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MONITORING GEODYNAMIC PROCESSES USING GEODETIC AND GRAVIMETRIC METHODS: AN EXAMPLE FROM THE WESTERN CARPATHIANS (SOUTH POLAND)

Monitoring procesów geodynamicznych z wykorzystaniem metod geodezyjnych i grawimetrycznych: przykład z Karpat Zachodnich (Polska południowa)

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Abstract: Multidisciplinary studies conducted along two geodynamic test transects across the Polish segment of the Western Carpathians, crossing the Orava Basin in the west and the Pieniny Klippen Belt and Magura Nappe along the Dunajec River valley in the east, included gravity and geodetic surveys as well as geological investigations. Gravity and geodetic surveys were carried out annually in years 2004–2006. Their results appear to suggest recent subsidence of the Orava Basin, particularly intensive in a Quaternary graben in the northern part of the area, confirming conclusions derived from geomorphic analyses. Data obtained for the Dunajec River transect do not show any particular differentiation among individual benchmarks, what can point to either minor uplift of the entire area, minimal differences between successive slices of the Magura Nappe and the Pieniny Klippen Belt, or both. Horizontal displacements of benchmarks, different for the western and eastern transects, towards the west and SW as well east and SE, respectively, can result from general uplift of the area comprised between these transects. On the other hand, the N to NNE-oriented vectors of recent horizontal motions, observed for stations located south of the Pieniny Klippen Belt, point to the ongoing NNE-directed push of the ALCAPA block.

Key words: temporal gravity changes, neotectonics, Western Carpathians, South Poland

Treść: Zintegrowane studia grawimetryczne, geodezyjne i geologiczno-geomorfologiczne przeprowadzono na dwóch profilach przecinających szereg jednostek środkowej części Karpat polskich, wykazujących zróżnicowane tendencje neotektoniczne: w poprzek Kotliny Orawskiej na zachodzie oraz wzdłuż beskidzkiego przełomu Dunajca na wschodzie. Pomiary grawimetryczne i geodezyjne wykonywano corocznie w okresie 2004–2006. Ich wyniki wskazują na współczesną subsydencję Kotliny Orawskiej, szczególnie intensywną w obrębie rowu Wróblówki. Dane uzyskane dla profilu Dunajca nie ujawniają większego zróżnicowania pomiędzy poszczególnymi punktami pomiarowymi, co może sugerować słabe wypiętrzanie całego obszaru i/lub minimalne różnice mobilności kolejnych łusek płaszczowiny magurskiej oraz pienińskiego pasa skałkowego. Przemieszczenia poziome reperów usytuowanych w obrębie Karpat zewnętrznych, a skierowane ku zachodowi i SW w profilu zachodnim oraz ku wschodowi i SE w profilu wschodnim, mogą odzwierciedlać wypiętrzanie obszaru ograniczonego profilami, tj. masywu Gorców. Natomiast skierowane ku północy i NNE wektory współczesnych ruchów poziomych dla stanowisk ulokowanych na południe od pienińskiego pasa skałkowego zdają się wskazywać na nadal aktywny nacisk bloku ALCAPA ku NNE.

Słowa kluczowe: czasowe zmiany przyspieszenia siły ciężkości, neotektonika, Karpaty Zachodnie, Polska południowa

INTRODUCTION

The aim of our study was to study recent geodynamics in a portion of the Western Carpathians that shows contrasting tendencies of recent crustal mobility. The observation period spanned 36 months (2003–2006), during which geodetic, gravity and geological surveys were conducted on two test transects (KO and DD) crossing different geological units of the Inner and Outer Carpathians (Figs 1, 2). Results of geodetic and geophysical surveys are compared with those concerning morphotectonic characteristics, comprised in already published papers.

Gravity measurements are the basic research method in view of temporal changes of the Earth's gravity field, and are also very important in geodynamic studies and seismic risk assessment. Gravimetric methods applied to geodynamic purposes rely on measurements conducted by both absolute or superconducting gravimeters (SG), and those obtained by relative gravimeters of different types (Groten & Backen 1995, van Dam & Olivier 1998).

