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CONTINUOUS TECTONIC EVOLUTION OF THE ORAVA BASIN (NORTHERN CARPATHIANS) FROM LATE BADENIAN TO THE PRESENT-DAY?

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Abstract: The fault-bounded Orava Basin is situated on the boundary between the Inner and Outer Carpathians, close to the northern boundary of the Klippen Belt. The Orava Basin was formed during the Neogene times and was enlarged in its NE part during the Quaternary. According to the author's hypothesis, the crucial role has been played by a master transversal strike-slip fault named Prosiek-Domański Wierch–Lepietnica fault. The Orava Basin was opened by extension between the so-called Orava block rotated to the NW and the Tatra block shifted to the NE. According to palynological data it started 14–15 Ma and was probably synchronous with thrusting of the Magura Nappe and also with the uplift of the Tatra massif. Quaternary subsidence of the NE part of the present-day bottom of the Orava depression indicates, that probably the same tectonic mechanism is active now. Such an assumption is based on multidisciplinary studies: present-day activity of earthquakes (11 September 1995), geomorphological analysis of the Quaternary terraces aiming at the reconstruction of vertical tectonic movements, and on geophysical soundings. Some attempts aiming at understanding the role of paleostress field were made. The idea of a shift of tectonic process of subsidence and also of vertical uplift from the west to the east is supported by inferences derived from the thermal evolution of the western part of the Orava Basin.

Key words: Western Carpathians, fault-bounded Orava Basin, Quaternary alluvial or fluvio-glacial sedimentation and terraces formation, vertical tectonic movements, earthquake of 11 September 1995, seismic reflection data.

Introduction

The geographical position of the Orava Basin (Fig. 1) on the boundary between the Inner and Outer Western Carpathians is related to its evolution during the last 14–15 Ma. According to the author's assumption, the origin and history of the Orava Basin was closely associated with the structural history of the Inner and Outer Carpathians during this period. The crucial role has been played by a master transversal strike-slip fault which separates from west the massif of Veľká Fatra, Choč Mts, Skorušina Inner Flysch Range and a section of the Klippen Belt between Zázrivá and Trstená with Beskid Żywiecki and Babia Góra Range (Magura Flysch). From the east, the master fault separates the Nízke Tatry and Tatry massifs with Podhale Inner Flysch syncline, related section of the Klippen Belt from Staré Bystré to Plavec upon Poprad River and Magura Units with Gorce Mts and Beskid Sądecki Mts (Baumgart-Kotarba 1996), (Fig. 1). Numerous studies of the Neogene evolution of the Orava Basin have been published (Książkiewicz 1972; Oszast 1973; Watycha 1976; Oszast & Stuchlik 1977; Birkenmajer 1958, 1978, 1985; Pospíšil 1990, 1993; Bac-Moszaszwili 1993, 1995; Pomianowski 1995). Recent papers focus on micro-tectonic problems, attempting to reconstruct the paleostress field which affected the tectonic evolution of this area (Zuchiewicz 1994, 1998; Tokarski & Zuchiewicz 1998; Kukulak 1998).

In the author's opinion, the Orava fault-bounded basin represents a pull-apart basin. The Orava Basin became opened due to block-type horizontal movements. According to this hypothesis, the Orava Basin was opening by extension between the so-called Orava block rotated to the NW (~40°), and the Tatry block, shifted to the NE (Baumgart-Kotarba 1996). Opening of this basin, according to palynological data (Oszast & Stuchlik 1977), started 14–15 Ma ago (Upper Badenian, Serravallian). Quaternary subsidence in the NE part of the present-day bottom of the Orava depression indicates that probably the same tectonic mechanism, marked by the strike-slip Domański Wierch Fault, is active now, while the uplifted southwestern and southern part are now rather in a compressive regime (Fig. 2).

The aim of this paper is to demonstrate that the present day-activity of the earthquake of 11 September 1995 can be evaluated by geomorphological methods against the background of Quaternary vertical movements. Another problem is the presumed shift of subsidence from the west to the east. The uplift started in the west close to Ústie n. Priehradou town after the Pannonian, while at the Domański Wierch hill after the Dacian. Despite the change of the sense of vertical movements, the mechanism related to the activity of a large fault zone called the "Prosiek fault system" (Nemčok 1993), considered also as the Domański Wierch left-lateral strike-slip fault (Baumgart-Kotarba 1992, 1996), probably persists up to now.

