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QUATERNARY TECTONIC GRABENS OF WRÓBLÓWKA AND PIENIĄŻKOWICE AND THEIR RELATION TO NEOGENE STRATA OF THE ORAVA BASIN AND PLIOCENE SEDIMENTS OF THE DOMAŃSKI WIERCH SERIES IN PODHALE, POLISH WEST CARPATHIANS

Abstract. The fault-bounded Orava Basin was formed during the Neogene time and was enlarged in its NE part during the Quaternary. The relationship between Quaternary subsiding part of present-day Orava Basin and Neogene infill was studied by use geophysical soundings. Reflection and refraction seismic profiles document Quaternary horst and graben WE trending system and reverse character of fault limiting uplifted Pliocene molasses and subsided Quaternary fluvial/fluvioglacial deposits. Seismic sounding inform about complexity of Neogene basin. There are two different systems of faults. First, NE oriented concerns lateral strike-slip sinistral fault of the Domański Wierch, and perpendicular, conjugated faults (NW oriented), which opened the basin in NE direction since the Upper Badenian to the Pliocene. Second, younger system, W–E oriented seems to be related with the main horizontal compression caused by the Carpatho-Pannonian plate motion inferred from breakout analysis. This compression is probably responsible for reverse fault which uplift the Domański Wierch ridge above Wróblówka graben, but also for the Tatra Mts uplift and the Podhale Flysch sincline formation.

Key words: pull-apart basin, faults-bounded basin, Pliocene molasses, Neogene subsidence, Quaternary tectonics, oblique fault, reverse fault, geophysical sounding, seismic refraction and reflection profiling, earth-quake of 11 September 1995, Orava Basin

INTRODUCTION

Two different opinions have been expressed regarding the origin of the Orava Basin, West Carpathians. The synclinal character of the basin has been suggested by L. Watycha (1976a, 1976b), M. Klimaszewski (1988) and J. Chowaniec et al. (1996), whereas M. Książkiewicz (1972), M. Baumgart-Kotarba (1991–1992) and P. Pomianowski (1995) consider it to represent a tectonic trough. The first author of this paper maintains that the basin is an intramontane basin bounded by faults that have been active also in Quaternary times, particularly in the NE part (Baumgart-Kotarba 1991–1992, 2000, 2001). Judging from palynological studies of the strata drilled at Czarny Dunajec (Oszast and Stuchlik 1977), the Neogene trough was shaped in the Late Badenian through Middle and, possibly, Late Pliocene timespan. The age of the opening of the Orava Basin is synchronous with overthrust of Magura and Silesian nappes upon foredeep marine deposits (Lower and Middle Badenian) in Zawoja borehole (Oszczypko 1997). Neogene sedimentation in the Orava Basin terminated with the Domański Wierch series, whose top has been dated to the middle Pliocene (Dacian; cf. Oszast 1973). According to Slovak geologists, the series drilled at Hladovka, west of the Czarny Dunajec river valley, is capped by 90-m-thick Upper Pliocene deposits (Nagy 1993).

The whole Orava Basin, together with the surrounding Gubałówka and Skoruszyna Foothills in the south, as well as the Babia Góra Mt and Orava Foothills in the north, have been uplifted and erosionally dissected. As a result, the basin filled with poorly resistant fine-grained sediments has been more strongly eroded than the surrounding areas built up of more resistant flysch strata. Therefore, the present-day Orava Basin represents an erosional-denudational basin (Baumgart-Kotarba 1991–1992, 1996). However, tectonic subsidence of the Orava trough has continued in the Quaternary in the NE part, as shown by the results of wells drilled at Nowy Targ and Wróblówka and documenting the presence of 112-m-thick fluvial/glacifluvial Quaternary sediments overlying eroded flysch strata of the Magura nappe (Watycha 1973, 1976a, 1976b). The cited author interpreted thick Quaternary fill at Wróblówka as a proof of northward migration of the Quaternary subsidence.

The positive tectonic movements during the late Neogene to early Pleistocene times resulting in Domański Wierch and Frydman fault-controlled areas, close to Homole Gorge in the eastern part of Polish Klippen Belt and in Szaflary near Nowy Targ in vertical displacement and tilting were recognized on the north boundary of Pieniny Klippen Belt in the contact with MaguraNappe (Birkenmajer 1958, 1978).

OBJECTIVES AND METHODS

The aim of this paper is to present an hypothesis of tectonic development of the Orava Basin in Quaternary times basing on geomorphic and geophysical studies. Detailed geomorphological mapping and remote sensing study of the topography of the Czarny Dunajec river fan enabled us to chose the best transects for geophysical profiling, aiming at detection of faults in the subsiding part of the basin. These faults have been documented by seismic and, partly, magnetic techniques. Orientation of tectonic structures has been analysed taking into account the results of palaeostress data pertaining to fractured pebbles of the Domański Wierch series (Tokarski and Zuchiewicz 1998a, 1998b, 1998c, Kukulak 1998).

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GEOMORPHIC DATA

The hitherto-conducted geomorphological studies indicate that the western part of the Orava Basin has been uplifted and erosionally dissected in Quaternary times, resulting in the formation of a system of six strath terraces rising 150 to 10 m above the present-day Orava river bed, close to its mouth to the Orava reservoir (600 m a.s.l.). These are terraces of the Czarny Dunajec river which carries material from the Western Tatra Mts and Podhale area to the Orava and Vah rivers. Each terrace has a separate rock base and alluvial caps (cut-and-fill terraces) are overlain by thick solifluction-proluvial sediments. Higher-elevated terraces are also covered by aeolian, strongly clayey sediments, blown out from weathering mantles of the Neogene silts and clays (Baumgart-Kotarba 1991–1992). One can conclude, therefore, that Quaternary changes of the main European drainage divide that passes through the Orava Basin have been tectonically controlled. This divide used to attain position similar to the present-day one (Fig. 1) during infilling of the subsiding Wróblówka graben, and was located farther east at times when the Czarny Dunajec river, leaving the Tatras and Podhale areas, was directed westwards, flowing together with the Orava river to the Vah and Danube rivers, i.e. to the Black Sea. It is also possible that at some periods the Czarny Dunajec river could have supplied both the Dunajec and Orava rivers. Since the age of the Wróblówka basin fill has not been established precisely, except for preliminary palynological determinations (Mojski and Watycha 1984), and because the age of six terraces within the basin is arbitrarily determined (except for the last glacial terrace), we are not able to distinguish Quaternary tectonic phases. It is likely that fine-grained sediments intercalating Tatra-derived gravels in the Wróblówka well log indicate periods of local, flysch-derived supply of the basin, when the Czarny Dunajec river was directed westwards. Basing on the terrace sequence and TL age determinations of aeolian loams overlying alluvium of the 45–50 m terrace of the Orava river at Chyżne, M. Baumgart-Kotarba (1991–1992) inferred an old-Riss or Mindel (Drenthe or Elsterian) age of the terrace. Aeolian sediments are older than the Eemian interglacial (Saalian or, more precisely, Wartanian).

Irrespectively of age of individual Quaternary terraces, geomorphic studies appear to indicate that the main tectonically-controlled boundary runs diagonally as the shorter diagonal of the Orava Basin parallelogram: the area situated to the west of it has been uplifted in Quaternary times, whereas the eastern area has undergone subsidence (Fig. 1).

