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Holy Cross Mts. area — crustal structure, geophysical data and general geology

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At the start of international seismic experiment CELEBRATION 2000 an attempt at the compilation of the present geophysical and geological data in the Holy Cross Mountains and their surroundings has been made. Five geological units of the first order and four their dividing fault zones have been distinguished in the area studied: uplifted part of the Precambrian Craton (A), Lublin Unit (B), Radom-Łysogóry Unit (C), Kielce-Nida Unit (D), and Upper Silesian Massif (E). They are separated by fault zones: Kock Fault Zone (1) between A and B, Kazimierz Fault Zone (2) between B and C, Holy Cross Fault (3) between C and D, Cracow-Lubliniec Fold Zone (4) between D and E. The first and last units bordering the area are not discussed in this paper. Units B and C are built on the cratonic crust up to 54 km thick. Unit C is composed of poorly correlated mosaic of crustal blocks with crust 35–45 km thick. Fault zones 1 and 3 coincide with crustal fractures while zone 2 has not its counterpart in crustal structure.

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INTRODUCTION

A major seismic experiment, called CELEBRATION 2000 and aimed at the investigation of the Earth's crust, was made in southeastern Poland in the spring 2000. It seems useful — before the interpretation of new data — to compile the information gathered so far, concerning the deep crustal features of the area, and their possible influence on the geological evolution and the present structure of the sedimentary cover. Geophysical source data which are the basis for geological interpretation of the Holy Cross Mountains (HCM) and their neighbouring areas are the following:

1. Results of deep seismic sounding (shortly: DSS — refraction and wide angle reflection) along three regional lines: LT-3, LZW and VIII, and three shorter lines (Betlej *et al*., 1967; Guterch *et al*., 1976, 1984, 1986*a*, *b* — see Fig. 1).
2. Results of refraction survey (Młynarski, 1982) with later supplements (Młynarski, 1987).
3. Magnetometric map of Poland (Karaczun *et al*., 1978).
4. Gravimetric atlas of Poland which presents updated Bouguer anomalies recalculated according to the IGSN gravimetric system (Królikowski and Petecki, 1995).
5. Gravimetric images of pseudorelief prepared by S. Wybraniec using the method described by this author (Wybraniec, 1995*a*, *b*).
6. Results of seismic reflection survey in the northwestern Mesozoic cover of the HCM (Dziewińska, 1994).
7. Photogeologic map of Poland (Bażyński *et al*., 1984).

These data have been compared with subsurface geological maps: without Cenozoic rocks (Rühle, 1972) and without Permian and post-Permian rocks (Pożaryski and Dembowski, 1983; Żelichowski and Porzycki, 1983).

Geophysical information is of variable quality and importance. The only method allowing to identify the Moho unconformity is DSS. One of the profiles (VIII) cuts geological structures obliquely to their strike (Fig. 1). Two remaining regional profiles are perpendicular to this strike but they are separated from each other by more than 40 km. Thus, the correlation of structures between both profiles is partly hypothetical. Moreover, no profile gives information on the distribution of seismic velocities within the crust.

Magnetometric data come from relatively sparse regional network. Besides, the magnetic image in a larger part of the area is smoothed due to deep position of magnetically susceptible rocks. Thus, these data are not very suitable for interpretation.

