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ROTATION ALONG THE TRANSVERSE TRANSFORMING ORAVA STRIKE-SLIP FAULT: BASED ON GEOMORPHOLOGICAL, GEOPHYSICAL AND PALEOMAGNETIC DATA (WESTERN CARPATHIANS)

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Abstract: Morphostructure pattern suggests rotation of the Orava block along the Orava transforming transversal fault. The shortening of the Western Carpathians during their shift to the north in a N–S direction is well known, but the press in between the Bohemian Massif and the European Platform also caused substantial shortening in a W–E direction. The crucial role for such tectonic processes was played by the transversal Orava Fault and Orava block rotation. Paleomagnetic preliminary results and geophysical data seem to confirm such a hypothesis.

Key words: Neogene, Tatra Mts, Orava Basin, paleomagnetism, transforming fault, horizontal rotation, magnetotelluric profile, Bouguer gravity anomalies.

Introduction

There are commonly accepted geological models of the Polish Western Carpathians based on the relationship of this unit to northern geological paleostructures and structures. They are in most cases supported by deep geophysical measurements. This concerns mainly the relationship of the Carpathian Miocene foredeep with the Outer Flysch Carpathian units both underlain by crystalline rock with Paleozoic and Mesozoic rock sequences (Oszczypko 1997; Żytko 1999a,b; Ryłko & Tomaś 1999, 2001; Nemčok et al. 2000).

A new attitude to the tectonic structure of the Carpathians is presented in investigations of the Inner Western Carpathians. The geodynamic development of the regional structure is treated there as a result of tectonic escape from the Alps to the east of the ALCAPA (Alpine-Carpathian-Pannonian) microplate, and its collision with the Bohemian Massif and the European Platform plate (Kováč et al. 1998; Vass 1998; Kováč 2000). As a result, subduction of this plate is accepted. Palinspastic reconstruction of the Carpathian-Pannonian Basin region includes the results of outward thrusting of nappe piles of accretional prism and formation of flexural foredeep.

There are a few elements, which seem to be important for reconstruction of the geological history of the Carpathians, especially close to the boundary of the Inner and Outer Western Carpathians, west of the Tatra massif and even on the northern boundary of the accretional prism between Biała and Skawa Valleys (section Bielsko-Biała and Wadowice towns):

- The movement of megablocks is associated with uplifting of the asthenosphere (Vass 1998; Kováč 2000).
- As a consequence of continuing upwelling horizontal rotation of megablocks can be expected as a result of shear stress relaxation induced by heating and crust stretching of the asthenosphere (Vass et al. 1996).
- The horizontal rotation of blocks is analogous to strike-slip deformations, a sinistral fault is accompanied by Counter Clockwise Rotation, a dextral by Clockwise Rotation.
- Uplifting of lithospheric mass causes plastic mantle flow outside of uplifting formation. Due to this phenomena thickness of lithosphere decreases. Viscosity decreases in lithosphere in result of heat convection. This process causes increases of mobility of blocks and formation of crustal volcanism and magma eruptions (Lexa & Konečný 1998).
- The inhomogeneity in structure of the upper mantle can be interpreted as a partially melted state as a result of geodynamic processes and re-arrangements of deep lithological borders. In particular it is related to the Moho discontinuity (Bielik et al. 1998; Šefara et al. 1998).
- The crystalline blocks are lifted upward. According to fission track analysis the uplift of the crystalline core mountains from a depth of 5 km was evaluated for the last 53–10 Ma. The oldest uplift was measured in the Nízke Tatry and Žiar Mts (Kováč et al. 1994). Another group of Inner Carpathians were uplifted from 25–20 Ma (Veľká and Malá Fatra Mts, Malé Karpaty Mts) and then the youngest mountain uplift in the Tatra Mts took place 15–10 Ma. The last results on

fission track concern the uplift from a depth of 2 km (below 60 °C) and indicate that within the Tatra massif it is possible to distinguish some parts lifted at a different rate (Baumgart-Kotarba & Kráľ 2002).

The aim of this paper is to show that the geodynamic style of geological formation is also relevant to some units of Polish Carpathians. The stresses acting in the collision zone causes fragmentation of megablocks (Bielik et al. 1998) and these microblocks interact between themselves overriding even Neogene segments. The loss of adherence between the upper and lower parts of such terrain can also be expected, as well as their partial melting. The interpretation of profiles 2T and 3T according to Šefara et al. (1998) suggests such a possibility.