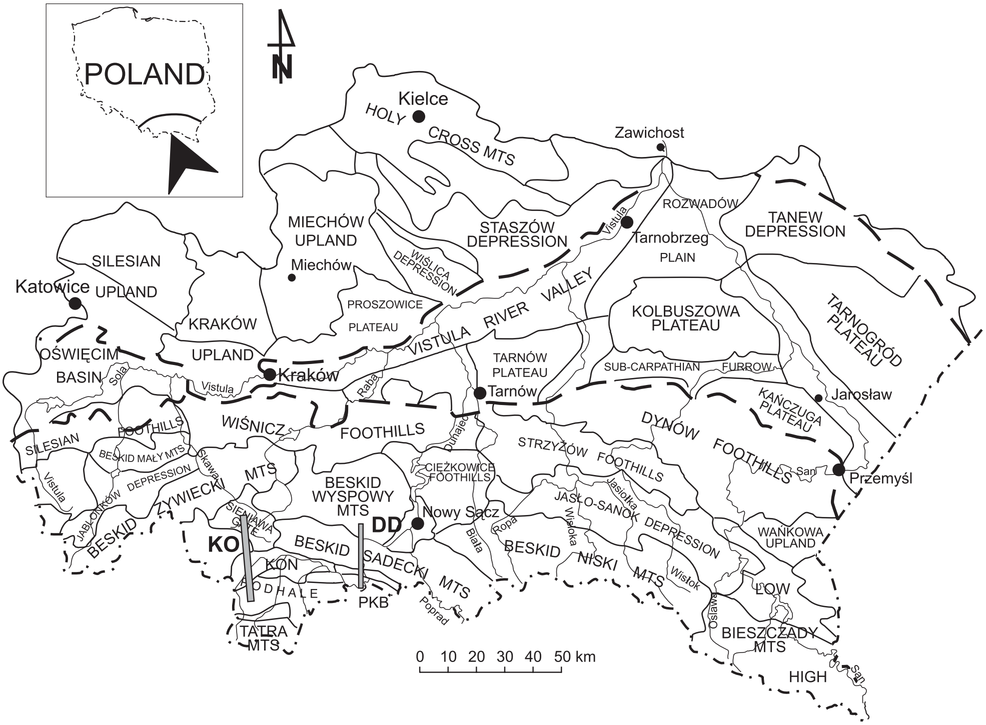


Fig. 1. Geomorphic units of the Polish Carpathians and their foreland (based on Starkel 1991, modified). Shaded rectangles show location of the studied transects

Fig. 1. Jednostki geomorfologiczne Karpat polskich i ich przedpola (wg Starkla 1991, zmienione). Szrafura wskazuje lokalizację badanych profili. Oznaczenia literowe: KON – Kotlina Orawsko-Nowotarska, PPS – pieniński pas skałkowy, KS – Kotlina Sądecka