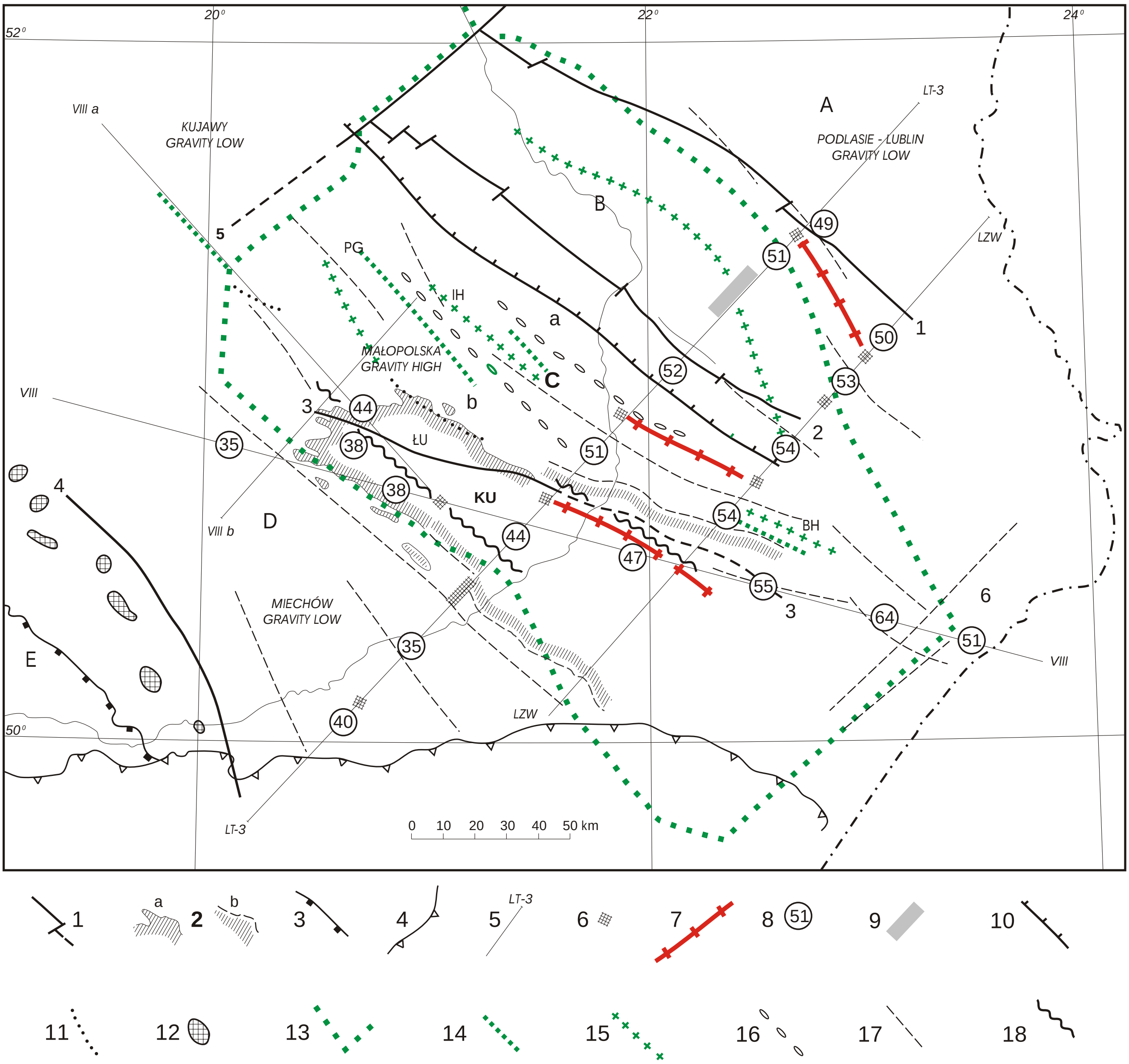

Fig. 1. Main geological units versus fundamental geophysical features

1 — boundaries of major geological units (major faults and fault zones), 2 — boundary of the HCM Palaeozoic core, exposed (a) and concealed below the Tertiary cover (b), 3 — boundary of the Upper Silesian Coal Basin, 4 — Carpathian front, 5 — lines of DSS seismic profiles, 6 — deep crustal fractures after DSS data, 7 — possible correlation of deep crustal fractures, 8 — thickness of the crust in km, 9 — anomalous crust, 10 — southwestern boundary of the top of cratonic crystalline basement after refraction seismic data, 11 — axes of magnetic lows, 12 — strong magnetic highs in the Cracow-Lubliniec Zone, 13 — boundaries of gravimetric provinces (regional gravity gradients except for the boundary between the Małopolska High and Miechów Low), 14 — local strong gravity gradients, 15 — local gravity highs, 16 — local gravity lows, 17 — main photolineaments, 18 — deep crustal fractures after Hakenberg (1997); BH — Biłgoraj High, IH — Iłża High, KU — Kielce Unit, ŁU — Łysogóry Unit, PG — Przysucha-Szydłowiec gravity gradient; for symbols A–E (main geological units), a, b (sub-units) and 1–6 (major fault zones) see text