Methods

Multidisciplinary studies make it possible to understand the complexity of the Orava Basin's evolution. Geological and

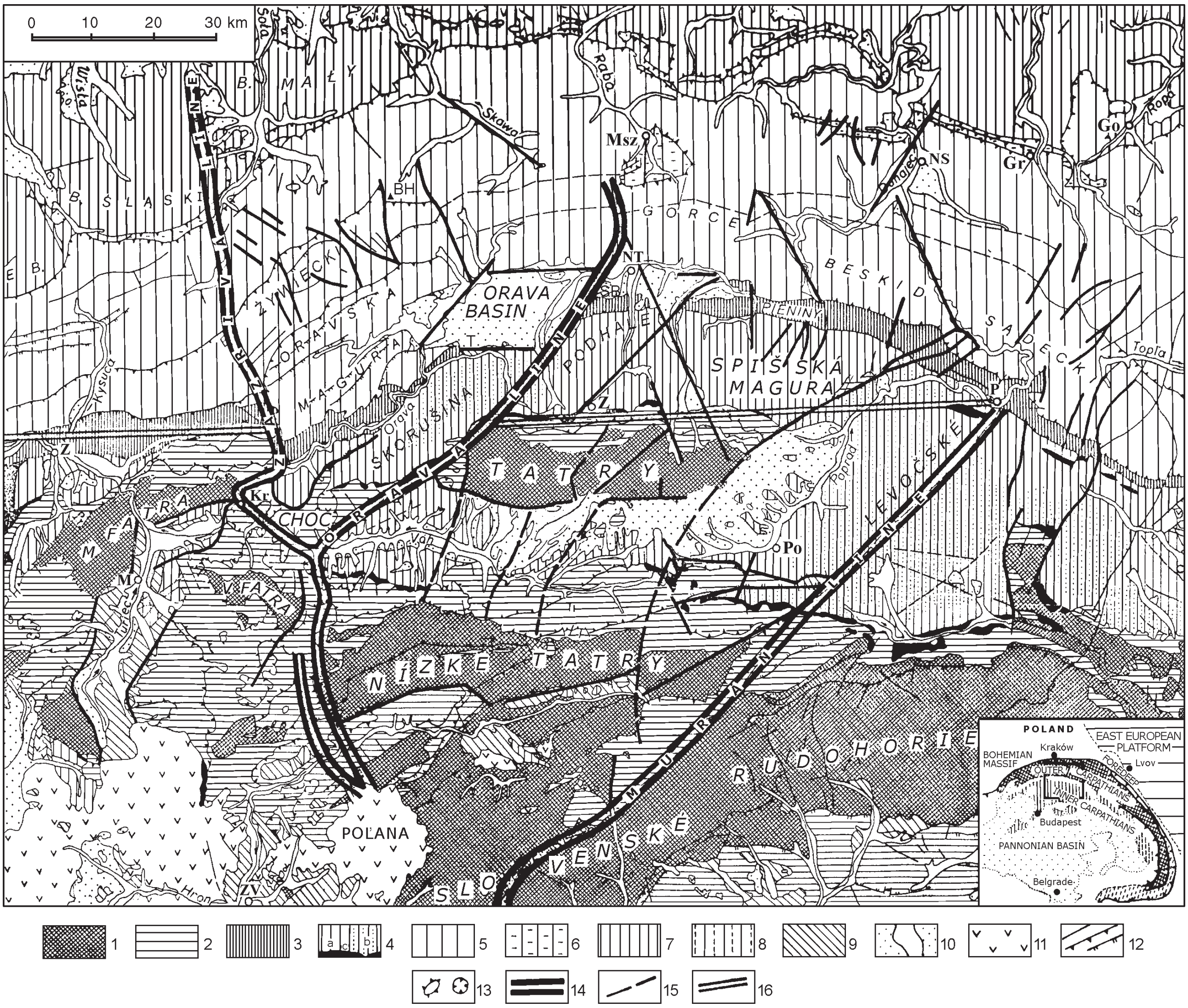

Fig. 1. The Orava Basin and Tatra Mts against the background of a simplified geological map of Western Carpathians, based on Buday et al. 1960 and Fusán et al. 1967. The author's interpretation of principal faults that bound the distinguished tectonic blocks. **1** — granitoid and metamorphic rocks, **2** — mainly Mezozoic faulted and thrusted sedimentary rocks of Inner Carpathians, **3** — Klippen Belt, **4** — Central Carpathian Flysch: **a** — Eocene, **b** — Upper Eocene, **c** — basal conglomerate, **5** — Magura Nappe, **6** — Dukla and Grybow units, **7** — Silesian Nappe, **8** — Subsilesian Nappe, **9** — Neogene molasses, **10** — Quaternary deposits, **11** — volcanites, **12** — overthrusts and faults, **13** — tectonic windows and remnants of nappes, **14** — transversal, important faults (Zázrivá, Orava, Muráň f.), **15** — other important faults, **16** — satellite lineament Zlín–Plavec named lineament of the northern limit of the Tatra Mts (Baumgart-Kotarba 1981, 1983).

geomorphological analyses are of fundamental importance, but the seismic reflection and refraction data reveal the complex architecture of the Neogene basin and the relationship between older Neogene structural units and newly-formed Quaternary grabens (Dec et al. 1998; Baumgart-Kotarba 2000). The earthquake of 11–12 September 1995 with the main shock of Mz ~3.7 and I > 5.5, not so weak on a Western Carpathians scale (recurrence time 30 years), was studied using micro- and macrostructural analyses (Baumgart-Kotarba & Hojny-Kołoś 1998). It is very interesting, that the calculated effects of focal mechanisms, compression or dilatation are in good agreement with long-lasting tendencies of vertical crustal movements. The latter can be reconstructed from an analysis of distribution of the Quaternary terraces in the bottom of the Orava Basin. The author's interpretation of 6 joint stereograms from sites: Lipnica, Hladovka, Staré Bystré, Miętustwo is preliminary, but together with geophysical sounding and geomorphological study seems to be coherent in terms of stress field reconstruction.