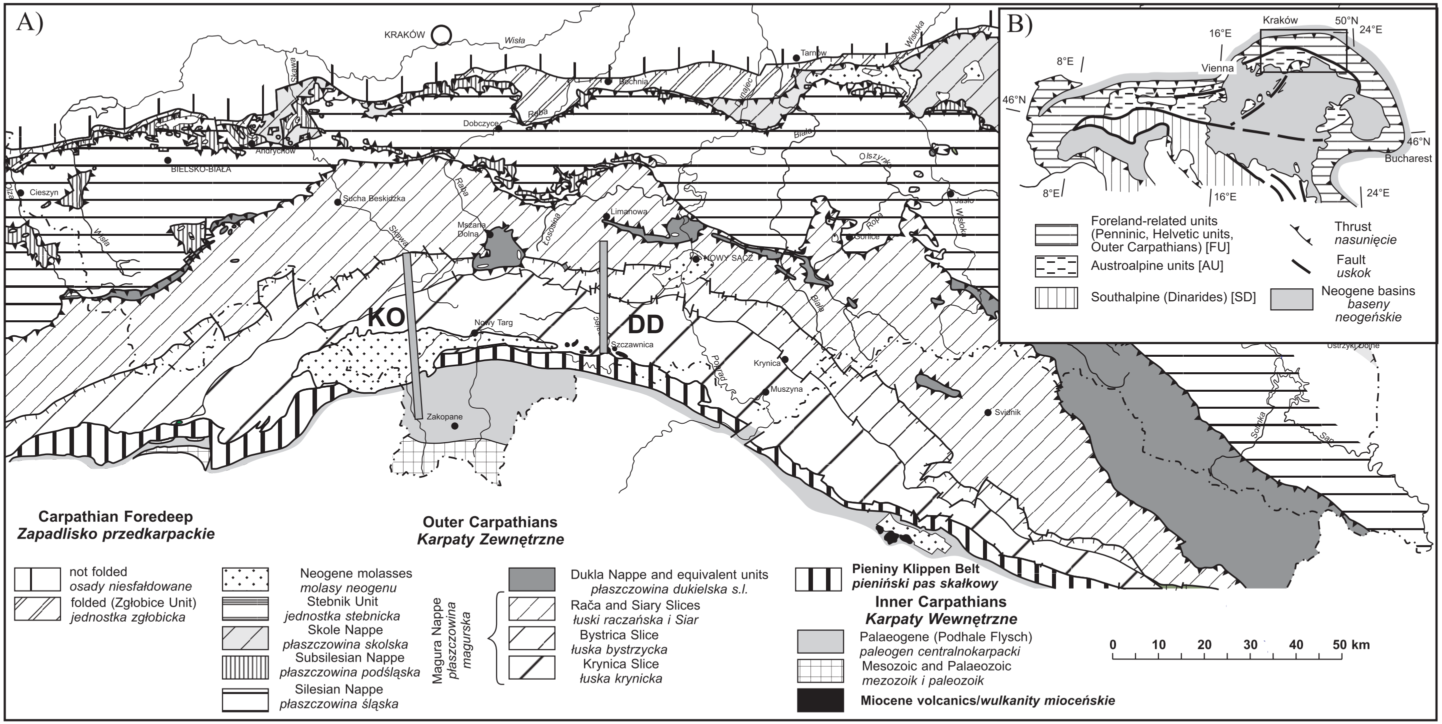


Fig. 2. Geological sketch-map of the Polish segment of the Outer Carpathians (based on Żytko *et al*. 1989, modified) (A), showing location of the studied transects. Inset map showing structural sketch of the Carpatho-Pannonian region (based on Neubauer *et al*. 1997, modified) (B)

Fig. 2. Szkic geologiczny polskiego segmentu Karpat Zewnętrznych (wg Żytki *et al*. 1989, zmienione) (A), wraz z lokalizacją badanych profili. Szkic strukturalny regionu karpacko-panońskiego (wg Neubauera *et al*. 1997, zmienione) (B): FU – jednostki związane z przedpolem (pennińskie, helweckie, Karpaty Zewnętrzne), AU – jednostki austroalpejskie, SD – jednostki południowoalpejskie (dynarydy)

Absolute gravimetric studies conducted in the Rhine Graben since 1987 (Keysers & Kümpel 2000, Almavict *et al*. 2004) revealed a drop in gravity by *ca*. –1.5 μGal, indicative of slow subsidence. Absolute and superconducting gravimeters are used, for instance, within the framework of the Global Geodynamics Project (GGP; Crossley *et al*. 2005) aiming, i.a. at detecting changes of crustal surface and density in the Po Plain (Zerbini *et al*. 2001). Relative gravity observations were also made along the 63 parallel across Northern Europe, to detect postglacial rebound of Fennoscandia (Ekman & Mäkinen 1996), in a seismogenic zone in West Bohemia (Mrlina *et al*. 2003), and the Friuli seismic area in northern Italy (Becker *et al*. 1994) with a view to monitor seismic premonitory signs.

Previous studies of the temporal gravity changes in Poland, applied to geodetic and geodynamic purposes (cf. Zanimonsky *et al*. 2000, Ząbek & Pachuta 2000), relied on measurements in geodynamic test areas, particularly in the Sudetes (Barlik 2000, Cacoń *et al*. 2003, Kontny 2003, Barlik *et al*. 2004), less frequently in the Carpathians (Czarnecka 1986, Ząbek *et al.* 1988, 1993, Barlik *et al*. 2003, Czarnecki *et al.* 2004). Another aspect represent gravity studies aiming at monitoring tectonically and man-induced ground motions in active and abandoned mining areas (*cf.* Fajklewicz 1980, Barlik 1993). The area chosen for our study has not been analyzed by these techniques, except a portion of the Pieniny Klippen Belt situated west of the DD transect.

The assumed gravity measurements are long-term ones. Finding and analyzing temporal changes of the gravity field will require as much as tens of years. Therefore, the work performed within this project should be treated as an input, basic material for future investigations.