An information about gravity field is much more dense (over 2.5 measurement points per square kilometre). However, these data are a sum of effects from different depths and different structural stages of the sedimentary cover + crystalline crust. Thus, the gravity Bouguer map portrays a general distribution pattern of heavy and light masses in the whole profile of the Earth's crust. It gives a basis only for a general subdivision into regional gravity units or provinces (gravity lows and highs) as well as for an analysis of gravity gradients. In the study area none transformations of the Bouguer gravity field aiming at stripping off the influence of shallower parts of the crust have been made thus far.

The maps of gravity shaded relief have also been used. They show the horizontal gravity gradients obtained by a method of directional illumination (Wybraniec, 1995*a*, *b*). They highlight minor and major gravity gradients which indicate primarily the presence of faults in the sedimentary cover. This method offers a wide array of different images dependent on the number of light sources (artificial suns) and the angle of illumination. In view of the data abundance, only a few selected images could be used. Because of the prevalent NW–SE trend of geological structures, the images illuminated by the angle = 60° from the north-east and south-west, i.e. roughly perpendicular to structures have been selected. As auxiliary the images illuminated form the north-west and south-east have been used as well as the relief images of local anomalies of Saxov type for radii R_1 = 5 km and R_2 = 1 km, R_1 = 20 km and R_2 = 5 km. In general, the images obtained from this method are nondiversified in the northeastern and southwestern corners of the study area. They can be used for interpretation in the remaining parts where they are more complex within the exposed Palaeozoic core of the Holy Cross Mountains. A selection of shades (gradients) which are the most distinct, the longest and relatively rectilinear, was made; these shades suggest the existence of regional faults.

The reflection seismic survey of fairly good quality is available in a limited area of the northwestern part of the Mesozoic covering the Palaeozoic core. The results reached down to the Zechstein base only; however, some implications can be drawn from these data as to the significance and persistence of main fault zones in the Zechstein basement.

Synthetic data from all the methods has been presented in Figure 1 and — for the last two methods — in a larger scale in Figure 2.

In general, geophysical data remind a puzzle with numerous missing elements. The lack of deep, near-vertical reflection seismics, as well as of refraction — wide angle reflection seismics with a full information about the pattern of seismic velocities in the crust are of great disadvantage. In gravimetry, the essential is processing of source data with the application of various methods, aimed at successive elimination of the influence of shallower parts of the crust on the gravity field.

MAJOR GEOLOGICAL UNITS

On the basis of geological studies performed in exposed areas and in numerous boreholes, as well as of geophysical data, several units (crustal blocks?) of distinctly different character and different evolution of sedimentary cover can be distinguished in the area studied. They are separated by major fault zones of deep roots and long-lived activity (see Fig. 1). These blocks (denoted in Fig. 1 by capital letters) and fault zones (denoted by numbers) are, from the north-east to the south-west:

A — The inner portion of the Precambrian craton characterized by thin, full of stratigraphic gaps and almost undisturbed sedimentary cover overlying the crystalline basement.

1. The Kock Fault Zone.

B — The Lublin Unit. The downfaulted crystalline basement is overlain by thicker and more complete epicratonic sequence from the Cambrian to the Devonian and Carboniferous. The Upper Carboniferous forms a superimposed Lublin Graben (Lublin Coal Basin). To the south-east this unit is not sharply delineated due to its partial closure by elevations built of the Devonian rocks. The whole block is covered by relatively thin veneer of Mesozoic sediments beginning mainly with the Middle Jurassic.

2. The Kazimierz-Ursynów Fault Zone (in short: Kazimierz Fault Zone).

C — Radom-Łysogóry Unit. The Palaeozoic strata are here uplifted relative to the Lublin Unit. It was thus far divided into: (a) the Radom-Kraśnik Uplift (sub-unit) in the north-east, with the Devonian rocks subcropping the Permian or younger strata and (b) the Łysogóry sub-Unit of the HCM together with its northern foreland in the south-west. The latter sub-unit is characterized by the Cambrian to Devonian strata exposed at the surface or covered by Quaternary only. Farther to the north they are covered by the Permian and Mesozoic rocks. Thickness of the latter increases south-westwards marking the previous location of the Mid-Polish Trough. Beneath the Permian the existence of horsts built of the Devonian and intervening grabens filled in with Carboniferous is presumed.