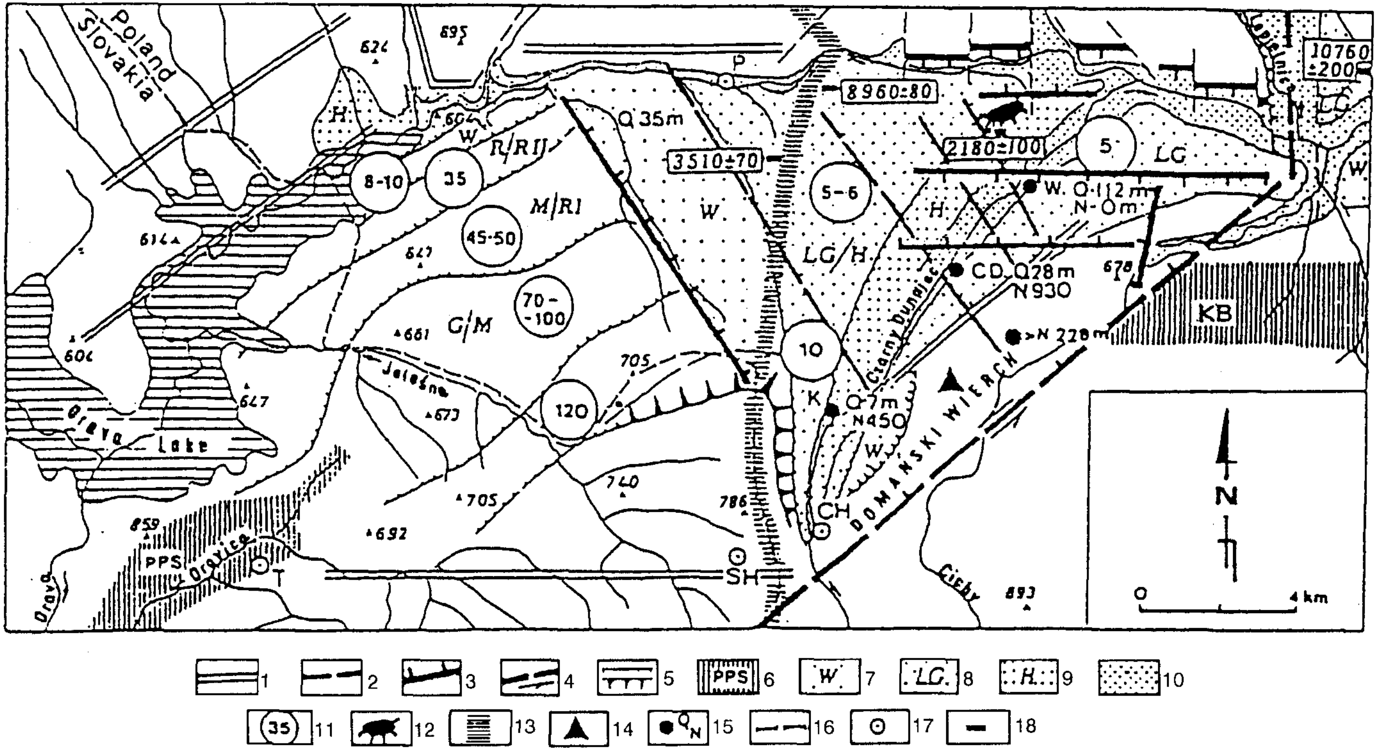

Fig. 1. Geomorphological features of the Orava Basin and system of faults acting during Neogene and Quaternary. 1 — faults bordering the fault-bounded Orava Basin, 2 — secondary faults, 3 — Quaternary faults, 4 — left-lateral strike-slip fault (Prosiek–Domański Wierch–Lepietnica), 5 — the extent of glacio-fluvial/fluvial terraces (G — Guünz, M — Mindel, R — Riss, W — Würm) with escarpment, 6 — Klippen Belt (PPS), 7 — Würm terrace, 8 — Late Vistulian terrace, 9 — Holocene terrace, 10 — braid-plain of Czarny Dunajec river, 11 — height above the Orava river, 12 — flysch hill, 13 — European water-divide, 14 — epicenter of earth-quake of 11 September 1995, 15 — location of drilling: W — Wróblówka, CD — Czarny Dunajec, K — Koniówka, D — Domański Wierch. Thickness of Neogene (N) and Quaternary (Q) deposits in meters, 16 — state boundary, 17 — sites: P — Piekielnik, T — Trstena, SH — Sucha Hora, Ch — Chochołów, 18 — radio-carbon dating

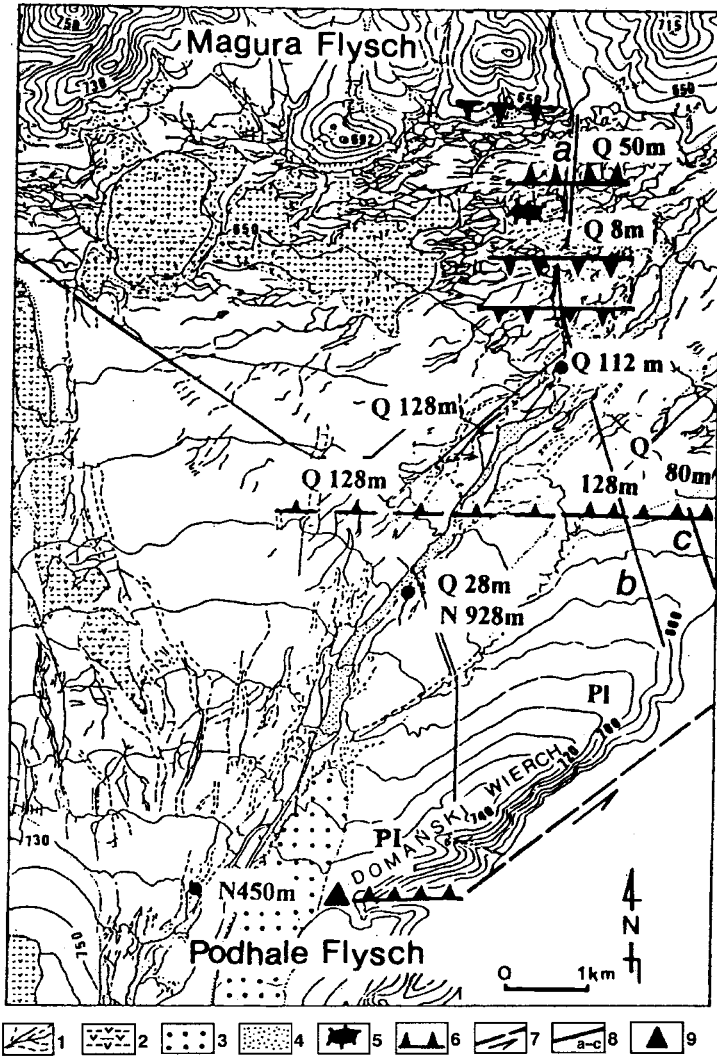

Fig. 2. Geomorphological map and Quaternary faults documented by geophysical sounding (a — refraction, b, c — reflection profiles). 1 — braided-river pattern, 2 — peat bogs, 3 — Würm terrace, 4 — present-day braid-plain, 5 — flysch hill, 6 — W–E faults, 7 — Domański Wierch oblique fault, 8 — geophysical profiles, 9 — the epicenter of earth-quake of 11 September 1999

Another geomorphic indicator is morphology of the Czarny Dunajec river alluvial fan, whose surface has been shaped in the Vistulian Late Glacial and the Holocene, as shown by palynological studies performed on clays underlying the peatbog Puścizna Wielka, situated on the main European drainage divide, as well as by dating of the bottom peat layers (Obidowicz 1988). The surface of the fan bears numerous traces of braided channels and it is overtopped by a 5-m-high hill built up of flysch strata, situated west of the Pieniążkowice–Wróblówka road (Fig. 2). The hill is elongated E–W and separates the distal part of the fan into the northern part, spreading along the steep slopes of the Orava Foothills near Odrowąż, and the southern part, with numerous braided palaeochannels of the Czarny Dunajec river between Czarny Dunajec and Wróblówka–Długopole. It should be mentioned that the channel pattern north of the hill is a meandering one, quite unlikely the Czarny Dunajec style. These channels were cut by a small Piekielnik stream, supplied mainly from slopes built up of the Magura flysch strata, although also carrying Tatra-derived gravels. The topography of this part of the Orava Basin enables us to put forward an hypothesis of tectonic origin of the youngest Pieniążkowice graben. The third piece of geomorphic evidence concerns the probably fault-like contact between the uplifted Domański Wierch area and the Quaternary Wróblówka graben.