The south-west part of the Polish Carpathians is the area of consideration in this paper. The thickness of lithosphere under the European Platform and the Outer Western Carpathians varies from about 110–120 km in the western part to 150 km in the central and eastern segments (Bielik et al. 1999, 2002). Due to such variation stresses acting in collision also vary. In spite of this, the rise of the asthenospheric diapir, which controlled the evolution of the Central Slovak Volcanic Field and graben and horst formation related to back-arc extension (Turiec Basin, Žiar Basin) (Lexa & Konečný 1998; Konečný & Lexa 1999; Vass 1998), north to the Central Slovak Volcanic Field, has produced inhomogeneity in stress distribution between the southward sloping subducted European Platform plate in the Polish section of the Carpathians and the NNE shifted Central Western Carpathian block. It is shown in this paper, that in this zone a structural microblock was formed, having the above described properties, rotated and deformed. The geological, morphostructural, paleomagnetic and geophysical data were used to prove this model. The border between this part of geological unit, which is based on extension of older, northern paleostructures and the rotating microblock is also proposed. The authors' proposition is to name this rotated block the Orava microblock.

The Orava transforming fault

The Orava transverse fault seems to be very important tectonic zone of the Western Carpathians. It is rather young fault transforming during the last 15 Ma the main morphostructures from the western side, the Veľká Fatra, Choč, Skorušina Inner