3. The Holy Cross Fault.

D — The Kielce-Nida Unit. In its northern part the exposures of Palaeozoic form the Kielce sub-Unit of the HCM. The remaining area is downfaulted and covered by Mesozoic strata (so-called Nida Trough).

4. The Cracow-Lubliniec Fold Zone.

E — The Upper Silesian Massif.

The area of study is bounded from the north-west and south-east, respectively, by:

5. The Grójec Fault Zone and

6. The Hrubieszów Fault Zone.

The following considerations will focus on geophysical data documenting the above subdivision, except for the units A and E which are located outside the study area.

KOCK FAULT ZONE (1) AND LUBLIN UNIT (B)

In the magnetometric map the Kock Fault Zone is coincident with the southwestern margin of the shallow top of crystalline basement marked by very sharply outlined anomalies with amplitudes reaching 700 gamma. In the seismic profile LT-3 it is in concordance with a crustal fracture characterized by a small difference of crustal thickness on its both sides: 49 km from the north-east and 51 km from the south-west (Fig. 1). Both values are characteristic of the cratonic crust. At the crossing with seismic profile and farther north-westwards this fracture converges with one of the strongest regional gravity gradient in Poland, reaching as much as 2.5 mgal/km and stretching as long as 200 km. It makes up the boundary between the Podlasie-Lublin gravity low and the Małopolska Gravity High. An additional zone of distinct gravity highs, underlying the whole Lublin Unit, adjoins it from the south-west.

