of the orogenic wedge and the related foredeep basin in the HCMts. area, and thereafter, right-lateral strike-slip movement of a part of Baltica composing the present MM. Such a model is also considered probable by Pharaoh (1999) who stressed that the supposed "Cadomian" (Gondwanan) provenance of the Małopolska terrane is not yet proven and that it may have "...dispersed dextrally along the Tornquist margin from a Neoproterozoic source region elsewhere in Baltica, rather than crossing the Iapetus-Tornquist Ocean directly...". The MM crust could have been originally located close to the present region of Dobrogea, as proposed by Dadlez *et al.* (1994) based on regional comparisons (Fig. 7). It seems however not unlikely that it was located in a more north-westerly position, i.e. closer to the present HCMts.

## GENERAL CONCLUSIONS AND IMPLICATIONS

1. The depositional, subsidence and thermal development of the Łysogóry Block is consistent with the pattern observed in the adjoining EEC areas. This contradicts Pożaryski's (1990) hypothesis on the terrane nature of this block within the Caledonian orogen (see also Pożaryski *et al*., 1992; Franke, 1995; Unrug *et al*., 1999). The ŁB area is here interpreted as the part of a Late Silurian foredeep basin which developed on the Baltica margin in response to last phases of collision with the Eastern Avalonia (Fig. 7).

2. The development of the continuous Late Silurian foredeep basin along the Baltica margin from the Peri-Tornquist Basin in the north-west to the present northern HCMts. implies that the North German-Polish Caledonides orogen had its NE continuation near the present Holy Cross Mts. area (Fig. 7).

3. The southern HCMts. as well as the entire MM area reveals an Ordovician-Silurian subsidence development, thermal history and crustal structure pointing to a stable cratonic setting. Existing similarities in sedimentary succession (mostly Ordovician and Lower Silurian) as well as a clearly Baltic palaeobiogeography indicate a close spatial connection between MM and Baltica during the time interval analysed.

4. The juxtaposition of the MM against the ŁB area can be explained assuming, after Dadlez *et al*. (1994), that the MM is a part of Baltica detached from its margin due to right-lateral strike-slip. The time of such a translation is bracketed between the late Ludlow, an interval of distinctly different subsidence and sedimentation patterns in the MM *versus* ŁB areas, and the Emsian.

**Acknowledgements.** Preliminary subsidence analysis was accomplished within the framework of the project led by Dr Zbigniew Kowalczewski to whom I am indebted for valuable information and suggestions. I also thank Bart Birdsall (Apache Poland), Jan Malec, Wiesław Trela (both PGI Kielce), and Katarzyna Narkiewicz (PGI Warszawa) for providing unpublished thermal maturity data. Elrzbieta Tarka helped with drawing the figures. Paweł Poprawa is acknowledged for remarks on an earlier version of the manuscript.

## REFERENCES

ALLEN P. A. and ALLEN J. R. (1990) — Basin analysis: Principles and Applications. Blackwell Scientific Publications. Oxford.

ANGEVINE C. L., HELLER P. L. and PAOLA C. (1990) — Quantitative sedimentary basin modelling. Am. Ass. Petrol. Geol. Cont. Educ. Course Note Series, **32**: 1–133.

BARNES C., FORTEY R. and WILLIAMS S. H. (1996) — The pattern of global bio-events during the Ordovician period. In: Global Events and Event Stratigraphy in the Phanerozoic (ed. O. H. Walliser): 137–172. Springer-Verlag. Berlin.

BEDNARCZYK W. (1981) — Stratygrafia ordowiku Gór Świetokrzyskich. Przew. 53 Zjazdu Pol. Tow. Geol.: 35–41.

BELKA Z. (1990) — Thermal maturation and burial history from conodont colour alteration data, Holy Cross Mountains, Poland. Cour. Forsch.-Inst. Senckenberg, **118**: 241–251.

BELKA Z., AHRENDT H., FRANKE W. and WEMMER K. (2000) — The Baltica-Gondwana suture in central Europe: evidence from K-Ar ages of detrital muscovites and biogeographical data. In: Orogenic Processes: Quantification and Modelling in the Variscan Belt (eds. W. Franke, V. Haak, O. Oncken and D. Tanner). Geol. Soc. London, Spec. Publ., **179**: 87–102.