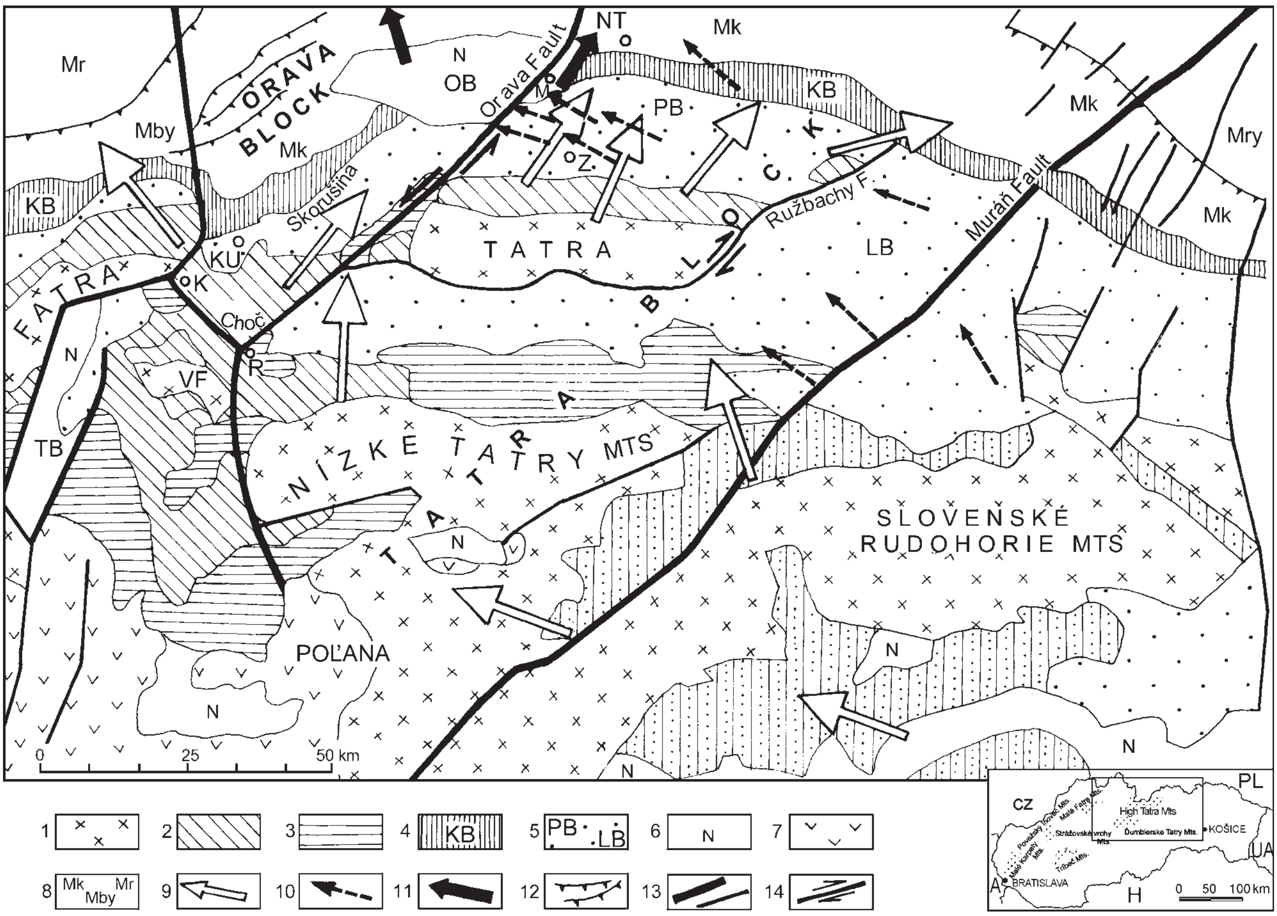

Fig. 1. Paleomagnetic directions on the structural map of the Western Carpathians according to Grabowski (2000) and Márton et al. (1999) with new paleomagnetic data from Neogene sediments giving evidence of opposite rotations along the Orava Fault. **1** — crystalline rock; **2** — Krížna Unit; **3** — Choč Unit; **4** — Klippen Belt; **5** — Podhale and Levoča Inner Flysch; **6** — Neogene sedimentary infill; **7** — Neogene volcanics; **8** — Magura Outer Flysch (**Mk** — Krynica Unit, **Mr** — Rača Unit, **Mby** — Bystrzyca Unit). Paleomagnetic direction: **9** — according to Grabowski (2000); **10** — according to Márton et al. (1999); **11** — samples collected by authors; **12** — front of thrust; **13** — important faults; **14** — strike-slip Orava and Ružbachy Faults. **OB** — Orava Basin, **TB** — Turiec Basin, **VF** — Veľká Fatra, **KU** — Dolný Kubín, **K** — Kraľovany, **R** — Ružomberok, **NT** — Nowy Targ, **M** — Miętustwo, **Z** — Zakopane.

Flysch Syncline, Orava Basin and Babia Góra range (Magura Unit Outer Flysch), and from the east, the Nízke Tatry, Liptovská kotlina Depression, Tatra Mts, Podhale Inner Flysch Syncline and Gorce Mts (Magura Flysch) (Fig. 1). As a result of this activity the Orava Basin has a pull-apart formation. The opening of the Orava Basin started ca. 14 Ma ago (Baumgart-Kotarba 1996, 2001). The uplift from a depth of 5 km of the Tatra Mts is relatively young, 10–15 Ma according fission track methods in comparison to the Nízke Tatry 52.9 Ma (Burchart 1972; Kováč et al. 1994). It was also a period of thrusting and pushing to the north Subsilesian, Silesian, Fore-Magura and Magura tectonic units on foredeep marine sediments Lower Badenian in age documented in the Zawoja borehole (Oszczypko 1997). Such activity seems to be prolonged into the Quaternary, because the NE part of the Orava Basin along the Domański Wierch oblique fault is infilled with 110–128 m of fluvial/fluvioglacial sediments laying directly on the Magura units, without Neogene deposits (Baumgart-Kotarba et al. 2001). The authors of this paper would like to prove a rotation of the so-called Orava block (Baumgart-Kotarba 1996, 2001) along the central part of this long transversal fault crossing the Western Carpathians from the Poľana strato-volcanic system (12.5–13.5 Ma, Dublan et al. 1997) in the south to the Mszana tectonic window in the north. This transversal fault is combined with the Central Slovak Fault system (Kovač & Hók 1993). The rotational features have the following locations:

- fault extended from Kraľovany to Ružomberok (Váh Valley gorge),
- arch shaped fault bordering from the south the Choč Mts (Prosiek Fault),
- fault bordering the Tatra Mts from the west passing through Oravice village and crossing the Inner Flysch between the Skorušina and Podhale regions,
- fault zone of Domański Wierch (uplifted Pliocene molasse), near Ludźmierz village changing direction from 45° NE to NNE along Lepietnica Valley (Magura Outer Flysch) (Baumgart-Kotarba 1992). The area on the east side of the Lepietnica Fault is also more uplifted (Gorce Mts).

The probably rotated Orava block is limited to the east by the fault zone of the Skawa Valley (Figs. 3 and 4).

Morphostructural and geological data

Looking at geological maps, the characteristic pattern of the Klippen Belt morphostructure (Zázrivá-Párnica sigmoid), double structure of the Oravská Magura ranges and faults within the Skorušina Flysch in contact with the Choč Mesozoic rock near Dolný Kubín (Gross et al. 1994) could be interpreted as a pattern related to shortening of the tectonic units in the zone of the hinge due to compression between the NW rotated Orava block and the stopped Malá Fatra block (Baumgart-Kotarba 2001). The sigmoid shape is also discernible on the shape of Choč Mts in its SW part along Váh Valley gorge from Kraľovany to Ružomberok and along the S fault of Choč. Even north of Zázrivá village the shape of the front of the tectonic Krynica slice (Mk) within the Magura Unit reflects rotation of the Orava block to the NW (Fig. 3). On the boundary between the Magura and Silesian nappes, the shape of the Żywiec tectonic window and the course (shape) of the isoline 1.5 km of depth to the crystalline basement (Geological map of the substratum of the Tertiary of the Outer Western Carpathians and their foreland 1:500,000, Geological atlas 1988-89) seem to be influenced by the same rotation. The front of the Magura Nappe changes its course from NE to NEE direction near Żywiec and follows this direction up to the Skawa Valley fault line.