GEOLOGICAL SETTING

Regional setting

The Outer Carpathians are a thrust-and-fold-belt, north-verging in the Polish segment (Fig. 2). The belt, composed largely of Lower Cretaceous to Lower Miocene flysch strata, comprises several nappes. The innermost and largest of the nappes is the Magura Nappe. This nappe is subdivided by north-verging reverse faults into four slices which are termed (from the south to the north) Krynica, Bystrica, Rača and Siary slices. To the north, the Outer Carpathian nappe pile is thrust over the Carpathian Foredeep, whereas to the south the Magura Nappe contacts along steep faults with the Pieniny Klippen Belt (Figs 2, 3), a narrow shear zone separating the Inner and Outer Carpathians and affected by Late Cretaceous and Neogene tectonic deformation. South of the belt, the Central Carpathian Palaeogene Basin occurs, which belongs to the Inner Carpathians, a continuation of the Northern Calcareous Alps. The intramontane Orava-Nowy Targ Basin, filled with Late Cenozoic fresh- -water molasses, is superimposed upon all these units.

Principal structural elements of the Outer Carpathians fold-and-thrust belt 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, 2001, Fodor *et al*. 1999).

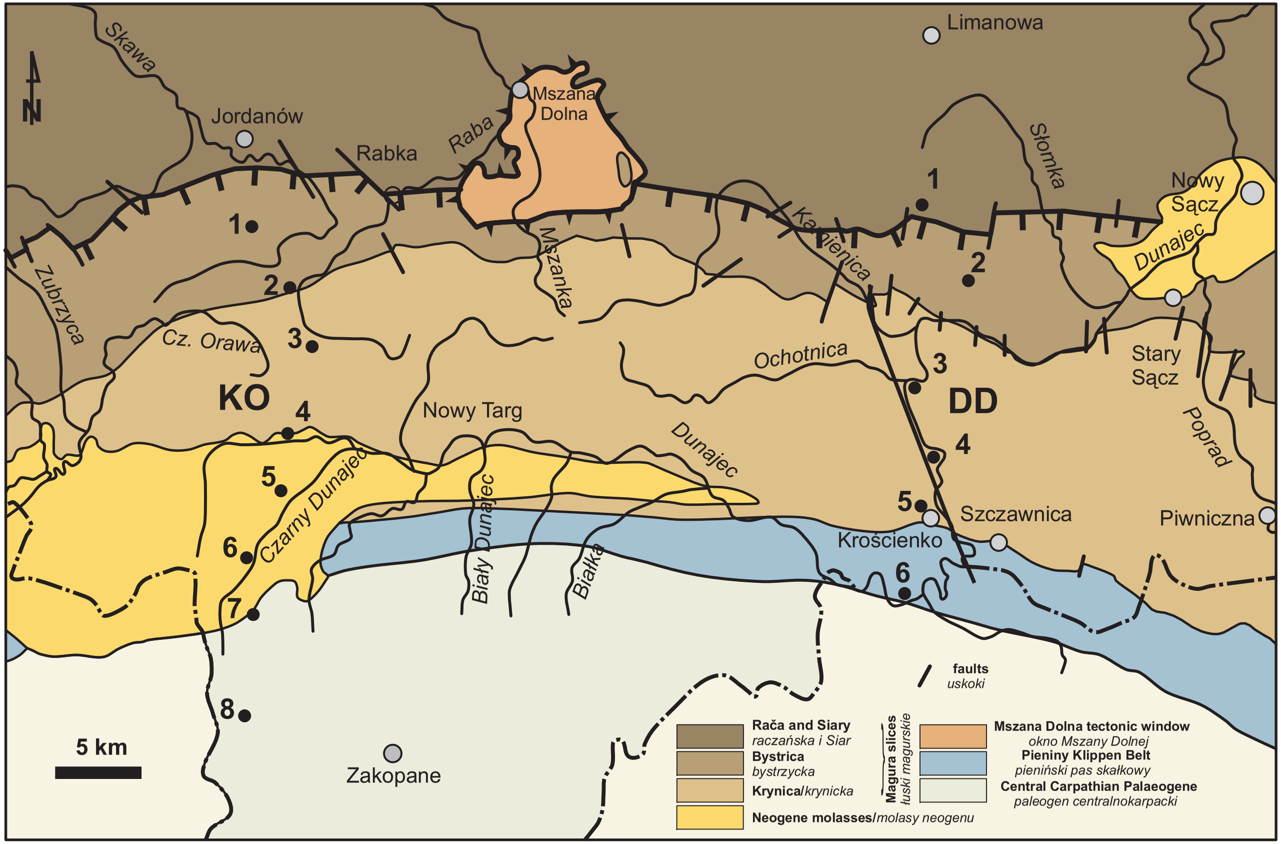


Fig. 3. Location of transects KO and DD. Geology based on Żytko *et al.* (1989) and Oszczypko (2001). Numbers refer to individual benchmarks of both transects