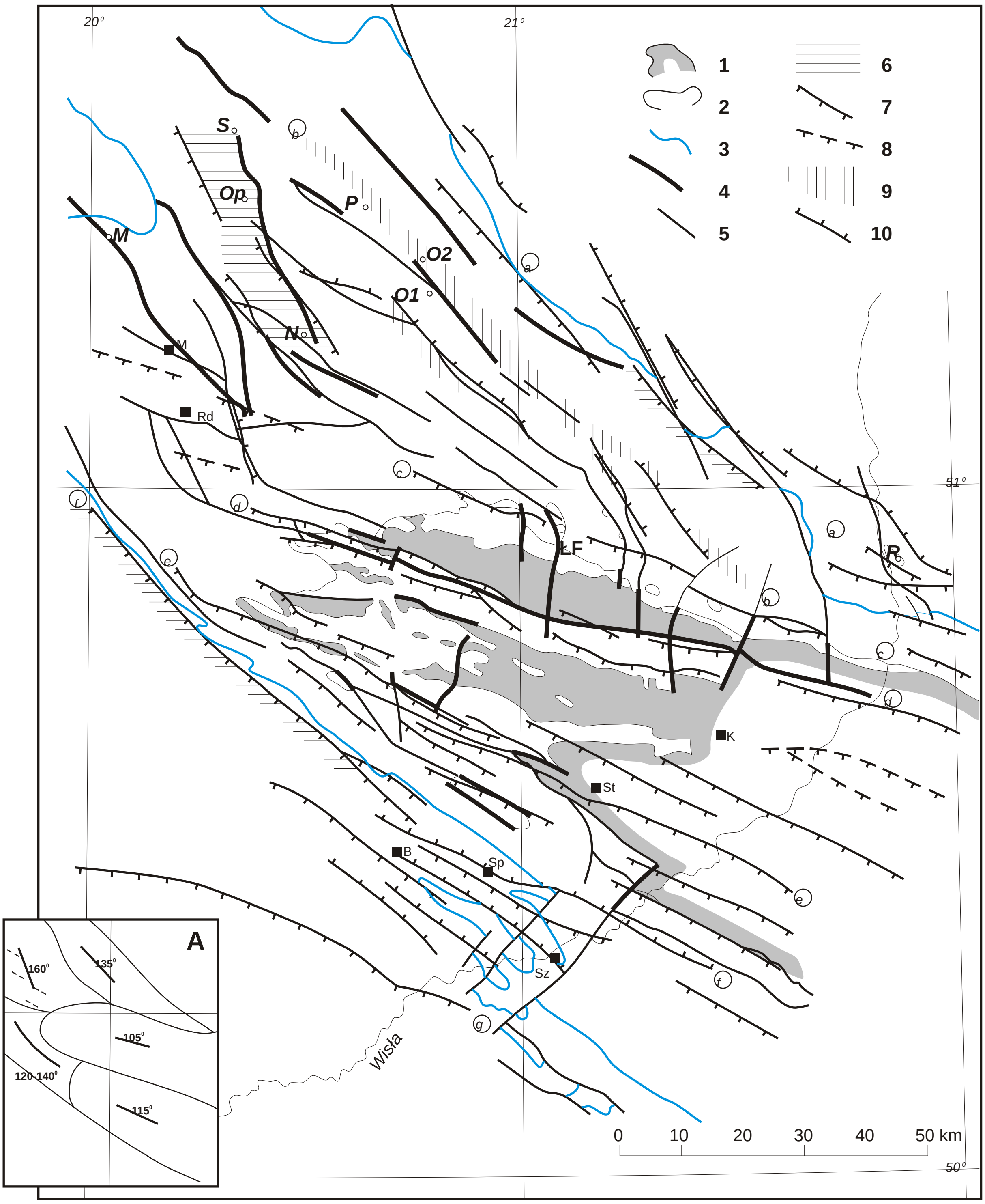

Fig. 2. Holy Cross Mts. and its surroundings versus selected features of the illuminated gravity relief; A — prevailing structural trends

1 — exposures of the Lower Palaeozoic rocks at the sub-Cenozoic surface, 2 — boundaries of the Upper Palaeozoic at the sub-Cenozoic surface, 3 — as above, of the sub-Upper Cretaceous, 4 — faults in the Palaeozoic, 5 — faults in the Mesozoic, 6–8 — shadows of the gravity pseudorelief (presumed faults and fault zones) illuminated from the north-east, 9, 10 — as above, illuminated from the south-west; boreholes: ***M*** — Mniszków IG 1, ***N*** — Nieświn IG 1, ***O1*** — Ostałów 1, ***O2*** — Ostałów PIG 2, ***Op*** — Opoczno IG 1, ***P*** — Przysucha 1, ***R*** — Rachów 1, ***S*** — Studzianna IG 2; ***ŁF*** — Łysogóry Fault; towns and villages: B — Busko, K — Klimontów, M — Maleniec, Rd — Radoszyce, Sp — Stopnica, St — Staszów, Sz — Szczucin; *a–g* — fault systems discussed in the text

Towards the south-east, behind the threshold partly locking the Lublin Graben, the picture becomes more complicated. Two crustal fractures recorded on the LZW seismic profile do not correlate with the major fault zones and are located within the Lublin Unit. Moreover, a zone of strong gravity gradient deviates westwards and runs obliquely to the trend of the unit and surrounding fault zones (Fig. 1).

The most probable explanation of this gradient seems to be a contrast between the rocks of different density in the crystalline basement (upper crust?): bodies of more acidic rocks occur on its northeastern side while more mafic ones — on its southwestern side. The existence, in the southwestern part of this zone, of relatively strong magnetic anomalies with highs reaching 400–500 gamma, speaks also for this interpretation. Additionally, it is indirectly evidenced by the presence — in the discussed part o the LT-3 profile — of an anomalous crustal zone coinciding with the axis of regional gravity high (Fig. 1) as well as by the inferred occurrence of Carboniferous diabases (related to deep-seated mafic rocks?) in the Lublin area close to this gradient zone.

The Kock Fault Zone is at some intervals detectable as regional photolineaments.

In the Lublin Unit the Upper Carboniferous Lublin Graben is superimposed on the Devonian strata which concordantly overlie the Lower Palaeozoic sequence. Altogether the sedimentary section is of a typical epicratonic origin. Therefore, the linking of this unit with the Teisseyre-Tornquist Zone (Guterch *et al.*, 1986*a*) seems unjustified.