The Quaternary activity of the Orava Fault is shown not only by the young infill of the NE part of the Orava depression, but also by the system of faults crossing the Pliocene sediments of Domański Wierch Hill. There are flower structures significant for strike-slip motions (Baumgart-Kotarba et al. 2001). The present day earthquakes (Baumgart-Kotarba 2001) manifest recent tectonic activity also.

Further geological data seems to confirm rotation of the Orava block. On the north limit of the rotated Orava block, between Bielsko and Andrychów towns the youngest Roczyny-Andrychów tectonic unit with folded and thrusted young Miocene Sarmatian and Panonian deposits was documented (Wójcik et al. 1999) on the front of Subsilesian and Silesian tectonic units. It means that the youngest parts of the Carpathian accretionary prism were formed and pushed to the north after the Pannonian period. The system of transversal faults crossing all tectonic units (Silesian, Subsilesian, Skole and Roczyny) near the northern limit of the Carpathians could be interpreted as tectonic shortening along the northern margin of the Carpathians conditioned by compression related to rotation of the Orava block. It is the North East corner of the NW rotated Orava block.

Paleomagnetic data

The new paleomagnetic data were obtained in framework of the scientific project — KBN No. 6P04E 01620. Samples were taken from 5 localities. For 3 localities (Miętustwo, Lipnica and Hladovka villages), the mean declinations were calculated from individual paleomagnetic vectors according to methods worked out by E. Márton in the Paleomagnetic Laboratory in Budapest.

The first results of the paleomagnetic study carried out by Márton (Baumgart-Kotarba et al. 2002) seem to confirm the activity of the Orava Fault during the Sarmatian and Upper Pliocene time. South of the Domański Wierch Ridge, at Miętustwo village, Sarmatian (Birkenmajer 1978) fluvial sediments gently sloping to the north were sampled. The results of the mean paleomagnetic direction Dc = 28° and Ic = 53° indicate clockwise rotation in the south-east of Orava transforming oblique fault during the last 10 Ma. It is interesting that Grabowski's (2000) paleomagnetic results from the Middle Triassic to Lower Cretaceous strata from the Tatra Mts also indicate clockwise rotation.

The second set of new samples were collected near Lipnica village, 20 km to the west of the Orava Fault from young fluvial sediments tilted after deposition. These sediments are Pliocene/Quaternary in age (2.5–2 Ma) (Baumgart-Kotarba 2001). According to palynological studies by Stuchlik from the Institute of Botany of the Polish Academy of Sciences in the framework of grant KBN No. 6P04E02008, these sediments belong to the Pliocene-Quaternary boundary. Paleomagnetic results from "Young" Lipnica sediments indicate counterclockwise rotation (Dc = 344°, Ic = 64°). This result seems to indicate the rotation of the Orava block ca. 16° to the NW during the last 2 Ma. Rotation with a counterclockwise (CCW) direction started earlier from the Eggenburgian according to Kováč et al. (1989) in the western part of Carpathian arc (Bánovce Depression). The Váh block situated between Bratislava and Žilina (Baumgart-Kotarba 1996, 2001), was rotated to the NW as was measured by the paleomagnetic method in Eggenburgian (42°) and Karpatian (37°) marine deposits of piggy-back basins (Kováč et al. 1989). This was interpreted as the stopping role of the rigid Bohemian Massif during the general shift of the Carpathian to the north (Kováč et al. 1989; Baumgart-Kotarba 1996). According to new paleomagnetic research in the Orava pull-apart basin close to Lipnica village it is possible to document young CCW rotation in fluvial deposits 2 Ma in age.

The third set of samples from Hladovka (13 km SE of "Young" Lipnica concern the Pliocene deposits (Oszast & Stuchlik 1977). The mean declination in Hladovka also confirms CCW rotation, but by 38° (Dc = 142°, Ic = −49°).

The results from the Tatra Mts (Grabowski 2000): Dc 23°, 34° (Bobrowiec — NW Tatra Mts) and 40° (Havran — NE Belanské Tatry Mts) seem to be in opposition to the results from the Paleogene Inner Flysch of the Podhale and Levoča Basins by Márton et al. (1999). The mean direction from 6 localities from Podhale is Dc = 298° and Ic = 53° (Fig. 1). The data from the Levoča Basin and Podhale are in good agreement. The preliminary opinion is that the clockwise directions obtained by Grabowski (2000) from the Tatra Mts are comparable with the young rotation documented in Miętustwo. The explication of such coincidence is not easy. But it is possible that the young uplift of the Tatra massif was related to some horizontal clockwise rotation and this uplift was related to the whole shift of the Tatra block, together with the Magura Flysch (Gorce Mts) in compressional regime and with the Neogene deposits in the Nowy Sącz Basin.