The idea of a shift from the west to the east of both the tectonic subsidence later replaced by uplift was related to the thermal evolution of the Orava Basin (Nagy et al. 1996) and combined with geomorphological analysis.

Results

The results are illustrated in Fig. 2 which demonstrates the distribution of the succeeding 18 hypocentres (temporal aspect) of the main shock and aftershocks (1–6, 7–10, 11–12,

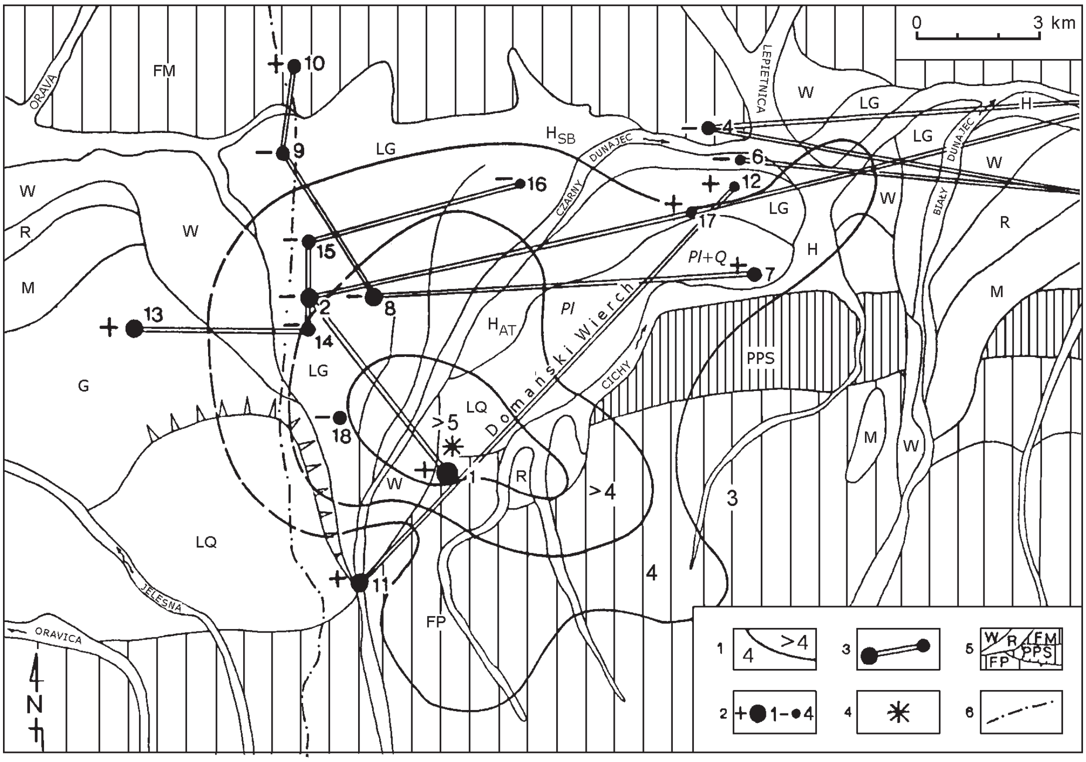

Fig. 2. Parameters of the earthquake of 11 September 1995 against the background of the Orava Basin tectonic units and Quaternary terraces. Seismic data elaborated by Hojny-Kołoś. **1** — isolines of earthquake intensity (MSK 64): >5.5, >4.5, > 4, >3, **2** — hypocenters 1 to 18, the black spots denote magnitude and their characteristics, compressive (+) or dilatation (–), **3** — temporal alternation of main shock and after-shocks, **4** — epicenter, **5** — geological structures: **FM** (Magura Flysch), **FP** (Podhale Flysch), **PPS** (Pieniński Pas Skałkowy — Pieniny Klippen Belt) and terraces: **LQ** — Lower Quaternary, **G** — Günz, **M** — Mindel, **R** — Riss, **W** — Würm, **LG** — Late Vistulian, $\mathbf{H_{AT}}$ — Holocene-Atlantic, $\mathbf{H_{SB}}$ — Holocene-Subboreal, on Domański Wierch hill Pliocene *Pl* and Pliocene covered by Quaternary deposits *Pl + Q,* **6** — European water divide.