KAZIMIERZ FAULT ZONE (2)

This structure does not correspond to any crustal fracture in the DSS data. The nearest one is observed about 25 km towards the south-west. On both sides of this fracture the crust is thick reaching 51–54 km (Fig. 1) as it is elsewhere below the entire Radom-Łysogóry Unit. Shallower refraction horizons with velocities of 6 km/s (top of consolidated basement descending here to a depth of 10–11 km) reach to the south-west beyond this zone to a distance of 15–20 km. In the earlier reports (Żelichowski, 1979; Pożaryski and Tomczyk, 1993) these horizons extended even farther toward the south-west (about 40 km and at least 25 km, respectively). New interpretations (Młynarski, 1987) do not accept this view. Nonetheless, the Kazimierz Fault Zone is without doubt overstepped by these horizons (Fig. 1) which indirectly indicates that the entire Radom-Łysogóry Unit is underlain by the cratonic crust.

The Kazimierz Fault Zone was sometimes identified with the so-called Trans European Fault (TEF); in this case it is named the Świdno Fault (Pożaryski and Tomczyk, 1993). Such an interpretation seems to be wrong for two reasons:

1. The term TEF was used for the first time by Berthelsen (1984) to determine an old pre-Cadomian transform fault which marked the former margin of the East European Craton. During the subsequent events it became transformed into a passive margin, folded later in the Early Palaeozoic. The TEF is then, in proper sense, a root zone of Caledonian overthrusts (EUGENO-S ..., 1988; BABEL ..., 1993). Later, this feature was sometimes improperly identified with the front of Caledonian overthrusts (CDF). The TEF and CDF are two genetically different zones, separated in the tectonotype zone by a distance of several tens of kilometres. Kazimierz Fault Zone cannot be the root fault of the Caledonian thrusts because of arguments given above.

2. The distance between the tectonotype area and the study area is about 800 km without any relevant data. If any solution could be proposed, then according to the proper definition of the TEF its role should be rather played by the Holy Cross Fault (see below).

The lack of coincidence between the Kazimierz Fault Zone and crustal fractures suggest a superficial character of the former. Being the southwestern boundary fault of the Lublin Graben it can be superposed on the presumed CDF and compensated in the underlying ductile Early Palaeozoic series.

RADOM-ŁYSOGÓRY UNIT (C)

In the magnetometric image this block is characterized primarily by a relatively distinct gradient zone (from about 300 to 0 gamma) which runs more or less through the centre of the block. This gradient marks the southwestern slope of the magnetic highs mentioned above which adjoin the area of magnetic low with poorly visible local anomalies reaching 50 gamma. Minimum values trend along the northern margin of the exposed Palaeozoic of the HCM (Fig. 1). This magnetometric depression may indicate the maximum downwarping of the magnetically susceptible bodies in the crystalline basement.

The gravity Bouguer picture is fairly diversified (Fig. 1): against the regional Małopolska High, local elevations (among others in the vicinity of Iłża and Biłgoraj) and depressions are outlined. These two elevations are connected by a distinct regional photolineament. Of particular interest are three local, strong gradient zones, each tens of kilometres long. One of them, averaging 2.5 mgal/km borders the Biłgoraj High from the south and is caused probably by an elevation of the deformed Early Palaeozoic rocks. The remaining two trend parallel to the northern margin of the HCM, i.e. along the Przysucha-Szydłowiec line (up to 3 mgal/km) and near Iłża (2.6 mgal/km).

The crust underlying the Radom-Łysogóry Unit is characterized by cratonic thickness of more than 50 km, except for its southwestern corner (see below). This fact contradicts the presumed terrane character of this unit (Pożaryski, 1990; Franke, 1994) although it does not exclude its overthrusting by Caledonian folds (see also Dadlez *et al.*, 1994).

On the basis of the shaded gravimetric relief (Fig. 2) two fault systems can be distinguished in the discussed unit. The first system (*a*) runs near sub-Cenozoic exposures of the Cretaceous base and is coincident with well known assemblage of *en-echelon* flexures interpreted as an effect of syn-Alpine dextral strike-slip movements (Jaroszewski, 1972). They seem to be rooted in a deeper fault zone. The Iłża gravity gradient is closely connected with this zone where the occurrence of Devonian rocks beneath the Mesozoic deposits is most probable (southwestern margin of the Radom-Kraśnik Uplift?). It is evidenced by the results of borehole Rachów 1 (southeastern part of the zone).