BELKA Z. and SIEWNIAK-MADEJ A. (1996) — Thermal maturation of the Lower Palaeozoic strata in the southwestern margin of the Małopolska Massif, southern Poland: no evidence for Caledonian regional metamorphism. Geol. Rdsch., **85** (4): 775–781.

BERTHELSEN A. (1993) — Where different geological philosophies meet: the Trans-European Suture Zone. In: Europrobe Symposium Jabłonna 1991 (eds. D. G. Gee and M. M. Beckholmen). Publ. Inst. Geophys. Pol. Acad. Sci. **A-20** (255): 19–31.

BROCHWICZ-LEWIŃSKI W., POŻARYSKI W. and TOMCZYK H (1981) — Large-scale strike-slip movements along SW margin of the East European Platform in the Early Paleozoic (in Polish with English summary). Prz. Geol., **29** (8): 385–397.

BUŁA Z., JACHOWICZ M. and ŻABA J. (1997) — Principal characteristics of the Upper Silesian Block and Małopolska Block border zone (southern Poland). Geol. Mag., **134** (5): 669–677.

BYERS C. W. (1977) — Biofacies patterns in euxinic basins: a general model. Soc. Econ. Paleont. Miner., Spec. Publ., **25**: 5–17.

COCKS L. R. M. (2000) — The Early Palaeozoic geography of Europe. J. Geol. Soc. London, **157** (1): 1–10.

DADLEZ R. (2000) — Pomeranian Caledonides (NW Poland), fifty years of controversies: a review and a new concept. Geol. Quart., **44** (3): 221–236.

DADLEZ R. (2001) — Holy Cross Mts. area — crustal structure, geophysical data and general geology. Geol. Quart., **45** (2): 99–106.

DADLEZ R., KOWALCZEWSKI Z. and ZNOSKO J. (1994) — Some key problems of the pre-Permian tectonics of Poland. Geol. Quart., **38** (2): 169–190.

DECZKOWSKI Z. and TOMCZYK H. (1969) — Geological structure of the Zbrza Anticline in the south-western part of the Góry Świętokrzyskie (in Polish with English summary). Biul. Inst. Geol., **236**: 143–175.

DZIK J. (1999) — The Ordovician of the Holy Cross Mountains. In: Inter. Symp. on the Ordovician System, Prague, Excursion Guide, Poland and Germany (eds. J. Dzik, U. Linnemann and T. Heuse): 3–7.

DZIK J. and PISERA A. (1994) — Sedimentation and fossils of the Mójcza Limestone. Palaeont. Pol., **53**: 5–41.

EINSELE G. (1992) — Sedimentary basins — evolution, facies, and sedimentary budget. Springer-Verlag. Berlin.

EPSTEIN A. G., EPSTEIN J. B. and HARRIS L. D. (1977) — Conodont colour alteration — an index to organic metamorphism. U. S. Geol. Survey Prof. Pap., **995**: 1–27.

FRANKE D. (1995) — The Caledonian terranes at the southwestern border of the East European Platform — evidences, speculations and open questions. Stud. Geophys. Geodet., **39** (3): 241–256.

GRADSTEIN F. M. and OGG J. (1996) — A Phanerozoic time scale. Episodes, **19** (1–2): 3–5.

GUTERCH A., GRAD M., MATERZOK R. and PERCHUĆ E. (1986) — Deep structure of the Earth's crust in the contact zone of the Palaeozoic and Precambrian platforms in Poland (Tornquist-Teisseyre Zone). Tectonophysics, **128** (2): 251–279.

GUTERCH A., KOWALSKI T. J., MATERZOK R., PAJCHEL J. and PERCHUĆ E. (1976) — O głębokiej strukturze skorupy ziemskiej w rejonie Gór Świętokrzyskich. Przew. 48 Zjazdu Pol. Tow. Geol.: 52–58.

HARLAND W. B., ARMSTRONG R. L., COX A. V., CRAIG L. E., SMITH A. G. and SMITH H. D. G. (1989) — A geologic time scale 1989. Cambridge University Press. Cambridge.

