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# YOUNG TECTONICS OF THE ORAVA BASIN AND SOUTHERN PART OF THE MAGURA NAPPE, POLISH WESTERN CARPATHIANS, IN THE LIGHT OF GRAVITY STUDIES: A NEW RESEARCH PROPOSAL

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**Abstract**
The aim of this paper is to present a multidisciplinary project dealing with analysis of young crustal movements in the Orava Basin, Polish Western Carpathians, on the basis of a three year long gravimetric, geodetic, geological and morphostructural study. The problem consists in quantitative interpretation of the obtained gravimetric results, *i.e.* in combining temporal gravity changes with those of geodynamic crustal processes. Gravity surveys conducted in 2004 and 2005 show a decrease in gravity values at benchmarks situated in the Central Carpathian Palaeogene Basin and Magura Nappe, while the central part of the Orava Basin reveals the opposite trend. Such changes, if confirmed by successive measurement campaigns, appear to indicate recent uplift of the basin margins and subsidence of the basin itself.

**Key words:** gravity survey, neotectonics, Orava Basin, West Carpathians, Poland

## INTRODUCTION

Neotectonic tendencies of the Carpathians and their foreland have frequently been described for many years (see reviews by Zuchiewicz 1995, 1998, Zuchiewicz *et al.* 2002). Previous views on the dominating role of vertical crustal movements are recently supplemented by those underlining importance of horizontal displacements in shaping the neotectonic setting, inferred from geodetic studies (Hefty 1998) and borehole breakout analysis (Jarosiński 1998).

Geodetic and gravimetric observations have been carried out at the contact between the Central Carpathian Palaeogene Basin (Podhale Basin) and the Pieniny Klippen Belt by the Institute of Geodesy and Geodetic Astronomy, Technical University, Warsaw, since the end of the 1970s. Registered variations of the gravity field amount to 100 mGal (Makowska, Jaroszewski 1987, Makowska 2000, 2003, Czarnecki *et al.* 2002, 2004).

The Department of Geophysics, AGH University of Science and Technology in Kraków initiated in 2004 a new research proposal (Łój *et al.* 2005), the aim of which is to compare the results of studies throughout the Polish segment of the Western Outer Carpathians, showing differentiated young tectonic movements. It is a multidisciplinary project; analysis of young crustal movements will be conducted basing on the results of three years long gravimetric, geodetic, geological and morphostructural studies. The problem consists in quantitative interpretation of the obtained gravimetric results, *i.e.* in combining temporal gravity changes with those of geodynamic crustal processes.

## NEOTECTONIC SETTING

Principal structural elements of the Outer Carpathians were shaped in the Palaeogene and Neogene, when the study area represented an accretionary prism associated with the south-directed subduction of the European Platform under the ALCAPA block (Tomek, Hall 1993, Oszczypko 1998, Fodor *et al.* 1999). Synsedimentary shortening of the Carpathian basins started in the Eocene in the inner part of the Magura Nappe, and continued until the Badenian–Sarmatian in the Zgłobice Unit (Oszczypko 1998, 2004, Świerczewska, Tokarski 1998, Zoetemeijer *et al.* 1999; see also Fig. 1). The last episode of thrusting of the Carpathian margin probably occurred after the Pannonian (Wójcik *et al.* 1999).

The Late Miocene gravitational collapse resulted in the formation of numerous sets of normal faults (Decker *et al.* 1997, Zuchiewicz *et al.* 2002), some of which became reactivated in the Pliocene and Quaternary. A good example is provided by the Orava-Nowy Targ Basin which is bounded to the north and south by *ca*. W–E trending normal faults of throws up to a few hundreds of metres (Fig. 2). These faults originated in the Late Miocene (Pomianowski 1995, 2003), and some of them have also been active in the Pliocene and