The second system (*b*), with which the Przysucha-Szydłowiec local gradient zone is connected, seems to evidence — as the results of recent deep boreholes north of the HCM indicate — a system of narrow grabens filled in with Carboniferous deposits and horsts built of the Devonian rocks. The posthumous relationship between these structures and the configuration of the Zechstein base (well mapped in this area by reflection seismics) is not clear enough due to strong block faulting. The northeasternmost graben of this system, recorded by boreholes Ostałów 1 (Eifelian below the Zechstein) and Ostałów PIG 2 (Westphalian below the Zechstein — see Fig. 2) may extend far to the south-east; it corresponds with the earlier concept of the Odrzywół-Jastrząb-Ćmielów Carboniferous Graben (Kowalczewski, 1985). The strike of structures in this area is 135°; westwards it turns into 60° (Fig. 2A).

The third distinct fault system, determined by the same method, is the Bronkowice-Wydryszów-Słupcza Fault Zone (*c*). It may define the southern margin of the Lower Palaeozoic elevation, displaced by transversal faults. Its southeastern extension trends toward the Biłgoraj High (see also Znosko, 1996). This system reveals a strike of 105° i.e. the so-called "HCM direction" (Fig. 2A). The traces of this direction can be observed westwards (among prevalent strikes of 160°) also in the Mesozoic cover of the western margin of the HCM (dashed lines in Fig. 2A). Its posthumous secondary effects are the faults trending in this direction and separating Triassic-Jurassic blocks in this area (near Radoszyce and Maleniec — see Fig. 2).

Within the exposed Lower Palaeozoic rocks of the Łysogóry sub-Unit, several subordinate gradients are visible; they may represent the overthrusts within the Cambrian-Silurian strata.

HOLY CROSS FAULT (3) AND KIELCE-NIDA UNIT (D)

The Holy Cross Fault (HCF) correlates well with the Moho fracture recorded in profile LT-3; it separates the cratonic crust 51–55 km thick from the transitional one, 44–47 km thick (Fig. 1). A similar crustal boundary is observed to the east at the junction of profiles VIII and LT-3. Farther westwards and southwards the pattern becomes more complicated. In the profile LT-3 south-west of the HCF there occurs a broad fracture zone separating the crust 44–45 km thick from the thinner one (34–36 km). It coincides roughly with the southern boundary of the elevated, exposed Palaeozoic core of the HCM. In turn, in additional profiles VIIIa and VIIIb the HCF is in concordance with the boundary between the crust 44 km thick (from the north) and the one 38 km thick (from the south). In other words, a difference in crustal thickness on both sides of the HCF remains constant (6–7 km) but the crust thickens eastwards (Fig. 1). In this direction the crustal fracture shifts to the south relative to the fault trend recorded at the surface which seems to suggest the southwestern dip of the fault plane and thus the overthrusting to the north[1].

Anyway, in the east, the basement of the Łysogóry sub-Unit would be characterized by the crust of cratonic thickness; westward it would become thinner (transitional thickness). The latter crustal type underlies the eastern part of the Kielce sub-Unit of the HCM, while the western corner of this unit as well as the basement of the Nida Unit would have a crust about 35 km thick. Considering this, all the recent data indicate the great diversification of crustal thickness and its mosaic character in the southern part of the study area. However, these data are not complete and only a new, modern seismic investigations can solve these problems. So far, the Kielce-Nida Unit is considered to be a part of a proximal Małopolska Terrane (Dadlez *et al.*, 1994).