Interpretation of the geophysical data

Two kinds of geophysical measurements are considered in the paper. The first are results of magnetotelluric sounding (MTS) along the profile "Chyżne-Spytkowice" (Królikowski et al. 2000). The interpreted results are similar to those presented in a paper by Bielik et al. (1998). Five parts were distinguished by the authors of this paper in electrical cross-section obtained from those data. Coming from the north, the first 15 km (Fig. 2), is not disturbed in deep structure by Carpathian movements and represents a style of foredeep. In the second part (II) from Wadowice (ca. 5 km south from Tomice (Fig. 2)) to the Sucha borehole, low resistivity masses are push into the space between the maximum resistivity basement and a 55 km deep layer also with high resistivity. In the third part (III), between the Sucha borehole and Babia Góra foreland all structural elements in the upper part of the cross-section are dipping intensively to the south, and a further 15 km to the south, there is a break in the continuity of all the upper layers in the fourth part of profile (IV). Low resistivity masses filled all the cross-section. Finally, at the south end of the profile a high resistivity block appears again (part V). Close to Chyżne village the top of the crystalline block is sloping to the south.

It seems that the rigidity of masses can influence the resistance of rock masses against their rotation. From this point of view the border between parts III and IV in the MTS profile is also a border between rigid and soft masses. The second important boundary concerning the deep structure is the boundary between parts I and II (Fig. 2).

The results of other geophysical measurements, two gravitational maps, were used for location of this border in the area of investigations. One of them (Fig. 3) was the original Bou-

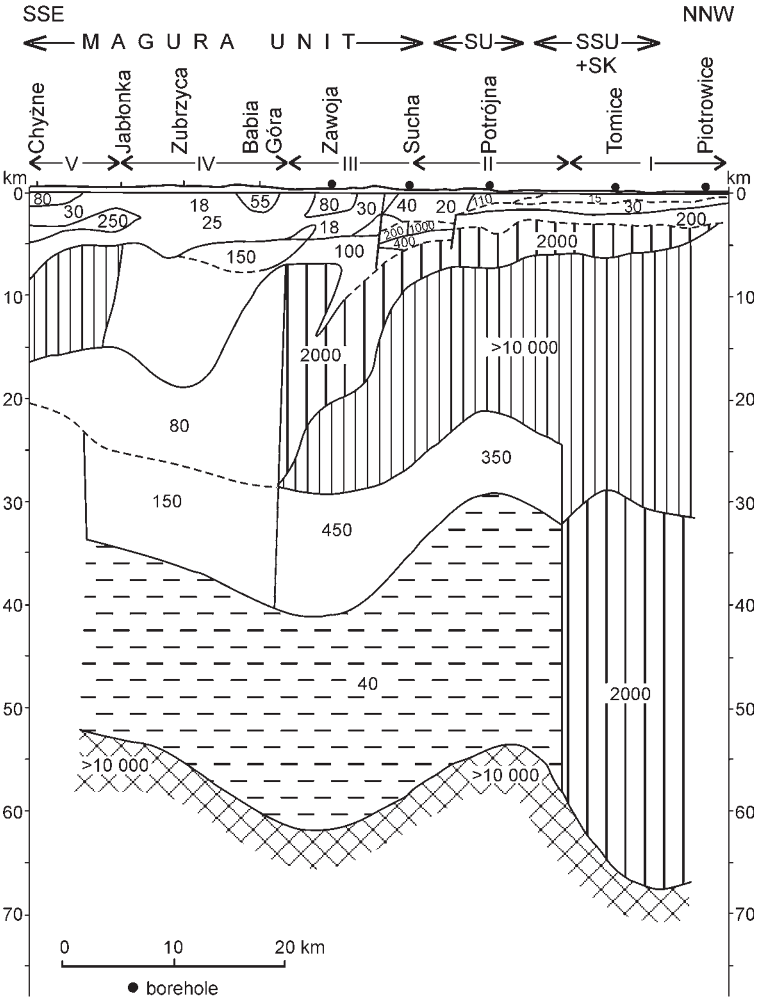

Fig. 2. Magnetotelluric profile Chyżne-Spytkowice (location on Fig. 4) according to Królikowski et al. (2000). Resistivity in Ωm. I–V parts of profile distinguished by authors of the paper.

guer gravitational map and second was the result of its transformation. It can be observed, that the intensive trend in the gravity field, and its decrease towards the south direction have the result, that the structure of the field cannot be recognized properly (Fig. 3). In second map (Fig. 4), elimination of the general trend was calculated by the authors of the paper, by subtracting from each gravity value in a grid constructed along the S–N and W–E directions the mean value calculated along W–E lines. The structure of the map (Fig. 4) can be divided into three parts. The north part of the maps consists of intensive anomalies, showing NW–SE directions, which are characteristic for stresses in the Bohemian Massif (Jarosiński