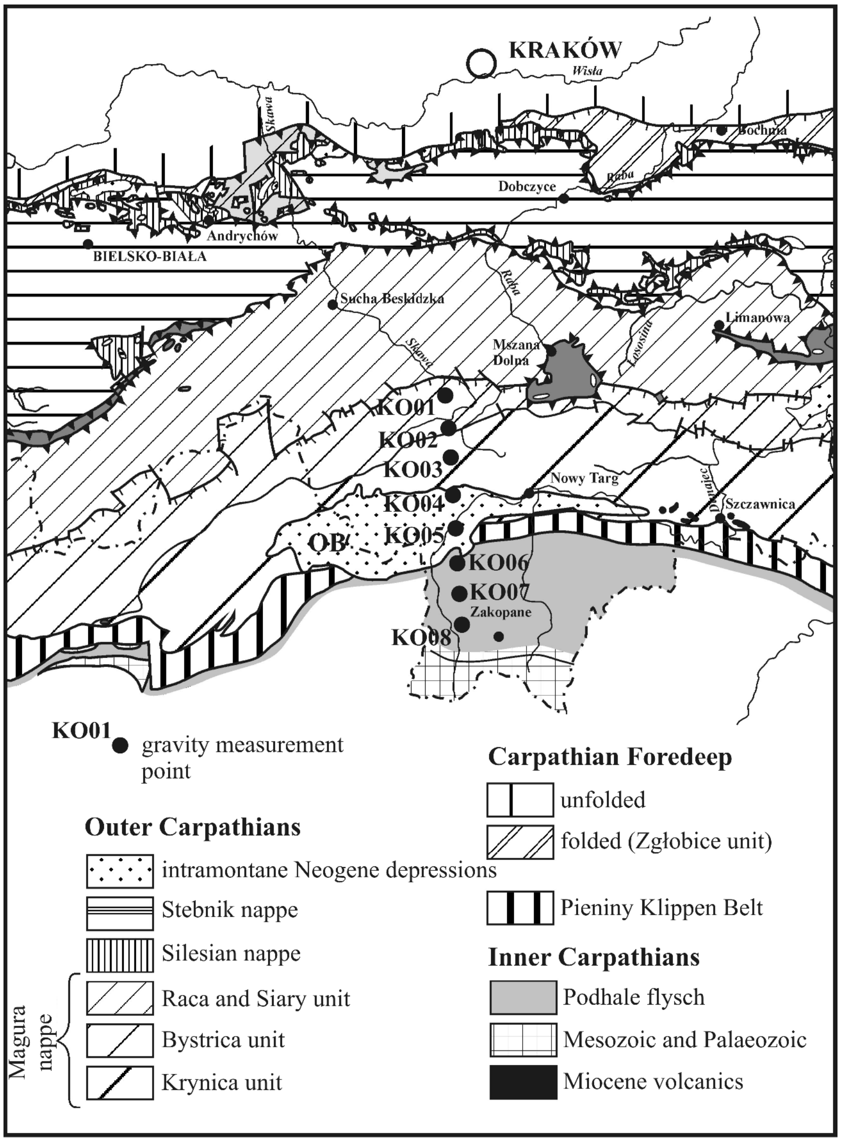

**Fig. 1.** Geological sketch-map of the Polish Western Carpathians showing location of the studied transect (geology after Żytko *et al.* 1989; simplified). OB – Orava – Nowy Targ Basin.

Quaternary (Niedzielski 1971, Birkenmajer 1978, Baumgart-Kotarba 1991-92, Tokarski, Zuchiewicz 1998), including the Holocene (Baumgart-Kotarba 1996, 2000).

Following subduction and collision, structural development of the Polish Outer Carpathians proceeded mainly in an extensional regime. Within intramontane basins, this extension survived until the Late Quaternary (cf. discussion in Zuchiewicz *et al.* 2002).

Analysis of deformed longitudinal profiles of terraces of the main Carpathian rivers points to the presence of several elevated and subsided zones, whose strike is nearly parallel to that of principal thrusts. The maximum of Quaternary uplift (150 m) was found to characterize the southern part of the Polish segment of the Outer West Carpathians (Starkel 1972, Zuchiewicz 1984, 1998). Episodes of intense erosional dissection of straths, largely induced by uplift, occurred in the following intervals: 800–470 ka (0.15–0.21 mm/yr), 130–90 ka (0.18–0.40 mm/yr), and 15–0 ka (0.2–2.0 mm/yr; cf. Zuchiewicz 1991).

The rates of recent vertical crustal motions in the Polish Outer Carpathians range between 0 mm/yr in the western and medial segment to *ca.* +1 mm/yr in the east (Wyrzykowski, 1985), whereas those in the Pieniny Klippen Belt do not exceed 0.5 mm/yr (Ząbek *et al.* 1993, Czarnecki 2004). The results of recent GPS campaigns point, in turn, to NNE-directed horizontal motions throughout the area (Hefty 1998).

Recent seismicity concentrates along the southern marginal fault of the Pieniny Klippen Belt and along some normal and strike-slip faults, transverse to the former (Prochazková *et al.* 1978, Baumgart-Kotarba, Hojny-Kołoś 1998, Guterch, Lewandowska-Marciniak 2002, Guterch 2005). Local magnitudes do not exceed 4.3 on the Richter scale, averaging between 2.5 and 3.4 (Pagaczewski 1972, Prochazková *et al.* 1978, Guterch, Lewandowska-Marciniak 2002).