In the gravity Bouguer map the HCF is not marked by a gradient zone. It is situated on the southern, rather gentle slope of the Małopolska Gravity High. However, in the shaded relief image (Fig. 2) it is markedly visible as a narrow belt of gradients (*d*) striking 105°. The same direction is visible in the exposed Palaeozoic Kielce sub-Unit. The next gradient zone (*e*) coincides with the southern margin of the exposed HCM Palaeozoic. Again, on the Bouguer map it is not marked by more intense gradients, even though the boundary between the Małopolska Gravity High and the Miechów Gravity Low is drawn exactly here. In this zone a change of structural directions from 105 into 115° takes place (Fig. 2A). The latter direction is visible in the southeastern corner of the area as a consecutive gradient zone (*f*); toward the north-west it passes gradually into direction 120–140°. The zone (*f*) coincides almost perfectly with the northeastern extent of the Cretaceous in the Nida Trough, thus suggesting that crustal fault systems may have an impact on the Mesozoic structural pattern.

It is interesting that gradient zones with 115° direction extend from the area of exposed Palaeozoic rocks of the Kielce-Nida Unit far toward the east inside the apparently uniform "Małopolska Massif" (Fig. 2) which is outlined on the sub-Cenozoic maps as an area of the uppermost Precambrian (Lower Cambrian?) subcrops directly overlain by the Miocene deposits of the Carpathian foredeep basin. These zones agree well with faults dividing the Miocene rocks into minor blocks (Kubica, 1992) but their intensity may indicate posthumous character and a rooting in deeper faults cutting the basement.

In the western part of the Nida Trough, the image from the illuminated gravity relief is blurred and not suitable for interpretation. In the eastern part only (Fig. 2) several gradient zones, perfectly linked to an assemblage of Mesozoic synclines and anticlines in the Busko-Stopnica-Szczucin area, were recorded. This enables referring them to the block system of the basement. South-west of this assemblage a gradient zone (*g*) runs far westwards; it corresponds to the Książ Fault Zone (Jurkiewicz, 1974) separating the uplifted Palaeozoic blocks to the south from downfaulted blocks to the north.

In the magnetometric image, the whole Kielce-Nida Unit has a flat "relief" with anomalies varying from 0 to 150 gamma. From the south-west it is distinctly limited by a zone of local strong positive anomalies reaching 250 to 400 gamma; they are caused by igneous bodies of the Cracow-Lubliniec Fold Zone (4 in Fig. 1).

In general, the Kielce-Nida Unit can be divided into the western and eastern parts. The boundary between the both cannot be defined precisely. The eastern part, built over a thicker crust, seems to be more elevated than the western one. This subdivision can also reach the southern margin of the Radom-Łysogóry Unit. It can be geologically expressed

[1]The correlation of faults by Hakenberg (1997) is different from presented here and seems to explain the pattern of crustal blocks in a simpler way. However, the discrepancies between both interpretations may result from inaccuracies in the location of the intersection points of deep fractures with the LT-3 profile (see Fig. 1). These points are taken by the present author from the original drawings by A. Guterch in the scale of 1:1 000 000 (map) and 1:2 500 000 (cross-sections) which were later reduced for publication (Guterch *et al.*, 1986*a*).

(Fig. 2) by the eastward increase of the Cambrian uplift near Staszów and in the eastern part of the Klimontów Anticlinorium, as well as by major transversal Łysogóry Fault, and — in the Nida Trough — by the Busko-Stopnica-Szczucin assemblage of anticlines mentioned above.

A few words should be referred to the Grójec (5) and Hrubieszów (6) Fault Zones. The former (Fig. 1) is well correlated with a strong, NE–SW trending regional gravity gradient (1.3 mgal/km). It played a fundamental role in the geological history of the area. It is one of the principal geological boundaries in Poland, separating crustal blocks of the southeastern part of the country from those of the central part of Polish Lowlands. The arrangement of crustal blocks in the latter area is aligned NW–SE while in the former it is more variable. The Hrubieszów Fault Zone, located at the Polish-Ukrainian state boundary, is poorly identified. It corresponds with the Jaśliska-Hrubieszów regional photolineament.

CONCLUSIONS

1. The cratonic crust underlies the Lublin and Radom-Łysogóry Units reaching the Holy Cross Fault. Only in the southwestern margin of the latter unit its boundary can run north of this fault. This unit is presumably covered by the overthrusted Caledonian folds.

2. South of this area, a complicated, poorly recognized mosaic of crustal blocks with unsatisfactorily defined boundaries occurs. The detailed reconstruction of its pattern requires primarily a modern deep refraction and reflection seimics.

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