GEOPHYSICAL DATA

Due to the scarcity of well logs in the study area, we have decided to carry out refraction and reflection profiling to recognise the character of structures within the Orava Basin, considered by L. Pospišil (1993) and M. Baumgart-Kotarba (1993, 1996) a pull-apart trough.

A group of geophysicists led by R. Ślusarczyk from the Department of Geophysics, Faculty of Geology, Geophysics and Environmental Protection of the University of Mining and Metallurgy in Kraków, shot 7 seismic profiles in the years 1995–1998 (Figs. 2, 3). Geophysical profiling was preceded by well-log testing to estimate the reliability of applied techniques in detecting the top of flysch strata and Neogene/Quaternary boundary. For the refraction-reflection profiling, 24-channel Terraloc MK–3 equipment and a pounding source EWG-III were used. Measurements were performed on 230-m-long segments along which 24 geophones every 10 m were located. Magnetic studies on three profiles were conducted under the supervision of M. Lemberger. These studies aimed at locating possible fault zones and were conducted parallel to the main seismic profiles.

The seismic refraction studies were performed in close relation to well logs of Wróblówka and Czarny Dunajec (prolife 2, Fig. 5A). It occurred that the registered high velocities of 2,100–2,000 m/s point to the presence of coarse-clastic Quaternary sediments, whereas the flysch substratum does not give refraction wave from a depth of 60–70 m. On the other hand, measurements performed near Czarny Dunajec well, where 28-m-thick coarse-clastic Quaternary sediments were drilled, indicated that the boundary between Quaternary sediments and clayey-silty Neogene strata is not sharp, as shown by a drop in recorded velocities from 2,000 m/s in coarse-clastic Quaternary strata to 1,800 m/s within Neogene strata. Therefore, refraction studies were conducted along

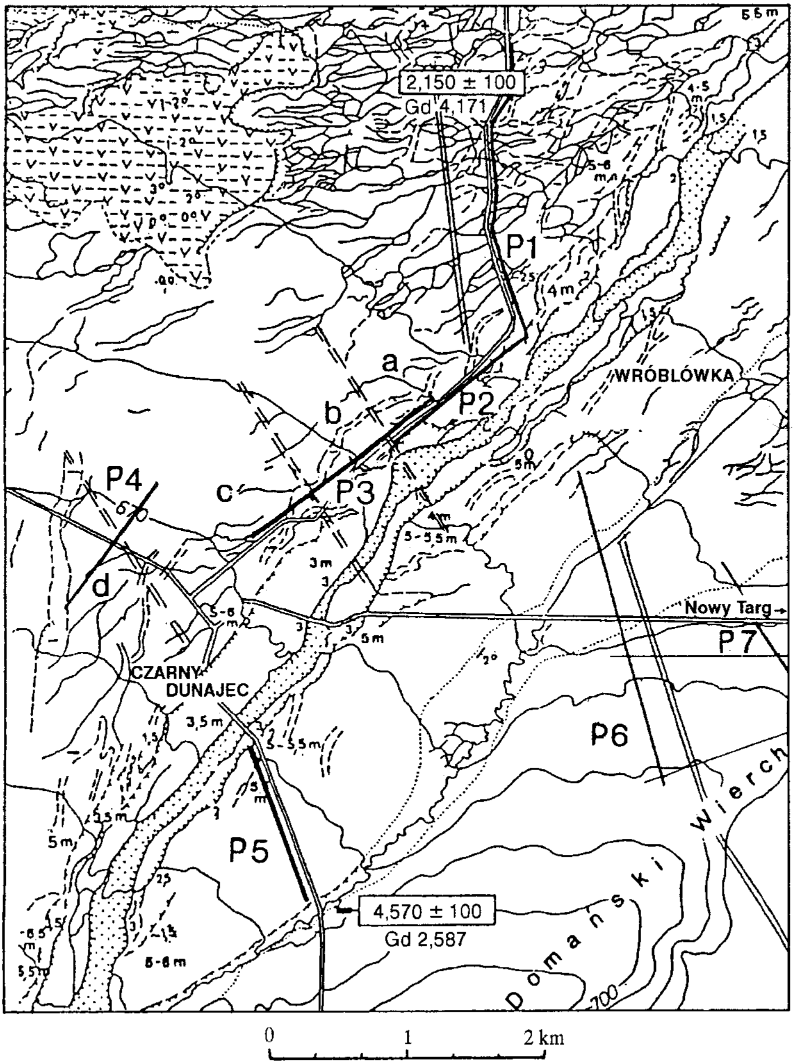

Fig. 3. Seismic profiles P1–P7 with extent of segments a, b, c, d on P3 and P4 profiles related to particular tectonic block of complex faults bounded Orava Basin. Oldest segment "d" and youngest segment "a"document NE direction of formation of pull-apart basin during Neogene

the longest profile, Pieniążkowice to Wróblówka (profile 1, Fig. 4) and Wróblówka– Czarny Dunajec (profile 2, Fig. 5A). In most cases reflection profiling was done as well.

The Pieniążkowice–Wróblówka (profile 1, Fig. 4) refraction profile can be subdivided into three areas: in the northern part Quaternary sediments rest on flysch substratum at a depth of some 50 m, then the top of eroded flysch rocks rises nearly to the groundsurface (8 m), in the area where 100 m west of the

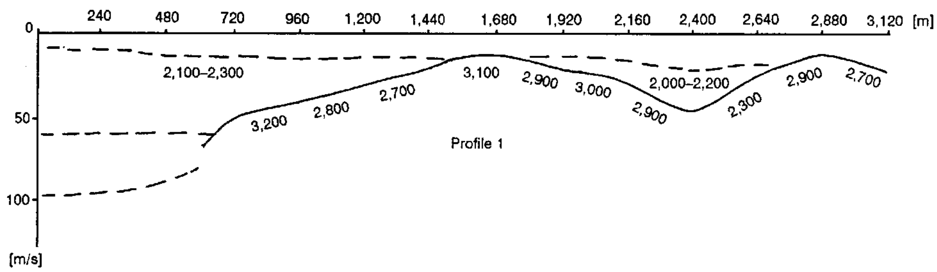

Fig. 4. Refraction profile along the Pieniążkowice–Wróblówka road. The value means velocity in m/s

road a small "flysch" hill is located. Still farther southwards, the base of Quaternary slopes down and then rapidly subsides in a step-like manner (profile 1, Fig. 4) and cannot be traced any farther. There, Quaternary sediments attain a thickness of 112 m., as indicated by the Wróblówka well. The refraction profile has been verified by magnetic studies which were conducted along a N–S profile from the flysch hill, along the road to Wróblówka, on its western side. Two zones of distortion of the magnetic field have been recognised which can be correlated with two fault zones throwing down the flysch bedrock south of the flysch hill, towards the Wróblówka graben (Dec et al. 1998).