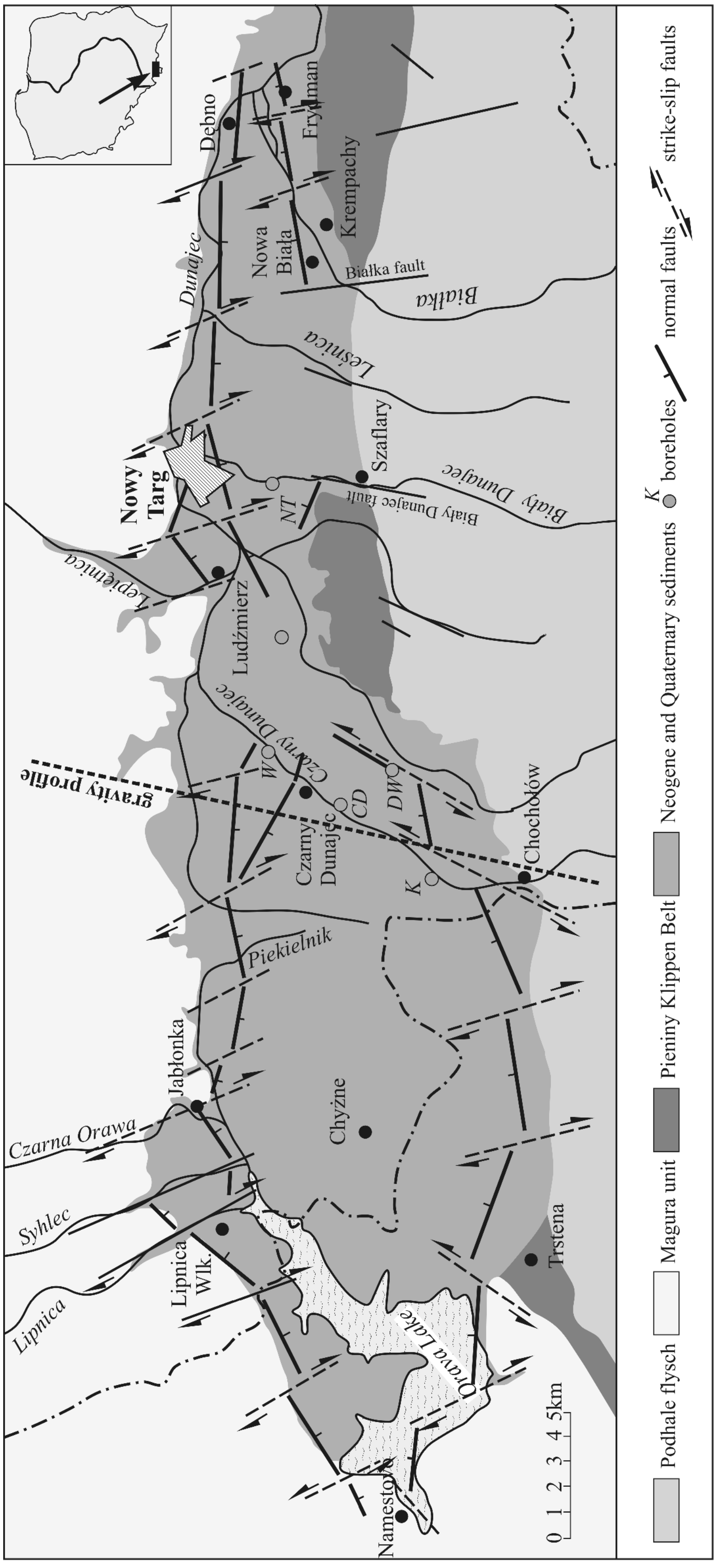

**Fig. 2.** Tectonic sketch of the Orava–Nowy Targ Basin (based on Pomianowski 2003; modified). Abbreviations: K – Koniówka, CD – Czarny Dunajec, W – Wróblówka, NT – Nowy Targ.

## ORAVA BASIN

From the geodynamic point of view, the Orava-Nowy Targ Basin is an extremely interesting structure. This is a bi-partite basin, formed in Miocene time and superimposed on structural units that build the contact between the Inner and Outer Carpathians, namely: the Central Carpathian Palaeogene Basin, Pieniny Klippen Belt, and Magura Nappe (Fig. 2). The maximum drilled thickness of sedimentary infill of the Orava Basin is 950 m, including 922 m of fresh-water Neogene molasses (Watycha 1976). The thickest Quaternary sediments (117 m) are confined to the Wróblówka Trough, in the northern part of this basin (Watycha, 1973).

The Orava Basin is a tectonic trough which is bounded to the north and south by a system of longitudinal normal faults of throws up to a few hundred metres. These are cut by several transverse, mostly strike-slip faults that are oriented NNW–SSE and NE–SW (Pomianowski 1995, 2003; cf. also Fig. 2). The basin-bounding faults became reactivated in Quaternary times (Niedzielski 1971, Birkenmajer 1976, Baumgart-Kotarba 1996), and their recent activity is indicated by earthquakes of magnitudes up to 4.3 (Guterch 2005, Guterch *et al.* 2005). The most recent earthquakes in the western part of the Orava Basin occurred in September and October 1995 (M = 3.3; I = 6–6.5; focal depth 2–3 km), and in November 2004 (M = 4.3; I = 6–7; focal depth 5 “ 2.5 km; cf. Baumgart-Kotarba, Hojny-Kołoś 1998, Guterch 2005, Guterch *et al.* 2005).

According to Baumgart-Kotarba (1991-92) and Bac-Moszaszwili (1993), the Orava Basin is an Early Miocene pull-apart basin, formed due to sinistral displacement along one of transversal faults. On the other hand, Pomianowski (1995, 2003) speculates about a releasing bend-type structure, associated with left-lateral displacement along the Pieniny Klippen Belt during regional Neogene transpression.