JUREWICZ E. and MIZERSKI W. (1987) — Major stages of tectonic deformations of Paleozoic rocks in northern Łysogóry region, Holy Cross Mts. (in Polish with English summary). Prz. Geol., **35** (1): 23–26.

JURKIEWICZ H. (1975) — The geological structure of the basement of the Mesozoic in the central part of the Miechów Trough (in Polish with English summary). Biul. Inst. Geol., **283**: 5–100.

KALJO D., BOUCOT A. J., CORFIELD R. M., LE HERISSE A., KOREN T. N., KRIZ J., MANNIK P., MARSS T., NESTOR V., SHAVER R. H., SIVETER D. J. and VIIRA V. (1996) — Silurian bio-events. In: Global Events and Event Stratigraphy in the Phanerozoic (ed. O. H. Walliser): 173–224. Springer-Verlag. Berlin.

KING L. M. (1994) — Subsidence analysis of Eastern Avalonian sequences: implications for Iapetus closure. J. Geol. Soc. London, **151** (4): 647–657.

KOWALCZEWSKI Z. (1994) — The Holy Cross Mountains in the Early Paleozoic. In: Excursion Guidebook, EUROPROBE Trans-European Suture Zone Workshop: 1–18, 24 Sept.–1 Oct. 1994, Kielce.

KOWALCZEWSKI Z., JAWOROWSKI K. and KULETA M. (1998) — Klonów Beds (uppermost Silurian-?lowermost Devonian) and the problem of Caledonian deformations in the Holy Cross Mts. Geol. Quart., **42** (4): 341–378.

LEWANDOWSKI M. (1987) — Results of the preliminary paleomagnetic investigations of some Lower Paleozoic rocks from the Holy Cross Mts (Poland). Kwart. Geol., **31** (4): 543–556.

LEWANDOWSKI M. (1993) — Paleomagnetism of the Paleozoic rocks of the Holy Cross Mts. (central Poland) and the origin of the Variscan orogen. Publ. Inst. Geophys. Pol. Acad. Sci., **A-23** (265): 1–84.

MALEC J. (1993*a*) — Lito- i biostratygrafia „szarogłazów niewachlowskich" górnego syluru. Posiedz. Nauk. Państw. Inst. Geol., **49 (**1): 80–82.

MALEC J. (1993*b*) — Upper Silurian and Lower Devonian in the western Holy Cross Mts. Geol. Quart., **37** (4): 501–536.

MALEC J. (2000) — Wstepne dane o przeobrażeniach termicznych materii organicznej w szaroglazach górnego syluru Gór Świętokrzyskich. Posiedz. Nauk. Państw. Inst. Geol., **56** (8): 109–111.

MALEC J. (2001) — A sedimentological study of deposits from around the Late Caledonian unconformity in the western part of the Holy Cross Mts. Geol. Quart., **45** (4): 397–415.

MARYNOWSKI L. (1999) — Thermal maturity of organic matter in Devonian rocks of the Holy Cross Mts (Central Poland) (in Polish with English summary). Prz. Geol., **47** (12): 1125–1129.

MIGASZEWSKI Z. (2002) — K-Ar and Ar-Ar dating of diabases and lamprophyres from the Holy Cross Mts. (central Poland) (in Polish with English summary). Prz. Geol., **50** (3): 227–229.

MIŁACZEWSKI L. (1981) — The Devonian of the south-eastern part of the Radom-Lublin area (eastern Poland) (in Polish with English summary). Pr. Inst. Geol., **101**.

MIŁACZEWSKI L., RADLICZ K., NEHRING M. and HAJŁASZ B. (1983) — The Devonian deposits in the substrate of the north-western part of the Lublin sector of the Marginal Trough (in Polish with English summary). Biul. Inst. Geol., **344**: 23–56.

MIZERSKI W. (1995) — Geotectonic evolution of the Holy Cross Mts in central Europe. Biul. Państw. Inst. Geol., **372**: 5–47.

MORYC W. (1985) — Structural evolution of pre-Miocene basement of Carpathian foreland east of Cracow. In: Geotraverse Kraków-Baranów-Rzeszów-Przemyśl-Ustrzyki Dolne-Komańcza-Dukla, Guide to Excursion 4. Carpatho-Balkan Geol. Assoc. XIII Congress, Cracow, Poland. Inst. Geol.: 6–17.