Reflection profiling was conducted across the Wróblówka trough, starting 130 m south of the church in Wróblówka up to the Czarny Dunajec–Nowy Targ road (profile 6, northern part, Fig. 6B). This NNW–SSE orientated profile shows that the Wróblówka graben has a constant depth of some 100 m and that it becomes deeper (to 128 m) some 400 m before the road. Similar thickness of Quaternary fill has been recorded along a refraction profile transformed into the time-profile that runs along the road Wróblówka–Jewish cemetery in Czarny Dunajec (profile 2, Fig. 5A).

WRÓBLÓWKA GRABEN VERSUS NEOGENE STRATA IN THE ORAVA BASIN

Since the top of eroded flysch substratum slopes down westwards close to the Jewish cemetery (0.4 km on profile 3), our studies were conducted by multiple reflection profiling (profile 3, Fig. 6A). This profile turned out to be a very important one, so it was continued outside the village of Czarny Dunajec to the NW corner of the Roman Catholic cemetery (2 km on profile 4) in Czarny Dunajec (close to the road to Jabłonka) and extended still farther behind this road (profile 4). Profiles 3 and 4 are shown together in Fig. 6A and called the "cemetery" profile. This profile is orientated SW–NE and runs parallel to the axis of the Domański Wierch (Fig. 3). Geological interpretation of the 3,380-m-long profile, between Wróblówka well and a point situated 0.5 km behing the Roman Catholic cemetery in Czarny Dunajec, confirms complex history of the Neogene trough (Fig. 6A). Along the entire length of the "cemetery" profile, in turn, thickness of Quaternary sediments ranges from 100 to 128 m.

The following segments, from the east to the west, showing differentiated amount of Neogene subsidence can be distinguished (Fig. 6A):

(a) flat-lying Quaternary on eroded flysch bedrock at a depth of ca 100 m (120 ms), similarly to the Wróblówka well (0–1,180 m in profile 2, Fig. 5A, 0–400 m in profile 3, Fig. 6A);

(b) Quaternary sediments resting on flat-lying Neogene strata whereas the flysch bedrock slopes to the west (400–1,100 m in profile 3, Fig. 6A);

(c) flat-lying Quaternary strata of comparable thickness, underlain by Neogene deposits whose top slopes westwards, and similarly sloping flysch bedrock (from 1,100 m to 1,850 m in profile 3, Fig. 6A);

(d) both Neogene and Quaternary sediments are nearly horizontal, but the thickness of Quaternary strata increases to 128 m and individual Quaternary layers show traces of tectonic disturbances (along the western end of profile 4, Fig. 6A).

Of particular importance are disturbances interpreted as faults (profile 3, Fig. 6A) situated at the boundaries of the above segments and whose share remarkably increases with depth. The faults continue from Neogene to Quaternary strata (profile 4, Fig. 6A).

Between (b) and (c) one can infer a period of erosion at the margin of the subsiding trough. Most probably, during subsequent subsidence of segment (d), segment (b) became eroded and coeval sediments of segment (c) attained increasing dips following the subsidence of (d) (profiles 3 and 4, Fig. 6A).

An attempt at dating of this tectonic phase has been made. Along the 1,120-m-long segment of profile 5 (Fig. 5B), between Czarny Dunajec well and a bridge at the foot of the Domański Wierch ridge, the reflection pattern suggests subsidence of the Domański Wierch molasse series to the NNW, towards the deepest part of the trough, and only close to the Czarny Dunajec well Neogene strata are nearly horizontal. Our reflection studies (at times 500 ms) have not reached flysch substratum in this part of the Orava Basin. In the Neogene log of the Czarny Dunajec well, the above-mentioned erosional episode recorded in "cemetery" profile can be correlated with a thick series drilled at a depth of 375–416 m. According to palynological determinations of J. Oszast and L. Stuchlik (1977), this interval represents Early Pliocene interval, although younger than the Pannonian boundary which was recorded at a depth of 478 m. This is a very rough estimation, since on reflection profiles the vertical scale is a time scale.

Another interesting aspect is the "transgressive" onlap of the youngest Neogene strata which rest horizontally upon the layers of the younger Neogene dipping towards the subsiding basin. Such a situation has been observed in segment (c), probably indicating a period of subsidence of the (d) segment, gradually affecting segment (c).

It is difficult to decide how far does the Neogene reach towards the Wróblówka well. Profile 3 (Fig. 6A) has been interpreted in such a way that horizontal Neogene strata occur close to Wróblówka. A similar interpretation was presented by L. Watycha (unpublished documentation 1968) basing on electrical resistivity profiling. Taking this for granted, one should assume that in Midle Pliocene times the Orava Basin had the greatest extent, since in Hladovka the Dacian sediments are 90 m thick (Nagy 1993) and in Domański Wierch even more (Oszast and Stuchlik 1977). Deposits drilled at Domański Wierch are lacking from the uppermost part of the Czarny Dunajec log, indicating a period of erosion. It is also unknown how long did sedimentation of the Domański Wierch molasses last and, hence, when the uplift of the Orava Basin together with its surroundings started. Most probably, these processes took place in Quaternary times.

The reflection profiling revealed that the Quaternary trough extends more than 3 km west of Wróblówka, where its depth attains 128 m (Fig. 2). Individual blocks of the Orava Basin which underwent subsidence in Neogene times were bounded by faults orientated NW–SE (Fig. 3), perpendicular to the Domański Wierch ridge, whereas Quaternary subsidence was controlled by W–E striking faults (Fig. 1). Such orientation of Quaternary vertical motions is indicated both by refraction profile 1 (Fig. 4) and the topography ("flysch hill", direction of drainage on the fan, meandering pattern of channels in the Pieniążkowice trough Fig. 2). We conclude that during the Quaternary vertical tectonic movements, the following (from the north southwards) structures have been formed: the W–E orientated Pieniążkowice trough, a flysch horst, and the vast Wróblówka trough. A rapid increase in thickness of Quaternary sediments north of Czarny Dunajec, from 28 m to 100–128 m at a distance of only 1–1.4 km, also points to the presence of a fault zone. Most probably, the fault bounding on the south the Wróblówka trough is a continuation of the fault zone which separates the Domański Wierch ridge, uplifted in Quaternary times, and the subsiding Wróblówka trough (Fig. 2), as indicated by two reflection profiles (6 and 7, Fig. 6B and Fig. 5C) shot obliquely to the Domański Wierch ridge (N45°E).

RELATION OF THE WRÓBLÓWKA TROUGH TO THE DOMAŃSKI WIERCH SERIES

The base of Quaternary in the Wróblówka trough north of the Czarny Dunajec–Nowy Targ road is nearly horizontal and overlain by coarse-clastic sediments showing velocities of 2,000 m/s. Along profile 6 (Fig. 6B), starting from a distance of 1,200 m (central segment of the profile), Neogene clays (velocity of refraction wave recorded during reflection profiling 1,800 m/s) occur at a depth of only a few metres. A similar situation has been recorded on profile 7 (Fig. 5C), after crossing the road to Nowy Targ (0.5 km on the profile 7). At the southern end of profile 6 (Fig. 6B) (starting from a distance of 1,350 m),