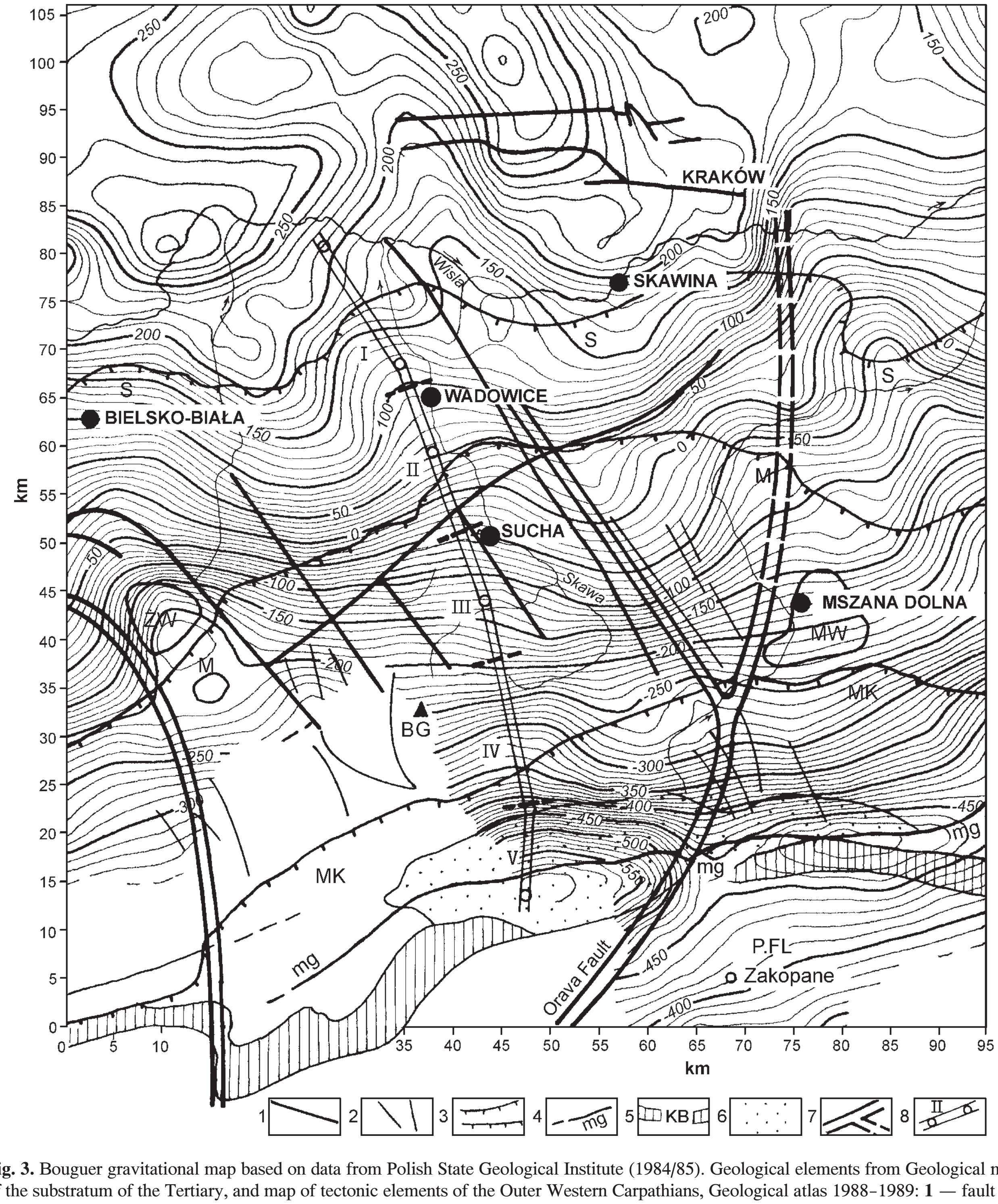

Fig. 3. Bouguer gravitational map based on data from Polish State Geological Institute (1984/85). Geological elements from Geological map of the substratum of the Tertiary, and map of tectonic elements of the Outer Western Carpathians, Geological atlas 1988–1989: **1** — fault according to the map of the Tertiary substratum; **2** — fault within Magura Unit; **3** — front of thrusts, **M** — Magura Unit, **MK** — Krynica Unit, **S** — Silesian + Subsilesian + Skole Units; **4** — axis of gravitation minimum (mg); **5** — Klippen Belt; **6** — Orava-Nowy Targ Basin; **7** — rotational Orava Fault; **8** — magnetotelluric profile Chyżne-Spytkowice (I–V parts). **BG** — Babia Góra, **P.FL** — Podhale Flysch.