13–16, 17–18, see Table 1), calculated from data registered by three seismic observatories — Ojców, Niedzica and Racibórz (Baumgart-Kotarba & Hojny-Kołoś 1998). The fourth observatory at Skalnaté Pleso in the Slovak High Tatra Mts. noted more shocks during this earthquake (personal information from Skalnaté Pleso Observatory). The sign "+" or "–" before the number of concrete shocks denotes compression or dilatation focal effects. The background of this map represents the main structural features of the Polish fringe of the Orava Basin. White colour in the bottom of the Orava Basin denotes Quaternary terraces (Fig. 2). In the Orava Basin, Late-Vistulian glacifluvial fan and Holocene fan-terraces are marked by small dots (Fig. 5). The flat (dotted) areas are probably related to Quaternary subsidence, documented at Wróblówka by the 112 m thick fluvial/glacifluvial deposits derived from the Tatra Mts (Watycha 1973; Baumgart-Kotarba 1992). The new seismic reflection and refraction profiles demonstrate that the Wróblówka graben is rather large (ca. 100–120 m deep, 2 km broad and 6 km lenght in west–east direction), and close to his southern bordering fault is ca. 128 m deep (Baumgart-Kotarba 1998). The second parallel west–east oriented Pieniążkowice graben, ca. 50 m deep, is separated from Wróblówka graben by a flysch horst, which rises only 5 m above the alluvial braid-plain.

Table 1: List of seismic events: No. 1-18 of September, 11-13, 1995, on Western Podhale and Eastern Orava basin, and No. 19-20 of October 13, 1995, on Eastern Podhale (Czarna Gora-Trybsz). According to M.Hojny-Kołoś in Baumgart-Kotarba (1998).

No	Date	GMT	M_sZ	C / D	I_o	h [km]
1	11 IX 1995	04^h 02'18	3,7	C	5^o	6
2	11 IX 1995	05^h 02'22	3,3	D	4^o	5
3	11 IX 1995	05^h15'12	2,2	D	2^o	5
4	11 IX 1995	06^h36;35	2,0	D	2^o	5
5	11 IX 1995	06^h59'13	2,1	D	2^o	5
6	11 IX 1995	07^h58'29	2,2	D	2^o	5
7	11 IX 1995	08^h10'56	2,5	C	3^o	5
8	11 IX 1995	09^h02'33	3,2	D	4^o	6
9	11 IX 1995	09^h42'21	2,6	D	3^o	5
10	11 IX 1995	10^h06'38	2,4	C	$2,7^o$	5
11	11 IX 1995	14^h14'40	2,7	C	3^o	5
12	11 IX 1995	15^h23'11	2,0	C	2^o	5
13	11 IX 1995	17^h17'19	3,4	C	5^o	6
14	11 IX 1995	17^h23'33	2,4	D	3^o	5
15	11 IX 1995	17^h42'24	2,3	D	2°	5
16	11 IX 1995	18^h09'15	1,9	D	2°	5
17	12 IX 1995	11^h48'24	1,9	C	2°	5
18	13 IX 1995	18^h59'43	2,3	D	3°	5
19	13 IX 1995	05^h47'31	3,7	C	5°	6
20	13 IX 1995	06^h02'15	3,7	C	5°	6

Note: C/D – compressive or dilatation effect

The compressive effects of the earthquake hypocentres are spatially related to areas characterized by uplift during the Quaternary, while the dilatation effects belong to flat areas of the NE part of the Orava Basin. The focal depth of the main

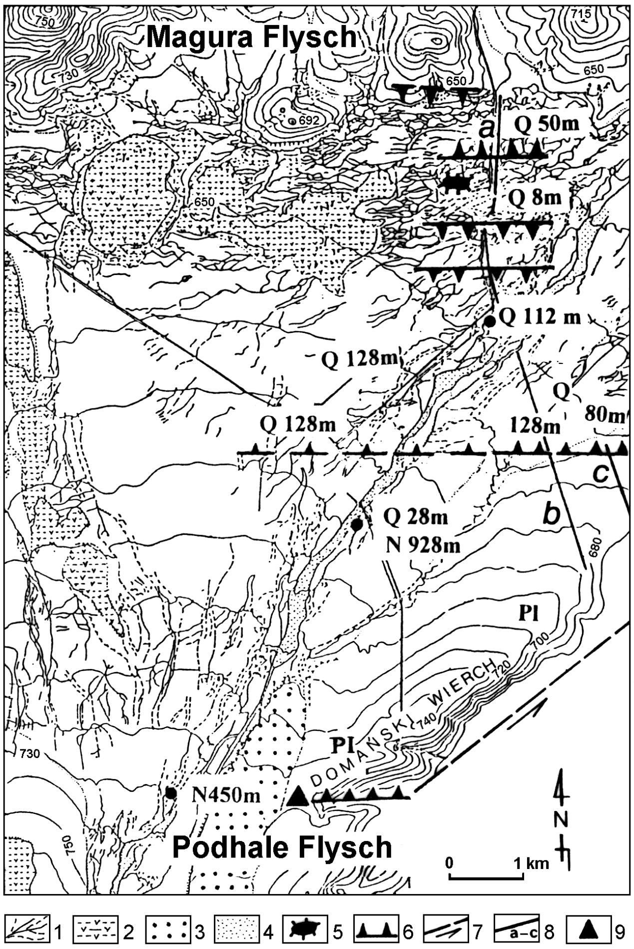

Fig. 3. Geomorphological map and Quaternary faults documented by geophysical sounding (Baumgart-Kotarba et al. 2001) (**a** — refraction, **b**, **c** — reflection profiles). **1** — braided river pattern, **2** — peat-bogs, **3** — Würm terrace, **4** — present-day braided plain, **5** — flysch hill, **6** — W-E faults, **7** — the Domański Wierch oblique fault (left-lateral strike slip-fault), **8** — geophysical profiles (a–c), **9** — the epicenter of earthquake of 11 September 1995.