The Domański Wierch alluvial fan series, nearly 500 m thick and situated in the southern part of the Orava Basin, is composed of terrestrial paraconglomerates alternating with sands, clays, and lignites. The southern part of this fan is of Sarmatian age (Birkenmajer 1979,

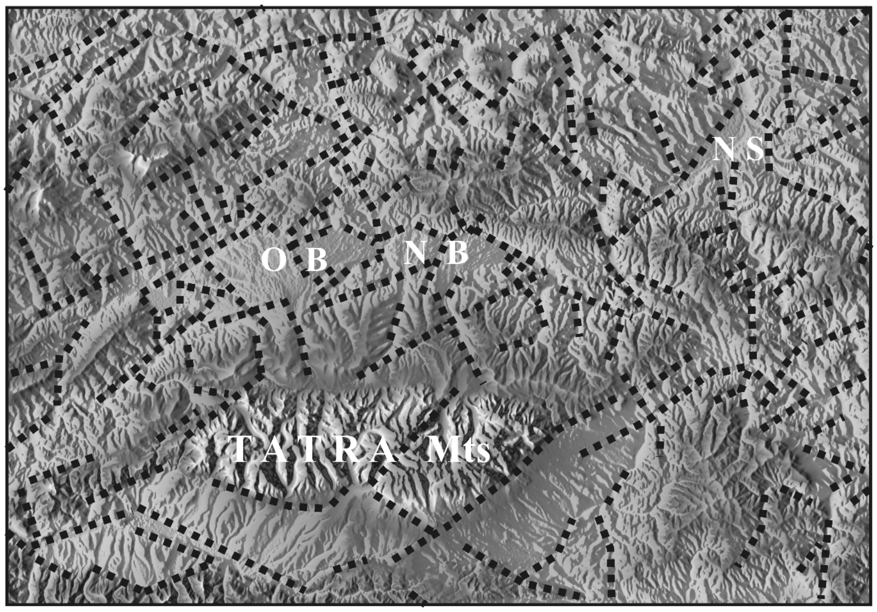

**Fig. 3.** Digital elevation model based on SRTM data of the medial portion of the Western Carpathians, showing location of major topolineaments. Abbreviations: OB – Orava Basin, NB – Nowy Targ Basin, Tatra Mts. – Tatra Mountains, NS – Nowy Sącz Basin.

and papers cited therein), whereas the northern one, *ca.* 220 m thick, is palynologically dated to the Early and Middle Pliocene (Oszast 1973, Oszast, Stuchlik 1977). Clasts of paraconglomerates within the Pliocene Domański Wierch series are commonly fractured (Tokarski, Zuchiewicz 1998, Kukulak 1999), and dominating fractures trend to form two sets intersecting at an angle of 20–25°, whose acute bisectrix is aligned N35–40°E, parallel to the maximum horizontal stress (Tokarski, Zuchiewicz 1998). This orientation is compatible with that of recent horizontal compression, documented in the Carpathians by borehole breakout analyses (Jarosiński 1998).

The results of geophysical soundings point to the presence of several, W–E trending Quaternary faults north of the Domański Wierch Mt. The greatest throws (128–112 m) reveal faults bounding the Wróblówka Trough (Baumgart-Kotarba 2001, Baumgart-Kotarba *et al.* 2001, 2004).

Topolineaments visible on a digital elevation model of the study area are largely coincident with major faults bounding individual structures, including those surrounding the Orava Basin (Fig. 3).

## MATERIAL

Our studies concentrate along a *ca.* 40-km-long, N–S trending, transect, which cuts the contact between the Inner and Outer Carpathians, showing contrasting tendencies of young (Pliocene–Quaternary) tectonic movements (Fig. 1). The Wróblówka Trough, situated in the medial segment of the transect (Fig. 2), reveals Late Pleistocene and Holocene subsidence, while the southern portion of the Magura Nappe, in the northern portion of the transect, displays minor uplift (Baumgart-Kotarba 1991-92, 2001).

The location of stationary points was selected in such a way that each of them represents a different structural unit (Central Carpathian Palaeogene, Pieniny Klippen Belt, Orava Basin, Krynica and Bystrica subunits of the Magura Nappe; Fig. 1). The construction of individual benchmarks enables for both gravity and geodetic measurements (Łój *et al.* 2005).

## METHODS

Gravity surveys across the profile will be carried out at yearly intervals. The choice of such methodology results from the fact that we want to study changes of the gravity field statistically, taking into account the expected small values of temporal anomalies of the gravity field and, first of all, their changes with time.

In July 2004 and July 2005, the first and second series of gravity measurements were made at fixed benchmarks of the profile, using three gravimeters (two CG-3 SCINTREX, and one LaCoste&Romberg (LCR)).

To secure great accuracy of gravity observations, the measurements are taken by the double chain method. In this method, the observation is made twice at each outer point of the chain and three times at the inner point (ABABCBC; cf. Fig. 4). This approach enables for the calculation of gravity field changes between stations on a triple increment-measurement basis, which considerably raises the precision of their calculation. It is the optimal method of the gravimeter drift elimination. Using this method, it is possible to calculate gravity field differences between observation stations determined with great accuracy (Łój *et al.* 2005).

According to the rules accepted in gravity survey, all results are presented as differences between neighbouring observation points, *i.e.* the so-called network legs values.