Fig. 3. Lokalizacja profili KO i DD. Sytuacja geologiczna według Żytki *et al.* (1989) oraz Oszczypki (2001). Cyfry oznaczają kolejne punkty pomiarowe

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 outermost part of the belt (Oszczypko 1998, 2004, Świerczewska & Tokarski 1998, Zoetemeijer *et al*. 1999). 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. 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 (see 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, the strike of which is nearly parallel to that of principal thrusts (Fig. 4).

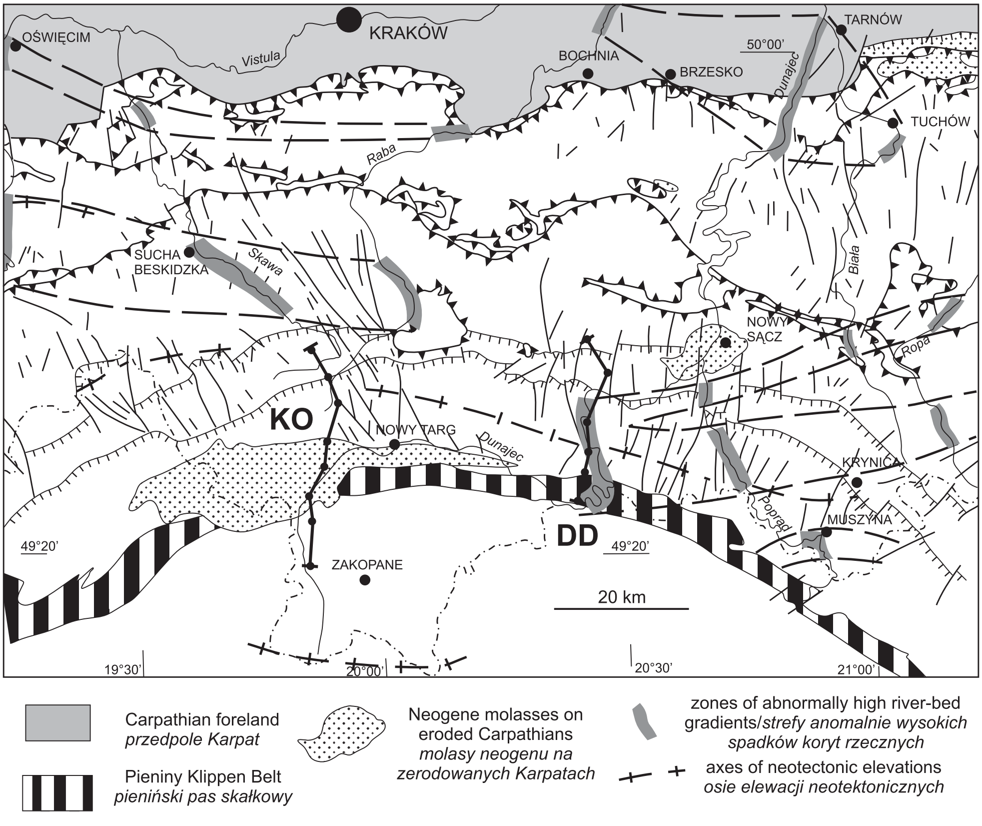


Fig. 4. Neotectonic sketch of the medial segment of the Polish Carpathians, showing location of the studied transects

Fig. 4. Szkic neotektoniczny środkowej części Karpat polskich wraz z lokalizacją badanych profili

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); an area showing a relatively high amount of erosional dissection. Episodes of intense downcutting of straths, largely induced by surface uplift, occurred in the intervals of 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 *et al*. 2004). The results of recent GPS campaigns (Hefty 2007) and borehole breakout analyses (Jarosiński 1998, 2006) point, in turn, to the NNE-directed horizontal motions throughout the area.

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, Guterch *et al*. 2005, Guterch 2006). Local magnitudes do not exceed 4.5 on the Richter scale, averaging between 2.5 and 3.4 (Pagaczewski 1972, Prochazková *et al*. 1978, Guterch *et al.* 2005).