shock was calculated at about 6 km. This depth corresponds very well with Lefeld–Jankowski's model of the depth structure of the Tatra Mts together with superimposed syncline of the Podhale Flysch and narrow structure of the Klippen Belt, pushed on light and low-resistivity rocks of unknown origin (Lefeld & Jankowski 1985). Thus, it is possible to suggest that the whole Tatra Mts massif with Podhale and the Klippen Belt have migrated to the NNE, and are shifting till now. The Quaternary opening of the Orava Basin with Wróblówka and Pieniążkowice grabens and horst structures of W-E orientation (Fig. 3) could be interpreted as an effect of extension perpendicular to the main stress direction from the south (probably 10–15°). Such an assumption is in good agreement with seismic profiles made across the uplifled Domański Wierch molasse, together with the Wróblówka graben. Close to the southern fault of the Wróblówka graben, the Pliocene deposits of Domański Wierch series are dipping to the south on reflection profiles (Fig. 4), whereas the Domański Wierch series in general is dipping at a low angle to the NNW (Birkenmajer 1958; Baumgart-Kotarba 1998, 2000).

The isolines in Fig. 2 indicate the intensity of the earthquake of 11 September 1995. It seems that these elongated isolines mark two orientations: the main SW-NE one, related to the strike-slip fault of Domański Wierch, and the perpendicular one, NW–SE. The second orientation can be interpreted as a line marking the subsidence. This line seems to be parallel to the zone of change of vertical movements (shorter diagonal of the the Orava Basin parallelogram) (Fig. 5). Hypocenter no 13, with sign "+", belongs to the uplifted part of the bottom of the Orava Basin. Also, the hypocenter no 10 with "+" is located on the uplifted northern fringe of the Orava Basin.

A reconstruction of the stress field during the Upper Pliocene and Quaternary was made on fractured pebbles of the Late Pliocene (Dacian) age of the Domański Wierch at Staré Bystré (Zuchiewicz 1994, 1998; Tokarski & Zuchiewicz 1998; Kukulak 1998). These diagrams are interpreted as a result of horizontal maximum stress oriented 35–45° NE. It is also the orientation of the Domański Wierch uplifted ridge and that of the assumed strike-slip fault of the Domański Wierch (Fig. 3). The author's interpretation of Tokarski & Zuchiewicz's measurement of fractured clasts of Sarmatian age at Miętustwo, south of Domański Wierch, is that the main direction 13–23° represents σ_1 of the regional stress field in the Tatra Mts. — Podhale block. The Domański Wierch oblique fault has SW-NE direction (45°).

This regional stress field of N13–23° E orientation of the maximum horizontal stress is comparable with the NNE-orientated present-day horizontal stress direction, inferred from breakout studies by Jarosiński (1998). At locality Miętustwo A, one distinct maximum of N15° E of joints was interpreted as an extensional one (Tokarski & Zuchiewicz 1998). Thus, the Quaternary formation of grabens and horsts in the NE part of the Orava Basin seems to be related to the NNE-orientated regional maximum stress direction. The fault situated between the Domański Wierch uplifted molasse series and subsided Wróblówka graben is — judging from reflection profiles (Fig. 4) — a reverse fault and can be interpreted as a result of a push of Pliocene molasses on relatively young Quaternary fluvial/glacifluvial Czarny Dunajec river sediments. Activation of such a fault can be related to Quaternary uplift and shifting of the Tatra massif together with Podhale region and a segment of the Pieniny Klippen Belt, due to NNE-directed compression. In front of the compressive zone, the region showing E-W extension is probably bounded by normal (?) faults. On the west, the NW-oriented fault is placed between the western part of the Orava Basin, uplifted during Quaternary times, and its subsiding NE part (Fig. 5). On the east, the Wróblówka graben is probably bounded by a N-S-orientated fault which, farther south, borders Pliocene deposits of the Domański Wierch hill. This hill is elevated less than the Pieniny Klippen Belt segment with the locality Rogoźnik and the Staré Bystré Beds (outer flysch) outcropping at the Cichy stream (Figs. 2, 5) which runs parallel to the Klippen Belt (Cieszkowski 1992, 1995). On the eastern side of the N-S running fault, the Pliocene molasses have been drilled by only one borehole located north of the Cichy stream. In this well-log, 35-m-thick Quaternary sediments overlie Neogene silty-clayey fluvial deposits. The extent of Neogene molasses needs supplementary seismic surveys.