Errors were calculated after each series. The calculation error was determined for each gravity value between the stations and for the average gravity value. The measurement precision was ca. 0.01 mGal, or 0.005 mGal during cycling measurement. An analysis of errors showed that in several

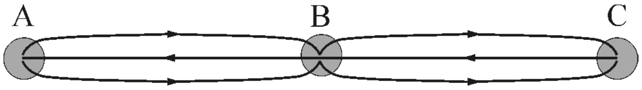

**Fig. 4.** Scheme of gravity survey by the double chain method.

cases only, *i.e.* for the measuring date, the error was larger than 0.005 mGal, and the overall error credibility limit attained a value of 0.01 mGal.

The average gravity error had a little higher value, although not exceeding 0.01 mGal. This could be a result of too small number of gravimeters used. Therefore, the temporal gravity analysis was done basing on gravity measurement values for each gravimeter, and not for the average gravity value.

The error of value determination was smaller than the accuracy of the apparatus used. It can be concluded that the gravity surveys were performed with high precision and in very stable measurement conditions.

## PRELIMINARY RESULTS

The first measurement series made in July 2004 is a base series, to which measurements of successive series will be referred. Additional measurements were conducted at points situated 1 km apart along the profile steps. These results, combined with geological data, will be used in gravity modelling aiming at determining mutual connections between gravity anomalies and geological structures. This modelling will also be helpful in describing the source of changes of the gravity field.

The second measurement series, conducted in July 2005, enables for the first comparison between gravity changes measured in 2004 and 2005 (Figs. 5, 6).

The results of gravity surveys in 2004 and 2005 were used to calculate first periodic gravity changes for each network legs. Figure 5 presents calculation results for both gravimeters (Autograv CG-3 and La Coste&Romberg) and the average value.

Different course of gravity changes at individual network legs could be explained by the influence of atmospheric conditions (humidity and atmospheric pressure) on the gravity electronic system during measurements.

However, some tendencies are worth to be taken into account. The middle part of the profile, situated in the Orava Basin close to the Wróblówka Graben, has a different character than the southern and northern segments of this profile, representing the Central Carpathian Palaeogene and Magura Nappe, respectively (Fig. 6). The tendency marked at the northern and southern ends of the profile can tentatively be explained as resulting from recent uplift, while that characterising the middle part of the profile can be indicative of recent subsidence. Such a trend is compatible with the results of geological and geomorphic studies. One should bear in mind, however, that gravity changes observed after two series of annual observations can be affected by a number of factors, including atmospheric conditions, differentiated compaction of underlying sediments, soil moisture, equipment sensitivity, and others. Therefore, any reliable conclusions can only be drawn when a series of future measurement campaigns confirm the observed trend.