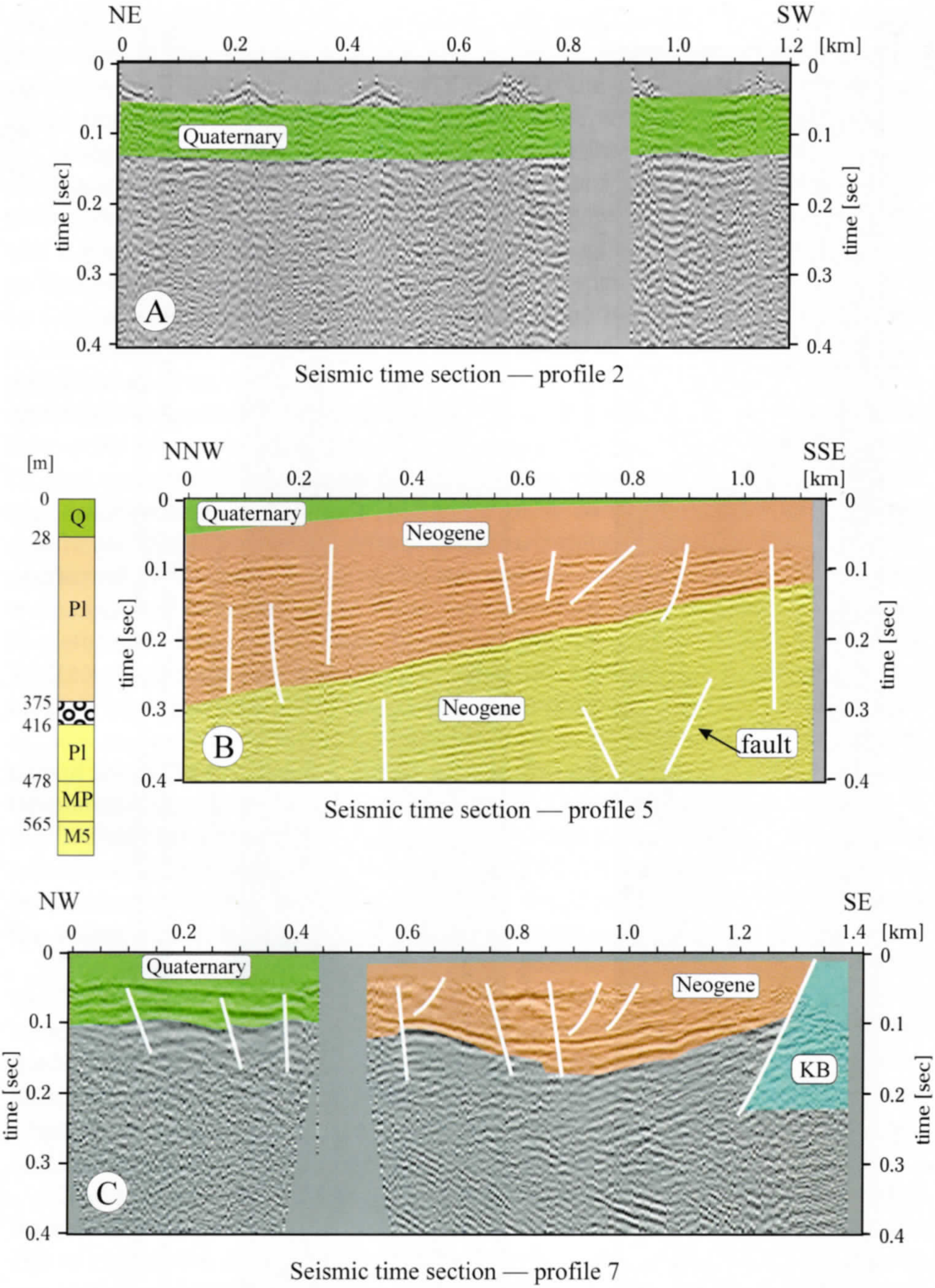

Fig. 5. Interpretation of three seismic profiles (No 2, 5 and 7 — localisation on Fig. 3). Time scale on the vertical axis. On Fig. 5A profile 2 present flat-lying Quaternary deposits of the thickness of 100 m (transposed refraction profile). Fig. 5B illustrates NNW deeping Neogene deposits of Domański Wierch ridge. Seismic interpretation due to Czarny Dunajec borehole. On Fig. 5C relation between the Domański Wierch Pliocene molasses and Quaternary infill of Wróblówka graben. Klippen Belt structure is buried

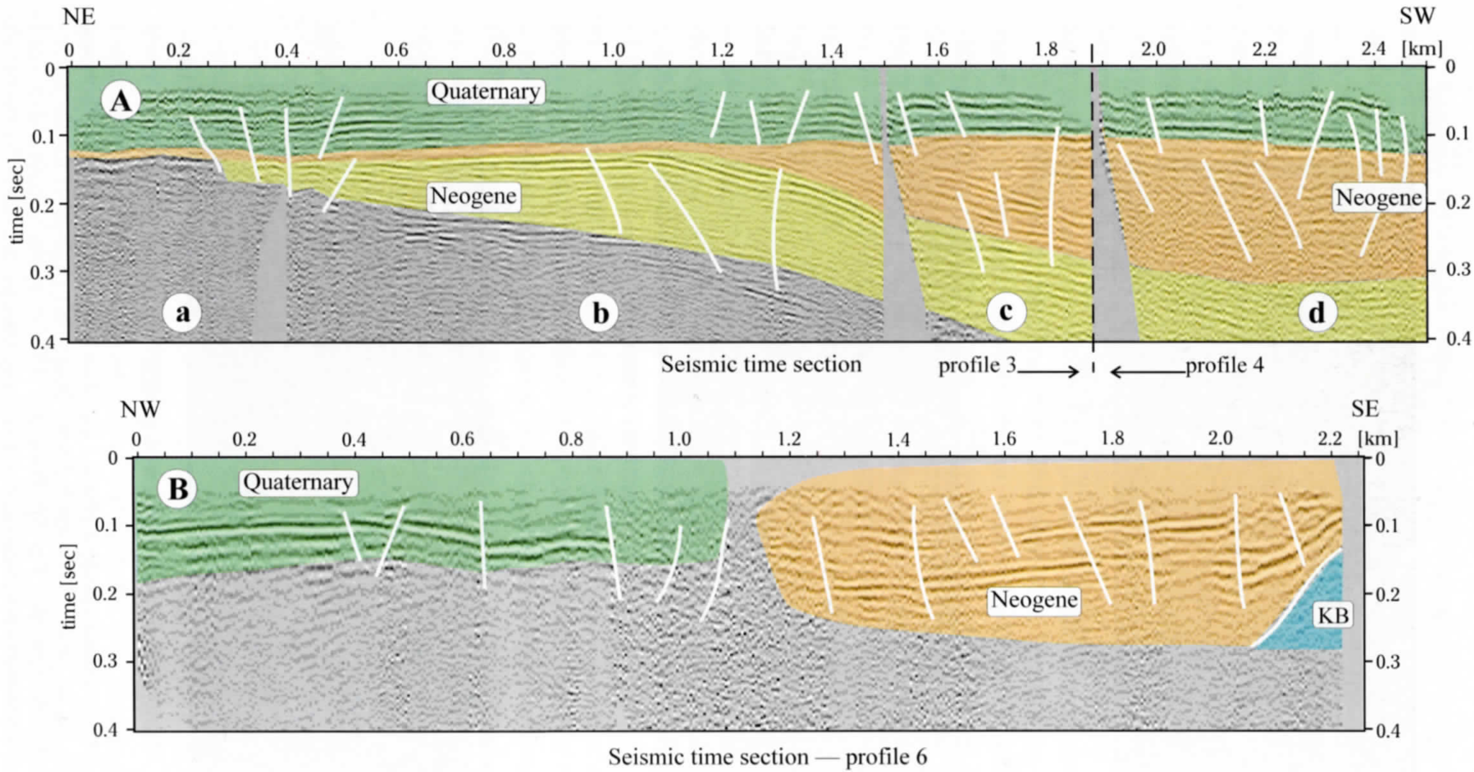

Fig. 6. Interpretation of three reflection profiles (No 3 and 4 on Fig. 6A and profile 6 on Fig. 6B). Profiles 3 and 4 named “cemetery profile” demonstrate complexity of Neogene Orava Basin formation. Segments “a”, “b”, “c” and “d” indicate the lateral tectonic evolution of the Orava Basin

some 850 m SSE of the road to Nowy Targ and close to Rogoźnik village, exposures of the Pieniny Klippen Belt occur, as shown by refraction wave velocities ca 2,700 m/s. On profile 6 (Fig. 6B), the Klippen Belt is marked at a distance od 2,200 m, i.e. 1 km SSE of the road, within the vast ridge top.