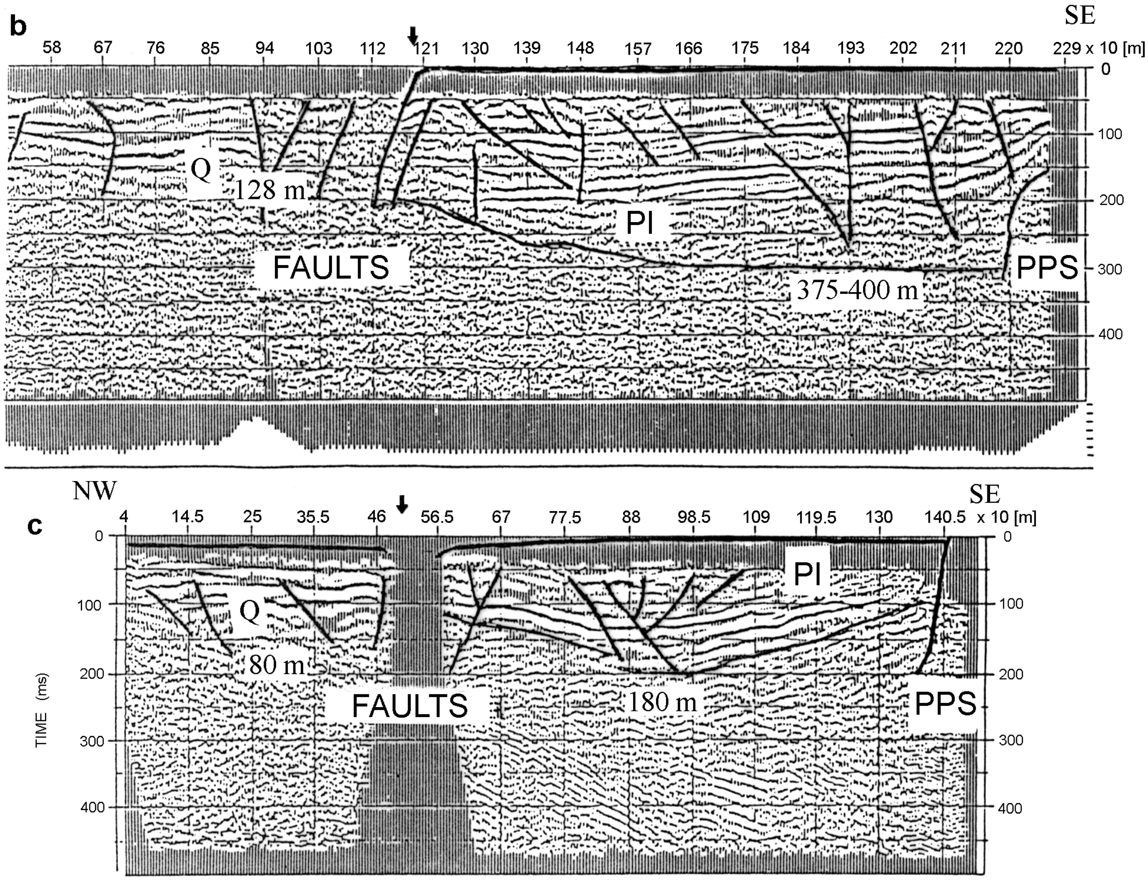

Fig. 4. Interpretation of two reflection profiles, "b" and "c" in the eastern part of the Orava Basin. „Faults" means the tectonic zone between uplifting Pliocene molasse of Domański Wierch hill and subsiding Quaternary in the fault-bounded Wróblówka graben; PPS: Pieniny Klippen Belt.