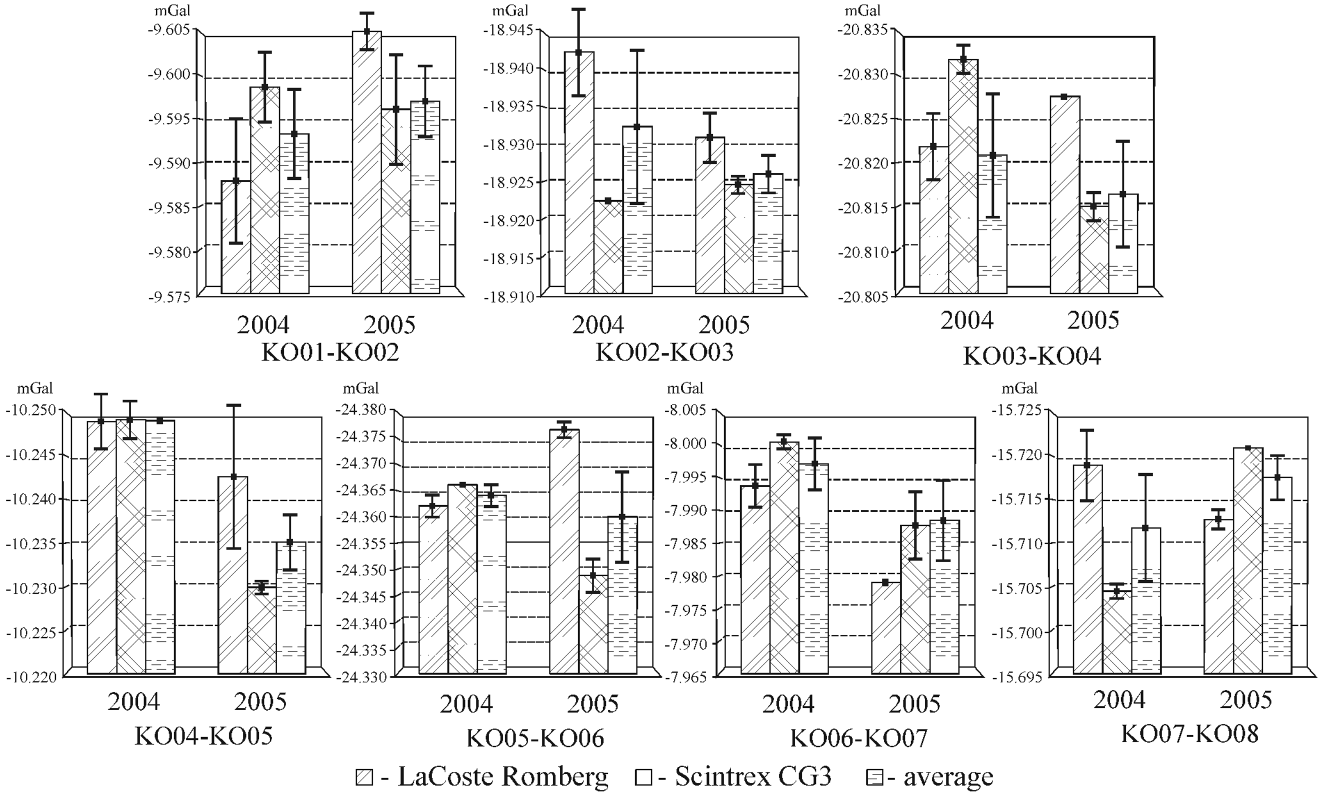

**Fig. 5.** Differences in gravity values and respective error bars measured between individual benchmarks in 2004 and 2005 years. See Fig. 1 for benchmark location.

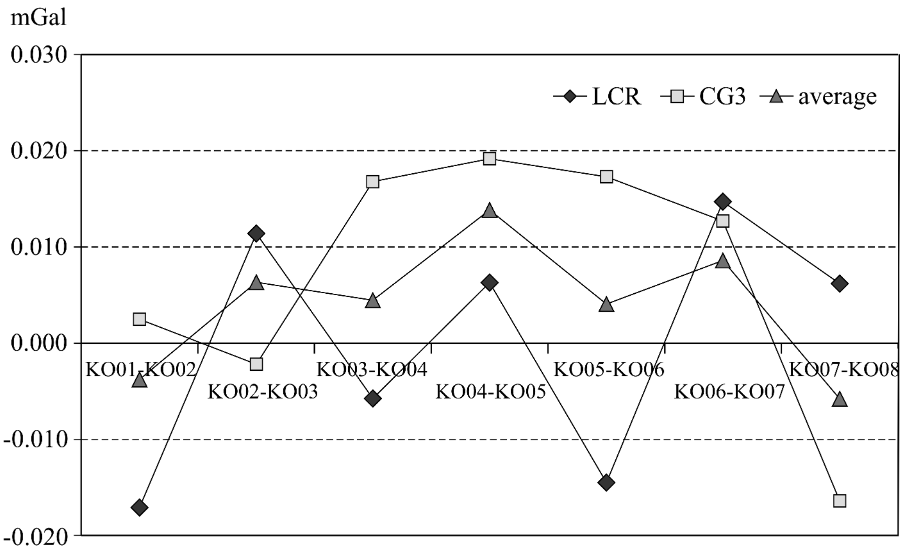

**Fig. 6.** Periodic gravity changes: first comparison of gravity changes measured between individual benchmarks in 2004 and 2005 years. See Fig. 1 for benchmark location.

## CONCLUSIONS

Gravity surveys conducted in 2004 and 2005 show a decrease in gravity values at benchmarks situated in the Central Carpathian Palaeogene Basin and Magura Nappe, while the central portion of the Orava Basin reveals the opposite trend. Such changes, if confirmed by successive measurement campaigns, appear to indicate recent uplift of the basin margins and subsidence of the basin itself.

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## REFERENCES

Bac-Moszaszwili M. 1993. Structure of the western termination of the Tatra massif. *Annales Societatis Geologorum Poloniae* 63, 167–193 (in Polish with English summary).

Baumgart-Kotarba M. 1991-92. The geomorphological evolution of the intramontane Orawa Basin associated with neotectonic movements (Polish Carpathians). *Studia Geomorphologica Carpatho-Balcanica* 25–26, 3–28 (in Polish with English summary).

Baumgart-Kotarba M. 1996. On origin and age of the Orawa Basin, West Carpathians. *Studia Geomorphologica Carpatho-Balcanica* 30, 101–116.

Baumgart-Kotarba M. 2000. Tectonique quaternaire de la dépression d’Orava (Carpates occidentales). *Géomorphologie: relief, processus, environnement* 1, 61–68.

Baumgart-Kotarba M. 2001. Continuous tectonic evolution of the Orava Basin (Northern Carpathians) from Late Badenian to the present-day? *Geologica Carpathica* 52, 103–110.

Baumgart-Kotarba M., Dec J., Ślusarczyk R. 2001. 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. *Studia Geomorphologica Carpatho-Balcanica* 35, 101–119.

Baumgart-Kotarba M., Hojny-Kołoś M. 1998. Relationship between the Quaternary Wróblówka graben and the Neogene Orava Trough in the light of geomorphic studies and an earthquake of 11 Sept., 1995 (original: Relacja czwartorzędowego zapadliska Wróblówki do neogeńskiego zapadliska orawskiego w świetle badań geomorfologicznych i trzęsienia ziemi z dnia 11 września 1995). *Sprawozdania z Czynności i Posiedzeń PAU* 61 (1997), 102–106 (in Polish).

Baumgart-Kotarba M., Marcak H., Márton E. 2004. Rotation along the transverse transforming Orava strike-slip fault: based on geomorphological, geophysical and paleomagnetic data (Western Carpathians). *Geologica Carpathica* 55, 219–226.

Birkenmajer K. 1976. Pleistocene tectonic deformations at Szaflary, West Carpathians, Poland. *Rocznik Polskiego Towarzystwa Geologicznego* 46, 309–323 (in Polish with English summary).