Judging from seismic images, when proceeding from the south one can distinguish, apart from the Klippen Belt, a zone of Pliocene sediments dipping to the NW, axial part of a syncline, a short syncline limb uplifted to the north and a zone of tectonic disturbances, interpreted as a Quaternary fault, as well as Quaternary sediments filling the Wróblówka trough, 128 m (profile 6, Fig. 6B) and 80 m (profile 7, Fig. 5C) thick. The axial zone is located 270–300 m south of the Quaternary fault, and its associated faults visible on reflection profiles appear to confirm a close relationship between the uplift of the northern limb and faults bounding the Quaternary trough. The contact zone between the Domański Wierch molasses and Quaternary infill of the Wróblówka trough is located on a fault, as indicated by numerous disturbances of Pliocene and Quaternary strata, and by the presence of a zone of wedges of distorted sediments that is visible on seismic images (profiles 6 and 7). This faults are confirmed by the presence of diffraction waves. Another characteristic feature is upturning of Neogene strata in the northern limb, showing that the molasse is deformed into a syncline. However, the proximity of the Quaternary Wróblówka trough and disturbances seen on its boundaries enable one for another interpretation of the observed pattern of Neogene strata. It is likely that original setting was represented by a monocline, dipping towards the deepest part of the Neogene trough, similar to that observed along the road leading to Domański Wierch (profile 5, Fig. 5B). Only in Quaternary times, when uplift of the Podhale area together with Domański Wierch was accompanied by coeval subsidence of the trough, the northern limb of the syncline was formed. The fault zone separating uplifted elements of the Domański Wierch series from the young trough is probably of reverse character.

The origin of the northern limb with Pliocene strata dipping to the south can be interpreted as a result of N–S compression. In such a case, the E–W trending Wróblówka graben should be associated with extension parallel to the N–S direction. Profiles 6 and 7 also indicate the presence of flower structures, indicative of strike-slip motions. We shall come back to this problem later when discussing palaestress data of fractured Neogene pebbles at Miętustwo and Stare Bystre.

The thickness of Neogene strata in the Domański Wierch area estimated from seismic profiles is 300 ms (some 220 m) in profile 6 and 180 ms (ca 160 m) in profile 7. In the Domański Wierch well the Neogene strata were not drilled until 220 m, hence, their thickness probably increases SW and attains its maximum farther to the west. This is confirmed by the thickness of Neogene strata drilled at Koniówka (450 m) and Hladovka (670 m). To the NE, in turn, the Domański Wierch series gradually disappears: at Rogoźnik the total thickness of Quaternary and Neogene strata is only 10–20 m, as shown by the position of the top of eroded Stare Bystre flysch strata, estimated by M. Cieszkowski (1992, 1993) to 625–635 m a.s.l. The eastern continuation of the Wróblówka trough and continuation of the Domański Wierch ridge close to Płazówka require further geophysical studies. Young tectonic control on the topography of the area is also indicated by difference in elevation of the Pieniny Klippen Belt at Koniówka (277 m a.s.l.) and Stare Bystre (650–630 m a.s.l.).

CONCLUSIONS

Basing on geophysical profiling and well log data, we conclude that the eastern part of the Orava Basin is a complex trough which migrated towards the NE in Neogene times due to extension, suitable for the formation of successive NW–SE orientated faults. In the Quaternary E–W trending structures have been formed, represented by the small Pieniążkowice and large Wróblówka troughs, separated by an horst built up of flysch rocks. Faults bounding these structures are visible on geophysical profiles and their spatial differentiation can be inferred from tectonically-controlled topography. Both fault strike and dip directions of Neogene strata are only roughly determined. The only fault marked precisely is that striking W–E and parallel to the road Czarny Dunajec–Nowy Targ between profiles 6 and 7. This fault controls orientation of the Wróblówka trough, as well as relief differentiation and palaeochannel pattern on the flat Czarny Dunajec alluvial fan.

The following conclusions can be drawn from the above presented data:
(1) The Neogene Orava Basin was shaped due to basin opening towards the NE in such a way that the older and deeper-located parts of the trough are situated in the west and the younger ones in the east. Since the "cemetery" profile is parallel to the axis of the Domański Wierch ridge, individual segments of the trough appear to be bounded by perpendicular faults orientated NW–SE (Fig. 3). This orientation is compatible with the trough boundary in the NE, marked on gravimetric maps (Pospišil 1990, 1993; Pomianowski 1995, 1998). Faults of such an orientation controlled opening of the Orava Basin, as suggested by the map of gravity lineaments by P. Pomianowski (1995). The same orientation is also typical for Quaternary tectonic boundary between the uplifted and subsided parts of the basin (Fig. 1). This zone strikes along the shorter diagonal of the recent Orava Basin parallelogram.
(2) The thermal history of the Orava Basin has been reconstructed for its western, Slovak part (Nagy et al. 1996). In the westernmost part of the basin, close to Ustie nad Priehradou, lignite-bearing Sarmatian strata are exposed at the level of the Orava reservoir. These lignites were turned into brown coals due to deep burial. Mineralogical studies indicate the presence

of vitrinite what testifies to alterations occurring at temperatures exceeding 70° and the depth of burial around 1,150 m. A. Nagy et al. (1996) relate this burial to the development of a pull-apart basin between the Middle Sarmatian and the Early Pliocene. These authors question Badenian age of Neogene strata drilled by the Czarny Dunajec well; they conclude about short hiatus and uplift in Pontian times, renewed deposition in the Early Dacian and rapid uplift from a depth of 1,000 m during 5 million years. The rate of uplift of the basin and its surroundings has been calculated at 0.18 mm/yr (Nagy et al. 1996). I. Kołcon and M. Wagner (1991) described hard coals from Sarmatian strata exposed near Lipnica Wielka and Mała in the Polish part of the Orava Basin. Soft, brown coals were to be associated with stratigraphically higher levels. High degree of coalification was related to thick overburden. The Sarmatian coal are presently exposed at the groundsurface, what also confirms the above thermal and geotectonic reconstruction and indicates tectonic uplift and erosion. One can hypothesize that in the Polish part of the basin, near Czarny Dunajec, the subsidence started earlier and lasted longer, i.e. from the Late Badenian up the end of the Early Pliocene. Increased erosion of the marginal part of the deepest part of the basin is indicated by gravels drilled at Czarny Dunajec at a depth interval of 375–416 m, as well as by erosionally truncated, inclined Neogene strata visible on seismic reflection profiles. These strata are preserved only in the deepest part of the basin (profiles 3 and 4).

A comparison of the Hladovka and Domański Wierch well logs indicates that in the marginal, southern part of the basin at Hladovka erosional hiatus occurred in the Early Pliocene (Nagy et al. 1996), whereas the Domański Wierch molasse series was deposited both in the Early and Middle Pliocene (Oszast and Stuchlik 1977). One can put forward an hypothesis of eastward migration of tectonic processes throughout the history of the Orava Basin. The western part of the basin was uplifted already in Pontian times, and it is where Sarmatian strata became exposed at the recent basin bottom, i.e. 600 m a.s.l. near Usti nad Priehradou and 630–650 m a.s.l. near Lipnica, whereas in the longer subsiding part, near Czarny Dunajec, the Sarmatian deposits occur at a depth of 565–848 m, i.e. between −166 m b.s.l. and +117 m a.s.l. The uplift of the deepest, i.e. Czarny Dunajec part of the basin occurred probably during the uplift of the whole area together with the Domański Wierch series, i.e. starting from the Late Pliocene (Romanian) onwards or at the turn of the Pliocene and Quaternary. The eastward migration of subsidence is testified to by reflection profiles 3 and 4 (Fig. 6A), whereas successive changes of stress fields resulting in tectonic uplift is indicated by Quaternary uplift of the western part of the basin which, in the Late Neogene, underwent subsidence.