NARKIEWICZ M. (2000) — Early Palaeozoic history of the Holy Cross Mountains in view of subsidence and thermal data. Joint Meeting of EUROPROBE (TESZ) and PACE Project, Zakopane/Holy Cross Mts., Poland, Sept. 16–23, 2000. Abstracts. Warsaw.

NAWROCKI J. (2000) — Late Silurian paleomagnetic pole from the Holy Cross Mountains: constraints for the post-Caledonian tectonic activity of the Trans-European Suture Zone. Earth Planet. Sci. Let., **179**: 325–334.

NEHRING-LEFELD M., MODLIŃSKI Z. and SWADOWSKA E. (1997) — Thermal evolution of the Ordovician in the western margin of the East-European Platform: CAI and $R_o$ data. Geol. Quart., **41** (2): 129–138.

PHARAOH T. C. (1999) — Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. Tectonophysics, **314** (1–3): 17–41.

PHARAOH T. C., ENGLAND R. W., VERNIERS J., ŻELAŹNIEWICZ A. (1997) — Introduction: geological and geophysical studies in the Trans-European Suture Zone. Geol. Mag., **134** (2): 585–590.

POPRAWA P. and PACZEŚNA J. (2002) — Late Neoproterozoic to Early Paleozoic development of a rift at the Lublin-Podlasie slope of the East European Craton — analysis of subsidence and facies record (eastern Poland). Prz. Geol., **50** (1): 49–63.

POPRAWA P., SLIAUPA S., STEPHENSON R. A. and LAZAUSKIENE J. (1999) — Late Vendian-Early Palaeozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis. Tectonophysics, **314** (1–3): 219–239.

POŻARYSKI W. (1974) — Struktury epoki tektonicznej alpejskiej. Obszar świętokrzysko-lubelski (in Polish). In: Budowa geologiczna Polski, **1** — Tektonika (ed. W. Pożaryski): 314–363.

POŻARYSKI W. (1990) — The Middle Europe Caledonides — wrenching orogen composed of terranes (in Polish with English summary). Prz. Geol., **38** (1): 1–9.

POŻARYSKI W., GROCHOLSKI A., TOMCZYK H., KARNKOWSKI P. and MORYC W. (1992) — The tectonic map of Poland in the Variscan epoch (in Polish with English summary). Prz. Geol., **40** (11): 643–651.

POŻARYSKI W. and TOMCZYK H. (1993) — Geological cross-section through SE Poland (in Polish with English summary). Prz. Geol., **41** (10): 687–695.

PRZYBYŁOWICZ T. and STUPNICKA E. (1989) — Petrographic characteristics of Upper Silurian rocks from Niestachów (Świętokrzyskie Mts.). Arch. Miner., **44** (1): 129–150.

RACKI G. (1993) — Evolution of the bank to reef complex in the Devonian of the Holy Cross Mountains. Acta Palaeont. Pol., **37**: 87–182.

ROMANEK A. and RUP M. (1989) — Greywackes from Jurkowice and the Upper Silurian greywacke series in the southern part of the Góry Świętokrzyskie (in Polish with English summary). Biul. Państw. Inst. Geol., **362**: 41–59.

SCLATER J. G. and CHRISTIE P. A. F. (1980) — Continental stretching: an explanation of the post-Mid-Cretaceous subsidence of the central North Sea basin. J. Geophys. Res., **85**: 3711–3739.

SERVAIS T. and FATKA O. (1997) — Recognition of the Trans-European Suture Zone (TESZ) by the palaeobiogeographical distribution of early to middle Ordovician acritarchs. Geol. Mag., **134** (5): 617–625.

STOAKES F.A. (1980) — Nature and control of shale basin fill and its effect on reef growth and termination: Upper Devonian Duvernay and Ireton Formations of Alberta, Canada. Bull. Can. Petrol. Geol., **28** (3): 345–410.

STUPNICKA E. (1992) — The significance of the Variscan orogeny in the Świętokrzyskie Mountains (Mid Polish Uplands). Geol. Rdsch., **81** (2): 561–570.