Site-specific setting

The studied benchmarks are placed on two transects (Fig. 3): KO (Orava Basin) and DD (Dunajec River valley), crossing geological structures of different age and tectonic style, and showing variable neotectonic trends (Żytko *et al*. 1989, Zuchiewicz 1995, 1998).

The Orava-Nowy Targ Basin is a bi-partite basin (Figs 3, 5), 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. 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 strike-slip faults that are oriented NNW-SSE and NE-SW (Pomianowski 1995, 2003). The basin-bounding faults became reactivated in Quaternary times, and their recent activity is indicated by earthquakes of magnitudes up to 4.5 (Guterch 2006).

According to Baumgart-Kotarba (1991–1992) 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 and subsequent gravitational collapse. A new study by Struska (2008) led to a concept of a composite pull-apart basin, formed due to linking of small-scale basins bounded by en echelon oriented strike-slip faults, and produced during a NNW-oriented extension event.

The Wróblówka Graben, situated in the medial portion of transect KO, indicates the late Pleistocene, or even Holocene, subsidence (Fig. 5). Minor uplift tendencies are observed in the southern part of the Magura Nappe, i.e. in the northern segment of the transect (Baumgart-Kotarba 1991–1992; Baumgart-Kotarba *et al.* 2001). The measuring stations were sited on the following geological structures: two stations in the Central Carpathian Palaeogene Basin (Podhale Flysch) area, three in the Orava Basin area (one of them in the Wróblówka Graben), one in the Krynica slice, and two in the Bystrica slice of the Magura Nappe (Fig. 3).

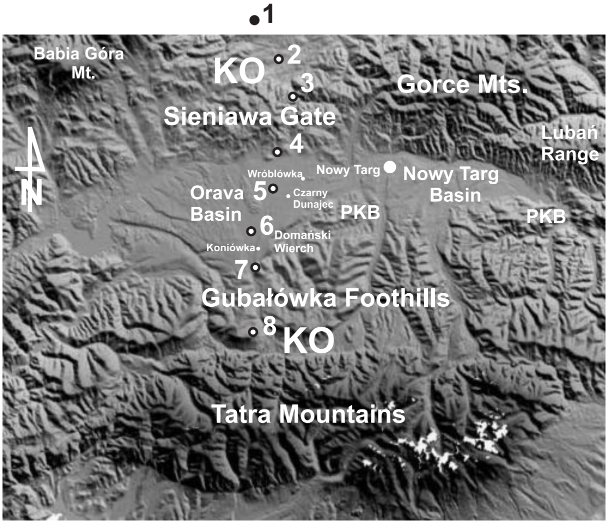


Fig. 5. Digital elevation model based on SRTM level 2 data of the Orava Basin and its surroundings, showing place names mentioned in the text. PKB – Pieniny Klippen Belt. Numbers refer to benchmarks of transect KO

Fig. 5. Numeryczny model terenu bazujących na danych SRTM level 2 Kotliny Orawskiej i jej otoczenia, z zaznaczeniem miejscowości omawianych w tekście. Orava Basin – Kotlina Orawska, Nowy Targ Basin – Kotlina Nowotarska, PKB – pieniński pas skałkowy, Sieniawa Gate – Brama Sieniawska, Lubań Range – Pasmo Lubania, Gubałówka Foothills – Pogórze Gubałowskie. Cyfry odnoszą się do punktów pomiarowych profilu KO

The second transect (DD) crosses the Pieniny Klippen Belt and three southern slices of the Magura Nappe. The nappe is composed of strata that build three structural complexes of the Late Cretaceous-Palaeocene, Early to Late Eocene, and Oligocene to Early Miocene age, which show decreasing degree of tectonic deformation towards the top of the nappe (Oszczypko 2001). Transect DD is passing through a fragment of the Polish Outer Carpathians which has been most strongly uplifted in the Quaternary. The antecedent Dunajec River water-gap in the medial segment of the transect crosses one of longitudinal neotectonic elevations (Fig. 4; *cf.* also Starkel 1972, Zuchiewicz 1984, 1991, 1998). One station of transect DD is situated in the southern part of the Polish segment of the Pieniny Klippen Belt, three in Krynica, one in Bystrica, and one in Rača slices of the Magura Nappe (Fig. 3). Two southern stations are located to the west, and four northern ones to the east of the dextral Dunajec Fault (Birkenmajer 1979, Oszczypko 2001), striking NNW-SSE and running largely along the western side of the Dunajec River valley. The last episode of activity of this fault was dated to 2.5–6.5 ka (Jurewicz *et al.* 2007).