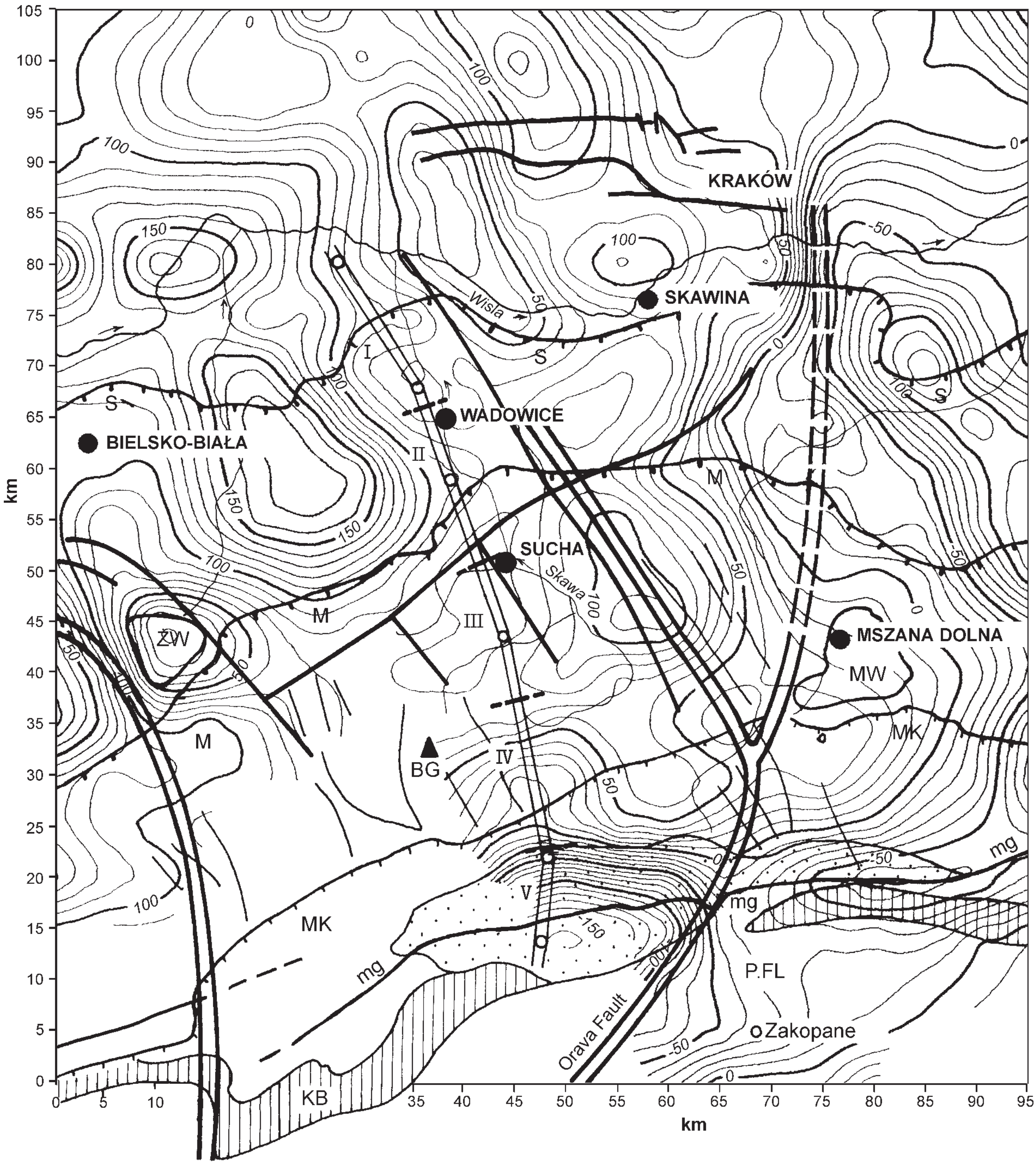

Fig. 4. Transformed Bouguer gravitational map. **BG** — Babia Góra summit, **ŻW** — Żywiec tectonic window, **MW** — Mszana tectonic window, **P.FL** — Podhale Flysch.

1998). The south part consists of anomalies oriented in W–E directions (Tatra direction). The middle part, having in the Fig. 4 rather low differentiation in gravity data, can be correlated with the III and IV parts in the MTS profile. That correlation allows us to construct a potential border of rotated masses at a distance of 10 km to the E sub-parallel to the Skawa Valley as it is shown in Fig. 4. Another interesting line crosses the Outer Carpathians on a prolongation of the Orava rotational fault from the west side of Mszana tectonic window to the north to Kraków. Near Kraków this line divides from the west the system of horst and graben, the so called Brama Krakowska Unit and from the east the Sandomierz Fore-Carpathian Depression.