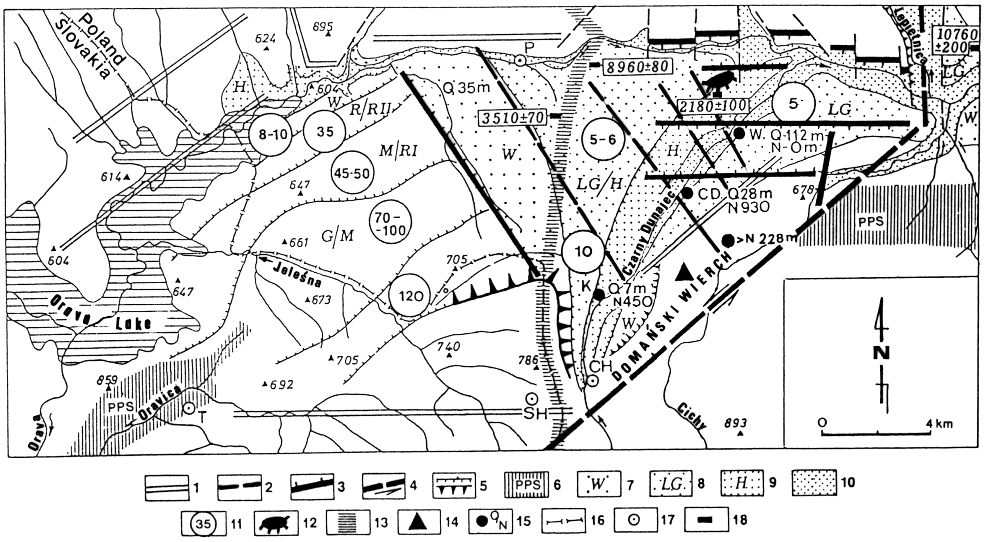

Fig. 5. Geomorphological features of the Orava Basin and system of faults active during Neogene and Quaternary. **1** — faults bordering the fault-bounded complex Orava Basin, **2** — secondary faults, **3** — Quaternary faults, **4** — left-lateral strike-slip fault (Prosiek-Domański Wierch–Lepietnica), **5** — the extent of glacio-fluvial/fluvial terraces (**G** — Gűnz, **M** — Mindel, **R** — Riss, **W** — Würm) with escarpments, **6** — Klippen Belt (PPS), **7** — Würm terrace, **8** — Late-Vistulian terrace, **9** — Holocene terraces, **10** — braid-plain of the Czarny Dunajec river, **11** — height above the Orava river, **12** — flysch hill, **13** — European water-divide, **14** — epicenter of earthquake of 11 September 1995, **15** — location of drillings: **W** — Wróblówka, **CD** — Czarny Dunajec, **K** — Koniówka, **D** — Domański Wierch. Thickness of Neogene (N) and Quaternary (Q) deposits in metres, **16** — state boundaries, **17** — sites: **P** — Piekielnik, **T** — Trstená, **SH** — Suchá Hora, **CH** — Chochołów, **18** — radiocarbon datings.

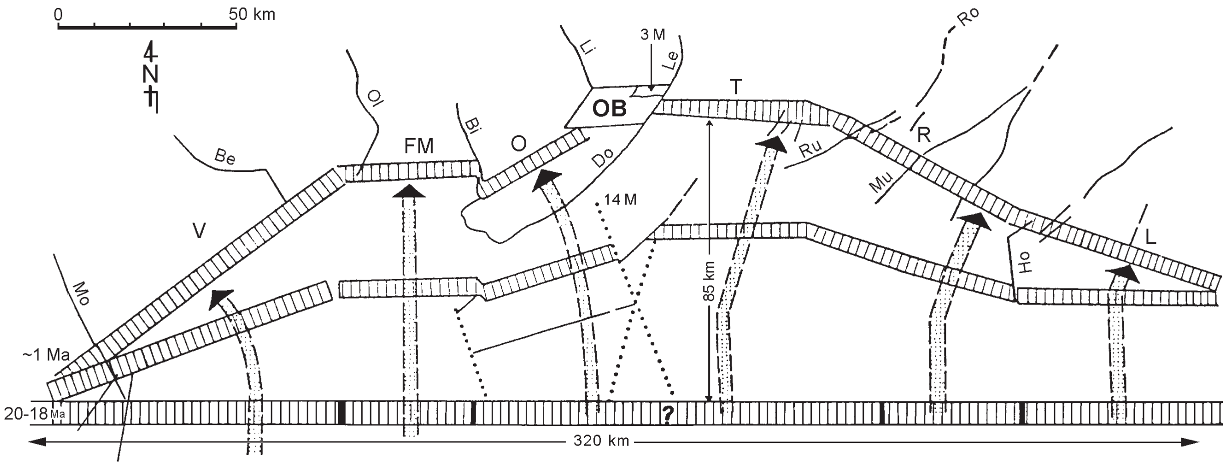

Fig. 6. Hypothetical model of the formation of the Western Carpathian arc during the time spans: 20–18, 14 and about 1 million years ago (according to Baumgart-Kotarba 1996). Hatchures show the Klippen Belt as a symbol of the Western Carpathians arc, whereas the arrows mark assumed direction of movements of the blocks (**V** — Váh block, **FM** — Malá Fatra block, **O** — Orava block, **T** — Tatra block, **R** — Rudohorie block). The model shows opening of the Orava Basin due to tension between the Orava block rotated to the NW and Tatra block migrating to the NE. Main block bounding faults: **Mo** — Morava fault, **Be** — Bečva fault, **Ol** — Olza fault, **Bi** — Biała (Zázrivá) fault, **Li** — Lipnica fault, **Do**–**Le** — Domański Wierch and Lepietnica faults (part of the Orava transversal fault), **Ru** — Ružbachy fault, **Ro** — Ropa fault, **Mu** — Muráň fault, **Ho** — Hornád fault, **L** — Laborec fault.

It is possible to assume that the long-persisting N to NNE-orientated horizontal stress, induced by the Alcapa's advance, has been responsible for formation of a large oblique Orava fault during the last 14 Ma. The conjugated NE-SW and NW-SE faults led to Neogene opening of the Orava Basin, beginning from the Late Badenian (Serravallian) times. This opening was directed towards the NE, utilising a system of parallel NW-orientated faults. Important changes in tectonic evolution of this part of the Western Carpathians could have been related to a substantial impact exerted by the close proximity to the then uplifted Tatra massif and formation of the Podhale synclinorium, controlling W-E and N-S orientated systems of faults and fractures. The exact timing of these events is difficult to constrain precisely. I suppose that at the Pliocene/Quaternary boundary, a gravel-bed river carrying quartzitic sandstones existed in that area, testifying to increased erosion. Close to Lipnica, Pliocene sediments resting on mildly folded Sarmatian strata were mapped by Watycha (1976). According to unpublished palynological analysis by L. Stuchlik (Institute of Palaeobotany, Polish Academy of Sciences, Kraków), a Plio-Quaternary age of the so-called Pliocene strata cannot be ruled out. That was the time of volcanic activity, documented by a layer of tuffite comprised in organic sediments filling an abandoned channel. The Tatra-derived crystalline cobbles and pebbles in the Orava Basin were described from the Wróblówka well-log. These clasts were deposited during a relatively cold Quaternary period, characterized by the presence of tundra and some forest patches (Watycha 1973).