Birkenmajer K. 1978. Neogene to Early Pleistocene subsidence close to the Pieniny Klippen Belt, Polish Carpathians. *Studia Geomorphologica Carpatho-Balcanica* 12, 17–28.

Birkenmajer K. 1979. Geological guidebook of the Pieniny Klippen Belt (original: Przewodnik geologiczny po pienińskim pasie skałkowym), 1–236. Wyd. Geol., Warszawa (in Polish).

Czarnecki K. ed. 2004. Geodynamical studies of the Pieniny Klippen Belt – Czorsztyn region. Monografia, 1–116. Instytut Geodezji Wyższej i Astronomii Geodezyjnej, Wydział Geodezji i Kartografii Politechniki Warszawskiej, Warszawa (in Polish with English summary).

Czarnecki K., Barlik M., Czarnecka K., Olszak T., Pachuta A., Szpunar R., Walo J. 2002. Geodynamic studies of the Pieniny Klippen Belt (Czorsztyn region) have been resumed. *Acta Montana Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic*, *ser. A* 20 (124), 85–91.

Czarnecki K., Barlik M., Czarnecka K., Olszak T., Pachuta A., Szpunar R., Walo J. 2004. Geodynamical studies of the Pieniny Klippen Belt – Czorsztyn region (2001–2003). In *Abstracts. 6th Czech-Polish Workshop 2004 "On recent geodynamics of the Sudety Mts. and adjacent areas", Łężyce, Poland, November 4-6, 2004*, 14–15. Dept. Geod. Photogramm., Agricult. Univ. Wrocław, Inst. Rock Struct. & Mech., Acad. Sci. Czech Rep., Sect. Geodyn., Comm. Geod., Pol. Acad. Sci., Center for Earth Dyn. Res., Acad. Sci. Czech Rep., Wrocław.

Decker K., Nescieruk P., Reiter F., Rubinkiewicz J., Ryłko W., Tokarski A.K. 1997. Heteroaxial shortening, strike-slip faulting and displacement transfer in the Polish Carpathians. *Przegląd Geologiczny* 45, 1070–1071.

Fodor L., Csontos L., Bada G., Gyorfi I., Benkovics L. 1999. Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data. In Durand B., Jolivet L., Horvath F., Seranne M. (eds) *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen*. Geological Society, London, Special Publications 156, 295–334.

Guterch B. 2005. Earthquakes along the Pieniny Klippen Belt, observed in the Podhale area (original: Trzęsienia ziemi obserwowane na Podhalu wzdłuż pienińskiego pasa skałkowego). In Zuchiewicz W., Przybylski B., Badura J. (eds) *Materiały VI Ogólnopolskiej Konferencji "Neotektonika Polski – Aktywne uskoki Europy Środkowej", Srebrna Góra, 26-28 IX 2005. Streszczenia referatów i komunikatów. Przewodnik konferencji terenowej*, 98–100. Komisja Neotektoniki Komitetu Badań Czwartorzędu PAN, Oddział Dolnośląski Państwowego Instytutu Geologicznego, Instytut Nauk Geologicznych Uniwer-sytetu Jagiellońskiego, Galicia Tectonic Group, Wrocław (in Polish).

Guterch B., Lewandowska-Marciniak H. 2002. Seismicity and seismic hazard in Poland. *Folia Quaternaria* 73, 85–99.

Guterch B., Lewandowska-Marciniak H., Niewiadomski J. 2005. Earthquakes recorded in Poland along the Pieniny Klippen Belt, Western Carpathians. *Acta Geophysica Polonica* 53, 27–45.

Hefty J. 1998. Estimation of site velocities from CEGRN GPS campaigns referred to CERGOP reference frame. *Reports on Geodesy* 9 (39), 67–79.

Jarosiński M. 1998. Contemporary stress field distortion in the Polish part of the Western Outer Carpathians and their basement. *Tectonophysics* 297, 91–119.

Kukulak J. 1999. Orientation of joints and faults in the SE part of the Orawa Depression. *Przegląd Geologiczny* 47, 1021–1026 (in Polish with English summary).

Łój M., Madej J., Porzucek S. 2005. Methodology of periodic gravimetric investigations in monitoring geodynamic processes – selected examples. *Acta geodynamica et geomaterialia* 2 (3), 103–112.

Makowska A. 2000. Tatra Mountains – geodynamic investigations. In Cacoń S. (ed.) *2nd Czech-Polish Workshop "On recent geodynamics of the East Sudety Mts. and adjacent areas", April 6-8, 2000, Bolesławów, Poland*, 24. Dept. Geod. Photogramm., Agricult. Univ., Wrocław.

Makowska A. 2003. Dynamics of the Tatra Mountains determined by geodetic techniques (original: Dynamika Tatr wyznaczana metodami geodezyjnymi). *Instytut Geodezji i Kartografii*, *Seria Monograficzna*, 6, 1–201 (in Polish with English summary).

Makowska A., Jaroszewski W. 1987. On present vertical movements in Tatra Mts. and Podhale. *Przegląd Geologiczny* 10, 506–512 (in Polish with English summary).