STUPNICKA E. (1995) — Phases of tectonic movements in the Upper Silurian and Lower Devonian of southern part of the Holy Cross Mts (Central Poland) (in Polish). Prz. Geol., **43** (2): 110–112.

STUPNICKA E., PRZYBYŁOWICZ T. and ŻBIKOWSKA B (1991) — Age of the Niewachlów greywackes and shales from Widełki near Bardo (Holy Cross Mts) (in Polish with English summary). Prz. Geol., **39** (9): 389–393.

SZCZEPANIK Z. (1997) — Preliminary results of thermal alteration investigations of the Cambrian acritarchs in the Holy Cross Mts. Geol. Quart., **41** (3): 257–264.

SZULCZEWSKI M. (1977) — Main facial regions in the Paleozoic of the Holy Cross Mts. (in Polish with English summary). Prz. Geol., **25** (8–9): 428–432.

SZULCZEWSKI M. (1995) — Depositional evolution of the Holy Cross Mts. (Poland) in the Devonian and Carboniferous — a review. Geol. Quart., **39** (4): 471–488.

SZULCZEWSKI M. (1996) — Outline of the Holy Cross Mountains geology. In: Sixth European Conodont Symposium, ECOS VI Excursion Guide (eds. M. Szulczewski and S. Skompski): 5–11.

TOMCZYK H. (1974) — Struktury epok tektonicznych bajkalskiej, kaledońskiej i waryscyjskiej. Góry Świętokrzyskie (in Polish). In: Budowa geologiczna Polski, **1** — Tektonika (ed. W. Pożaryski): 128–198.

TOMCZYK H. (2000) — Main phases of development of the Holy Cross Mts. (in Polish with English summary). Pr. Inst. Geogr. WSP Kielce, **4**: 67–91.

TOMCZYKOWA E. and TOMCZYK H. (1981) — Rozwój badań syluru i najniższego dewonu w Górach Świetokrzyskich. Przew. 53 Zjazdu Pol. Tow. Geol.: 42–57.

TOMCZYKOWA E. and TOMCZYK H. (2000) — The Lower Palaeozoic in the Daromin IG 1 borehole — confirmation of the concept of the terrane structure of the Łysogóry and Małopolska Blocks (Góry Świętokrzyskie Mts.) (in Polish with English summary). Biul. Państw. Inst. Geol., **393**: 167–203.

TORSVIK T. H., SMETHURST M. A., MEERT J. G., VAN DER VOO R., MCKERROW W. S., BRASIER M. D., STURT B. A. and WYLDERHAUT H. J. (1996) — Continental break-up and collision in the Neoproterozoic and Palaeozoic — a tale of Baltica and Laurentia. Earth Sci. Rev., **40** (3–4): 229–258.

UNRUG R., HARAŃCZYK C. and CHOCYK-JAMIŃSKA M. (1999) — Easternmost Avalonian and Armorican-Cadomian terranes of central Europe and Caledonian-Variscan evolution of the polydeformed Kraków mobile belt: geological constraints. Tectonophysics, **302** (1–2): 133–157.

VALVERDE-VAQUERO P., DOERR W., BELKA Z., FRANKE W., WISZNIEWSKA J. and SCHASTOK J. (2000) — U-Pb single-grain dating of detrital zircon in the Cambrian of central Poland: implications for Gondwana versus Baltica provenance studies. Earth Planet. Sci. Let., **184**: 225–240.

VAN GROOTEL G., VERNIERS J., GEERKENS B., LADURON D., VERHAEREN M., HERTOGEN J. and DE VOS W. (1997) — Timing of magmatism, foreland basin development, metamorphism and inversion in the Anglo-Brabant fold belt. Geol. Mag., **134** (5): 607–616.

ZNOSKO J. (1996) — The tectonic outline of the Holy Cross Mountains. Bull. Pol. Acad. Sci. Earth Sci., **44** (1): 51–65.

ŻELICHOWSKI A. M. and KOZŁOWSKI S. (1983) — Atlas of geological structure and mineral deposits in the Lublin region (in Polish with English summary). Inst. Geol. Warszawa.