Discussion and conclusions

The thermal evolution of the western part of Orava Basin was reconstructed by Nagy et al. (1996). On the Polish side at Lipnica, the Sarmatian strata are exposed above 650 m a.s.l., whereas at Czarny Dunajec borehole the Sarmatian strata are at –116 – +117 m a.s.l. (depth 848–565 m). At Lipnica, the coal seems to be controlled by high pressure and probably high temperatures (Kołcon & Wagner 1991). Geochemical data and thermal reconstruction of the basin indicate that the western part of the Orava Basin near Ústie n. Priehradou underwent subsidence (up to 1000 m depth, at temperature above 70 °C), and during the Pliocene (Nagy et al. 1996) was uplifted together with its fringe. Thus, the present depression of Orava is of erosional character due to exhumation of soft Neogene strata. Steep slopes bordering the Orava depression are built of flysch rocks and probably are close to earlier-formed slopes controlled by faults. The NE part of the Orava Basin is a young subsiding area. Fig. 5 illustrates both the older and younger faults.

The important question is whether the present-day and Quaternary mechanisms of the Orava Basin formation were different from those during Neogene times, or could this evolution be related with the same tectonic process of rotation of the so-called Orava Block (Choč with Skorušina, section of the Klippen Belt and Beskid Wysoki with Babia Góra and Romanka-Pilsko group), and a shift to the NE of the Tatra block. The reason for changes from subsidence to uplift in the Orava Basin can be interpreted as follows. A shallower platform basement in the west hampered the advance of the Outer Carpathians earlier than on the east. The Quaternary and present activity of strike-slip fault of Domański Wierch controls the young subsidence in the NE part of the bottom of the Orava Basin only. Such an effect was described by Kováč et al. (1989) in relation to the western part of the Western Carpathians in the Trenčín-Žilina section which was stopped by the crystalline Bohemian Massif. In this case the physical rotation to the NW was documented palaeomagnetically on Eggenburgian (42°) and Karpatian (37°) marine deposits filling piggy back basins. On the Polish side, in the Babia Góra

Range, Aleksandrowski (1985) has reconstructed two generations of folds. The younger NW-SE striking folds were considered as a result of folding in the East Carpathians and were superimposed on the older ones. The older generation was formed due to horizontal stress, which involved folding of the Magura Nappe. The author's assumption is that the older generation predates rotation, and the younger one could be related to rotation of the Orava block to the NW (Fig. 6). The age of the opening of the Orava Basin, evaluated till now due to palinological studies of fluvial deposits from the Czarny Dunajec borehole (Oszast & Stuchlik 1977), is presently very well supported by the data of Oszczypko (1997), showing that the Magura and Silesian nappes are overthrust upon foredeep marine deposits (Lower and Middle Badenian) in Zawoja borehole. Oszczypko (1997) concluded about multistage overthrusting, including the Late Badenian (stage 3) and after Sarmatian (stage 4) stages, and reconstructed the position of the front of the Carpathian nappes. Zawoja borehole is located 35 km to the NW of the Czarny Dunajec borehole, situated in the central part of the Orava Basin. Thus, the thrusting of Magura Nappe and the opening of Orava Basin have been synchronous. According to Cieszkowski's (1992, 1995) opinion, the youngest flysch rocks outcropping close to the Klippen Belt are Middle Miocene (Staré Bystré Beds), while younger Kopaczyska and Pasieka Beds are typical deep sea marine molasses. The Middle Miocene beds according to B. Olszewska's opinion Langian, and even Serravallian in age (Cieszkowski 1992, 1995). In such a case, the opening of the Orava Basin was manifested in a relatively short time. It is also interesting that the uplift of the Tatra Mts, according to fission track dating, is 15–10 Ma only (Kráľ 1977). It is possible to interpret that the beginning of the opening of the Orava Basin (Fig. 6) was also synchronous with the onset of the Tatra uplift from a depth of 5 km (Baumgart-Kotarba 1998). According to new data concerning K-Ar dating of the Miocene andesite intrusions in the southernmost part of the Magura units close to the Pieniny Mts (Wżar and Bryjarka Mts), Birkenmajer & Pécskay (1999) conclusion is that both the 1st and 2nd phases are similar in age between ca. 13.5–11Ma. It means that the andesitic subvolcanic activity is related to the same tectonic phase which uplifted of the Tatra Mts, opened the Orava Basin and induced thrusting of the Magura Nappe, as was documented by Oszczypko (1997).

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