(3) Quaternary tectonic processes have proceeded in different structural setting, as shown by E–W trending young faults (Figs 2, 3). The system of W–E striking

Pieniążkowice and Wróblówka grabens, separated by an flysch horst is parallel to the so-called "Tatra direction", similarly to a segment of the Pieniny Klippen Belt between Domański Wierch and Dunajec water-gap. It is likely that the W–E fault separating the uplifted part of the Domański Wierch from the Wróblówka graben is a reverse fault. Further geophysical studies, particularly reflection profiling in a N–S cross section Wróblówka–Pieniążkowice are required to decide about the nature of successive fault zones. Additional refraction profiles along the W–E Płazówka–Rogoźnik profile would be welcome to detect an inferred fault cutting the Domański Wierch structure.

DISCUSSION

Interesting aspect is the relation of the above results to structural interpretation of fractured pebbles of the Domański Wierch series, exposed at Stare Bystre and Miętustwo. A. Tokarski and W. Zuchiewicz (1998a, 1998b, 1998c) interpreted these fractures as resulting from Late Pliocene–Quaternary stresses exerted on the Pliocene Domański Wierch series (Oszast and Stuchlik 1977) and on Sarmatian strata at Miętustwo (Sikora and Wieser 1974). The inferred position of σ_1 at Stare Bystre was orientated N35–45°E (acute bisector of vertical shear joints intersecting one another under 20–25°), and at Miętustwo N15°E (Miętustwo A) to N23°E (Miętustwo B). At the last locality there also occur fractures orientated N68°W that are parallel to longitudinal normal faults bounding the Orava Basin, inferred from the gravity lineament pattern by P. Pomianowski (1995). Dominant fractures at Miętustwo B are similar to those measured by A. K. Tokarski at Hladovka (Baumgart-Kotarba 1998). At this locality, the top part of fine-grained sandy series of probably Dacian age is exposed (Nagy 1993). Differences between these two sites consist in change of rank of dominant orientations: at Hladovka N80°W orientation dominates; fractures N13°E are of minor importance. We interpret the fracture pattern in a different way, taking into account strike-slip character of the Domański Wierch fault.

The first author of this paper put forward an hypothesis (Baumgart-Kotarba 1996) on sinistral-dip-slip character of the Domański Wierch fault, along which the Orava pull-apart basin was formed in Neogene times. This fault is a fragment of a longer fault zone, called the Prosečno fault system (Nemčok 1993) or Krowiarki fault (Bac-Moszaszwili 1993). The last author concludes that the Krowiarki fault used to be first sinistral and then, in Pliocene times, dextral fault. M. Baumgart-Kotarba (1996) infers NW-directed rotation of the Orava block similar to rotation documented by M. Kovač et al.(1989) for Trenčin–Žilina section of the Western Carpathians. The activity of such rotational fault between Ružomberok and the Lepietnica river valley (Fig. 7) resulted by opening of Orava Basin. The NE boundary

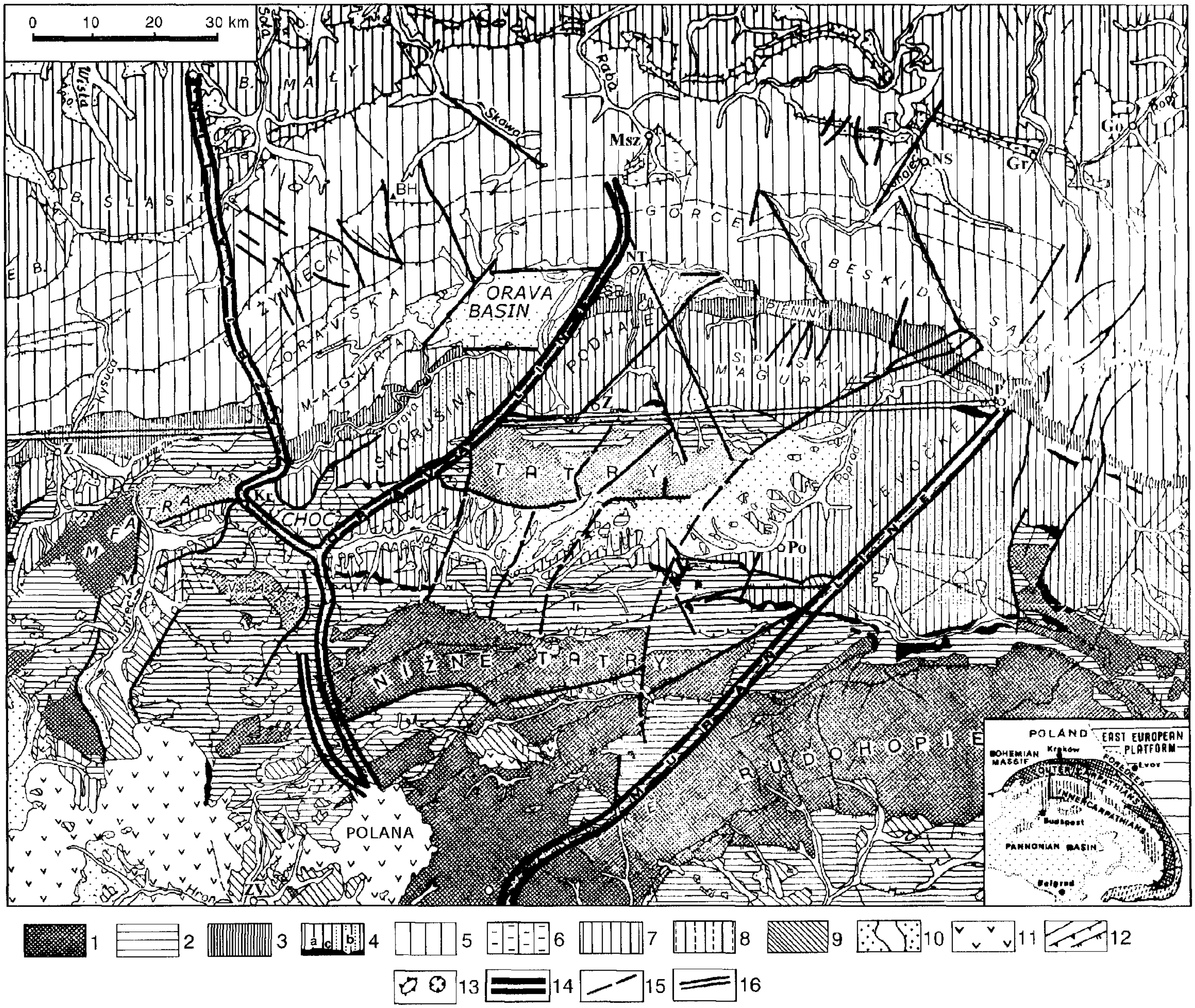

Fig. 7. The Orava Basin and Tatra Mts on the background of simplified geological map of Western Carpathians based on Buday et al. (1960) and Fusan et al. (1967). Author's interpretation of principal faults that bound distinguished tectonic blocks. 1 — granitoid and metamorphic rocks, 2 — mainly mezozoic sedimentary rocks faulted and thrusted 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 nape, 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 (Zazriva, Orava, Muran f.), 15 — another important faults, 16 — satellite lineaments Zlin–Plavec named lineament of northern limit of the Tatra Mts (Baumgart-Kotarba 1981, 1984)