Conclusions

The Orava transversal transforming fault is probably related to very deep geological structures. According to the magnetotelluric profile (Fig. 2) the rotation could be stimulated by structures which are deeper than 60 km. The rotation CCW could be higher than 16° to the NW, because this value was documented by the paleomagnetic method in relatively young sediments (2–2.5 Ma old). The CCW rotation in Hladovka on Pliocene sediments was determined as 38°. The results from the older (Sarmatian in age) deposit from "Old" Lipnica are not satisfied from the statistical point of view. Such rotation of the Orava microblock according to surface dimension with the crucial position of the Zázrivá-Párnica sigmoid and back thrusted section of Klippen Belt structure (profil IV on Geological map of the Western Carpathians without Quaternary formations compiled by K. Żytko et al. 1989, [in] Geological atlas of the Outer Western Carpathians and their foreland 1988–1989), and profil 2T (Vozár et al. 1998) seems to have had his geometrical central point (crossing of diagonals) ca. 8 km north of Babia Góra Mt. The value of shortening in the W–E direction can be evaluated as twice (100 km to 40 km). The length of the rotational fault from Kraľovany to the Mszana tectonic window is ca. 100 km and the width of the Magura Unit between the Żywiec tectonic window and the hypothetical east limit of the rotated block close to Sucha village is ca. 40 km. The related size on the northern margin of the Carpathians is similar (ca. 35 km).

The data presented in our paper lead to the conclusion that the rheological weak zone appears at the depth of 50–70 km. The lower lithosphere has differentiated structure under the Carpathians and under the foredeep. North of Babia Góra Mt, close to the mentioned crossing of diagonals of the hypothetically rotated Orava microblock the upper lithosphere seems to be rifted (at the distance of ca. 18 km) (Fig. 2). Thus probably here the European Platform is sinking to the south. According to Bielik et al. (1998), the inclination of the underthrusting European Platform is very steep 60–80°. The first separated crystalline block on the southern ending of the magnetotelluric profile seems to slope also to the south, when the axis of gravitational minimum is manifested (Figs. 3 and 4). Such rifted parts of the European Platform are postulated by Šefara et al. (1998) and Bielik et al. (1998). If this interpretation is good it is possible to suppose, that the Moho in this section of the Western Carpathians is situated at the depth of ca. 30–35 km. The value of depth of Moho position is comparable with Ryłko & Tomaś (1999) data from their western profile with the Moho generally at the depth of 35–40 km.

A difficult problem is interpretation of the position of the rotated Orava microblock. The lithosphere/asthenosphere boundary beneath the Orava microblock changes from 100-140 km according to Kováč (2000, fig. 15 — map summarizing data of Babuška (1987) and Horváth (1993)). The model of lithosphere evolution along the profiles 2T and 3T worked out by Šefara et al. (1998) presents very thin asthenosphere masses going up from the lower part of the lower lithosphere close to the Klippen Belt. The zone of the transversal transforming Orava faults directed to the N from the Poľana volcano (Central Slovak Volcanic Field) may be interpreted as such a narrow ductile zone responsible for structural rebuilding during the last 15 Ma.

It is interesting that ca. 30 km to the west from Chyżne village, close to the state boundary in Żywiec Beskid Mts, according to Ryłko & Tomaś' (2001) interpretation, the asthenosphere is dipping to the north from 60 to 80 km. Thus another interpretation of this rheological weak zone may also be assumed — the occurrence of some discontinuity within the lower lithosphere.

Some possibility to check the hypothetical rotation of the Orava microblock creates the comparison with the map of the depth of the crystalline basement of the Polish Carpathians. Such maps with presumed faults were worked out independently by Żytko (1999a) and Ryłko & Tomaś (1999) on the basis of magnetotelluric records. These maps differ much, especially in interpretation of the main faults. The zone of the transversal Orava Fault is clearly visible on Żytko's (1999a) map as the Podczerwienne–Mszana Dolna Fault with four sub-parallel faults on their west side. Żytko (1999a) named the line Ružomberok–Podczerwienne–Mszana Dolna "the most important in the western zone" (p. 193) of the Polish Carpathians. The comparison with Ryłko & Tomaś' (1999, 2001) maps seems to be more difficult. The authors mark the line Babia Góra–Rzeszotary (close to Kraków), but according to their map with depth isolines there are two independent lines; one from Babia Góra to north, to the northern margin of the Carpathians and a second similar to Żytko's (1999a) fault-line Podczerwienne–Mszana Dolna. The second one was incorrectly named by Ryłko & Tomaś (1999, 2001) the Babia Góra–Rzeszotary line. Ryłko & Tomaś (1999, 2001) mark the big transverse dislocation Zázrivá–Babia Góra–Rzeszotary but the transverse Orava Fault follows the line Ružomberok–Podczerwienne–Mszana Dolna.

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