Niedzielski H. 1971. Tectonic origin of the eastern part of the valley of Nowy Targ. *Rocznik Polskiego Towarzystwa Geologicznego* 41, 397–408 (in Polish with English summary).

Oszast J. 1973. The Pliocene profile of Domański Wierch near Czarny Dunajec in the light of palynological investigations (Western Carpathians, Poland). *Acta Palaeobotanica* 14 (1), 1–42.

Oszast J., Stuchlik L. 1977. Vegetation of Podhale in the Neogene. *Acta Palaeobotanica* 18 (1), 45–86 (in Polish with English summary).

Oszczypko N. 1998. The Western Carpathian Foredeep – development of the foreland basin in front of the accretionary wedge and its burial history (Poland). *Geologica Carpathica* 49, 415–431.

Oszczypko N. 2004. The structural position and tectonosedimentary evolution of the Polish Outer Carpathians. *Przegląd Geologiczny* 52, 780–791.

Pagaczewski J. 1972. Catalogue of earthquakes in Poland in 1000–1970 years. *Materiały i Prace Instytutu Geofizyki PAN* 51, 3–36.

Pomianowski P. 1995. Structure of the Orava Basin in the light of selected geophysical data. *Annales Societatis Geologorukm Poloniae* 64, 67–80 (in Polish with English summary).

Pomianowski P. 2003. Tectonics of the Orava - Nowy Targ Basin – results of the combined analysis of the gravity and geoelectrical data. *Przegląd Geologiczny* 51, 498–506 (in Polish with English summary).

Prochazková D., Brouček I., Guterch B., Lewandowska-Marciniak H. 1978. Map and list of the maximum observed macroseismic intensities in Czechoslovakia and Poland. *Publications of the Institute of Geophysics of the Polish Academy of Sciences* B-3 (122), 1–75.

Starkel L. 1972. The Outer Carpathians (original: Karpaty zewnętrzne). In Klimaszewski M. (ed.) *Geomorfologia Polski*, T. 1, 52–115. PWN, Warszawa (in Polish).

Świerczewska A., Tokarski A. K. 1998. Deformation bands and the history of folding in the Magura nappe, Western Outer Carpathians (Poland). *Tectonophysics* 297, 73–90.

Tokarski A.K., Zuchiewicz W. 1998. Fractured clasts in the Domański Wierch series: Contribution to structural evolution of the Orava Basin (Carpathians, Poland) during Neogene through Quaternary times. *Przegląd Geologiczny* 46, 62–66 (in Polish with English summary).

Tomek Č., Hall J. 1993. Subducted continental margin imaged in the Carpathians of Czechoslovakia. *Geology* 21, 535–538.

Watycha L. 1973. Quaternary deposits in the borehole Wróblówka in the Podhale Basin. *Kwartalnik Geologiczny* 17, 335–347 (in Polish with English summary).

Watycha L. 1976. The Neogene of the Orava-Nowy Targ Basin. *Kwartalnik Geologiczny* 20, 575–587 (in Polish with English summary).

Wójcik A., Szydło A., Marciniec P., Nescieruk P. 1999. The folded Miocene of the Andrychów region. *Biuletyn Państwowego Instytutu Geologicznego* 387, 191–195.

Wyrzykowski T. 1985. Map of recent vertical crustal movements on the territory of Poland. Instytut Geodezji i Kartografii, Warszawa.

Ząbek Z., Barlik M., Knap T., Margański S., Pachuta A. 1993. Continuation of geodynamic investigations in the Pieniny Klippen Belt, Poland, from 1985 to 1990. *Acta Geophysica Polonica* 41, 131–150.

Zoetemeijer R., Tomek Č., Cloetingh S. 1999. Flexural expression of European continental lithosphere under the western outer Carpathians. *Tectonics* 18, 843–861.

Zuchiewicz W. 1984. The Late Neogene–Quaternary tectonic mobility of the Polish West Carpathians. A case study of the Dunajec drainage basin. *Annales Societatis Geologorum Poloniae* 54, 133–189.

Zuchiewicz W. 1991. On different approaches to neotectonics:

A Polish Carpathians example. *Episodes* 14, 116–124.

Zuchiewicz W. 1995. Selected aspects of neotectonics of the Polish Carpathians. *Folia Quaternaria* 66, 145–204.

Zuchiewicz W. 1998. Quaternary tectonics of the outer West Carpathians, Poland. *Tectonophysics* 297, 121–132.

Zuchiewicz W., Tokarski A.K., Jarosiński M., Márton E. 2002. Late Miocene to present day structural development of the Polish segment of the Outer Carpathians. *EGU Stephan Mueller Special Publication Series* 3, 185–202.

Żytko K., Gucik S., Ryłko W., Oszczypko N., Zając R., Garlicka I., Nemčok J., Eliaš M., Menčik E., Dvorak J., Stranik Z., Rakus M., Matejovská O. 1989. Geological map of the Western Outer Carpathians and their foreland without Quaternary formations. In Poprawa D., Nemčok J. (eds) *Geological Atlas of the Western Outer Carpathians and their Foreland 1:500,000*. Publ. House Państwowy Instytut Geologiczny, Warszawa.