of the Orava block is marked by the Skawa fault. The N35–45°E orientation of σ_1 at Stare Bystre could have been associated with the activity of the Domański Wierch strike-slip fault. Supposing that the Prosečno fault continues south of Ružomberok into a fault that marks the eastern border of the Velka Fatra Mts, we obtain an important transversal fault zone of the West Carpathians, which is clearly visible on satellite images (ERTS from 26 June 1975) and described as the lineament of the Western Tatra margin (Baumgart-Kotarba 1981). The Neogene activity of this fault near Domański Wierch consisted in downthrowing molasse sediments filling a pull-apart basin in the eastern, marginal part of the Orava Basin. Later, in the Quaternary, the faulting was responsible for fracturing of Pliocene clasts. It appears, therefore, that the NE trend on rose-diagrams of fractures measured at Stare Bystre is related to the activity of the Domański Wierch strike-slip fault. The fault is active even today, as shown by macroseismic (based on interviews with local population) and microseismic (based on instrumental records of the Ojców, Racibórz and Niedzica seismic station) analyses of an earthquake of 11 September 1995, elaborated by M. Hojny-Kołoś from the Seismic Observatory at Ojców, Institute of Geophysics, Polish Academy of Sciences (cf. also Baumgart-Kotarba and Hojny-Kołoś 1998; Baumgart-Kotarba 1998, 2001). Elongated isoseismal pattern of the earthquake (11 Sept. 1995) points to recent activity along a SW–NE line in the Domański Wierch area. Distribution of seismic foci of the successive registered quakes and their microseismic analysis, in turn, indicate that along the axis of the Domański Wierch ridge foci of compressive types occurred, whereas under the flat Czarny Dunajec fan of Late Vistulian–Holocene age, dilatational foci dominated (Baumgart-Kotarba and Hojny-Kołoś 1998).

It is impossible to determine unequivocally the orientation of faults registered by seismic reflection studies in the Pliocene Domański Wierch sediments: these could be either W–E trending reverse faults, similar to those of the zone that separates the uplifted Domański Wierch ridge from the Wróblówka graben, or N35–45°E-orientated faults related to horizontal displacements (sinistral strike-slip) or to vertical displacement between uplifted Domański Wierch ridge above subsided areas of late Glacial and Holocene part of Czarny Dunajec alluvial fan (oblique faults). In such a case σ_1 means vertical axis. The first option would enable one to associate the faulting with N15–23°E maximum horizontal stress measured at Miętustwo. This orientation is comparable with that of the Carpatho-Pannonian plate motion and maximum horizontal compression within the Outer Carpathian nappes (NNE), inferred from breakout analysis by M. Jarosiński (1998). The W–E faults could then be interpreted as arranged perpendicular to the prevailing horizontal compression. This compression was probably responsible for the uplift of Pliocene molasses of the Domański Wierch ridge on a reverse fault.

It should be stressed out that tectonically-controlled Quaternary history of the Orava Basin is a continuation of its Neogene development, since the sinistral Domański Wierch fault is still seismically active. One cannot exclude that faults inferred from the reflection profiles, except for the W–E fault separating the Wróblówka trough from the uplifted Domański Wierch ridge, are parallel to the acute bisector of shear fractures measured at Stare Bystre (N35–45°E). Such interpretation can be accepted by applying the I. Davison's (1994) model in which flower structures are typical for strike-slip faults. These structures have been interpreted on seismic reflection profiles 5, 6 and 7. Further studies are required to explain stress pattern in which strike-slip motions directed N35–45°E are coeval with the formation of W–E trending tectonic grabens. It will be important contribution to the problem of Cenozoic stress field evolution studied by W. Zuchiewicz (1994, 1998).

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STRESZCZENIE

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CZWARTORZĘDOWE ZAPADLISKA WRÓBLÓWKI I PIENIĄŻKOWIC I ICH RELACJE Z UTWORAMI NEOGEŃSKIMI KOTLINY ORAWSKIEJ I PLIOCEŃSKIMI DOMAŃSKIEGO WIERCHU

Zapadlisko Kotliny Orawskiej tworzyło się od górnego badenu po pliocen. Brak osadów z piętra rumuńskiego wskazuje, że u schyłku pliocenu już nastąpiło podnoszenie obszaru, lub osady rumunu uległy erozji, a istotna zmiana tektoniczna nastąpiła na pograniczu pliocenu i dolnego czwartorzędu. W czwartorzędzie południowa i zachodnia część zapadliska była podnoszona a subsydencja objęła część NE i nastąpiło powiększenie zapadliska w NE części Kotliny.

Zastosowano metody geomorfologiczne i geofizyczne. Profilowania sejsmiczne metodą refrakcyjną i refleksyjną umożliwiły rozpoznanie budowy i rozeznanie przebiegu stref uskokowych. W oparciu o wiercenia we Wróblówce (czwartorzęd na utworach fliszu jednostki magurskiej), w Czarnym Dunajcu (czwartorzęd na utworach neogeńskich) i na Domańskim Wierchu (pliocen) dokonano interpretacji budowy, a wyniki zostały przedstawione wzdłuż 7 profili (Fig. 2, 3). Stwierdzono młodą budowę zrębową opartą na uskokach o kierunku W–E. Zapadliska czwartorzędowe Wróblówki i Pieniążkowic są rozdzielone horstem fliszowym. Udało się stwierdzić strefę uskokową W–E , która rozdziela podnoszony element utworów plioceńskich Domańskiego Wierchu względem rozległego i płaskodennego zapadliska Wróblówki. Interpretacja wskazuje, że uskok ten ma charakter uskoku inwersyjnego. Uskok ten podnosi północne skrzydło synkliny Domańskiego Wierchu, a miąższość utworów czwartorzędowych jest największa (około 128 m) w przyuskokowej części zapadliska Wróblówki (Fig. 6B, Fig. 5C). Świadczy to o młodej kompresji z południa.

Oś morfologiczna garbu Domańskiego Wierchu ma kierunek SW–NE, który w tym odcinku stanowi część długiego uskoku przesuwczo-zrzutowego ciągnącego się od Rużemberoka po dolinę Lepietnicy. Profile sejsmiczne poprowadzone równoległe do osi Domańskiego Wierchu na płaskim obszarze stożka Czarnego Dunajca między wsiami Czarny Dunajec–Wróblówka wskazują na złożoną budowę neogeńskiego zapadliska orawskiego. Stwierdzono występowanie bloków z utworami zalegającymi płasko bądź nachylonymi (segmenty a, b, c, d). Segmenty te ograniczone są uskokami o przebiegu zbliżonym do NW–SE, a więc prostopadłymi do kierunku głównego uskoku przesuwczo-zrzutowego. Wskazuje to na przesuwanie się procesu otwierania zapadliska ku NE w neogenie. Historia termalna basenu Orawskiego opracowana przez zespół geologów słowackich (Nagy et al. 1996) dokumentuje także przesuwanie się z zachodu na wschód procesu dźwigania tektonicznego utworów sarmackich pogrzebanych na głębokość 1000 m, a następnie podnoszonych tak, że obecnie odsłaniają się tuż pod poziomem wody zbiornika Orawskiego koło Namestowa. Trzęsienia ziemi potwierdzają współczesną aktywność tektoniczną obszaru i dlatego nie można wykluczyć aktywności współczesnej zarówno uskoku przesuwczego NE jak i nasuwania serii Domańskiego Wierchu w warunkach kompresji z południa. W pewnym stopniu na takie możliwości interpretacji wskazują także analizy mikrostrukturalne prowadzone przez A. Tokarskiego i W. Zuchiewicza 1998).