METHODS

Geophysical measurements were made at permanently stabilized geodynamic measuring stations, which were placed as down-hole earth benchmarks below the expected freezing point, i.e. *ca*. 2 m below the ground surface (Łój *et al*. 2005). The benchmark spacing was chosen at *ca*. 5 km, so as to meet the principle that each station should be located in a different geological structure.

Special constructions were prepared for fastening and disposing of certain measuring equipment in the measuring stations. For this reason, in the geodetic GPS method, steel bars screwed into the disc were made. During the measurements, the bars were fastened to the satellite antenna. Accurate connection of the bar and the stator elements of the measuring station had a positive influence on the stability and precision of geodetic measurements. In case of gravity measurements performed with various types of gravimeters, a base on which the equipment could be safely disposed had to be constructed (Łój *et al*. 2005). It was a universal stator having a circular base, the radius of which corresponded to the inner diameter of the pipe. The stator was finished off with a slotted steel plate, enabling disposal of the measuring equipment.

Geodetic works were made with the use of GPS, providing accuracy at a level of 3 to 5 mm at the coordinates X and Y, as well as 5 to 7 mm at the coordinate Z.

To determine horizontal changes of station location, static GPS measurements were made observing the following principles:

- duration of an observation session at the basic points of the transects lasted 48 hrs, with registration interval (time of calculations) less than 30 seconds,
- height of satellite observations over the horizon (cutting angle) attained 10°.

Geodynamic transects were tied to 6 permanent stations of an active geodetic network ASG-PL. Without burdening the inner accuracy of the network, the stations of the analyzed transects were “tied up” to the national gravity network at an accuracy better than ±5 cm.

The following parameters were calculated: geodetic coordinates and their mean errors after being compensated in the Euref’89 system, flat coordinates in the national system 2000, as well as distances between stations on the transects and mean errors of their determination. These parameters may form a basis for inferring on the possible movements of the stations. In view of the obtained values of length mean errors, which are less than 1 mm in case of the distance between the neighbouring stations on a transect, it can be assumed that the comparison of the results of successive observation epochs shall enable detecting station drifts in time between the epochs at a level of 3 to 5 mm.

Gravity measurements on each transect were made three times a year in 2004 through 2006 on two types of astatized gravimeters: two quartz gravimeters with automatic record of data by Canadian SCINTREX – CG-3 and CG-3M, and a metal gravimeter LaCoste & Romberg, model G, for which the read-outs were made by the interpolation method with an external volt meter. The devices used for field work measure gravity with the accuracy of up to 0.01 mGal ($1 \text{ mGal} = 1\cdot10^{-5} \text{ ms}^{-2}$). Owing to the fact that different types of gravimeters were used for geodynamic investigations, they were first calibrated, i.e. scale coefficients were determined for each device. These coefficients were calculated as a weighted average with its weight being proportional to the difference of the force of gravity acceleration. In such a way, one can directly compare the values obtained by various instruments.

Calibration was made on a profile at the southern fragment of the National Gravimetric Basic System, between Zakopane – Nowy Targ – Myślenice stations. The range of this fragment of the basic system equals to *ca*. 200 mGal, corresponding to gravity values expected in measurements on a complex geodynamic investigation area. This calibration was supposed to take place each time before the annual gravity measurements.

To provide high accuracy of gravimetric observations, the measurements were made with the double chain method (Łój *et al*. 2005), in which observation is made twice at each outer point of the chain and three times at the inner point. This approach enables for the calculation of gravity field changes between stations on a triple increment-measurement basis, which considerably raises the precision of calculation. It is the optimal method of the gravimeter drift elimination. According to the rules accepted in gravity survey, all results are presented as differences between neighbouring observation points, i.e. the so-called network leg values.

The measurements in a single area between stations accounted for corrections (height of the instruments in the stations, tide correction, and drift elimination), so that the final value Δg between the stations and the average error were obtained. The scale coefficients enabled to compare values obtained from various gravimeters between the same stations.

Each transect was tied up to the basic system of the National Gravimetric Network. The station at Nowy Targ was selected due to a relatively small difference of gravity force between the basic and selected stations in both transects.

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.

RESULTS

Neotectonic and geomorphic constraints

Orava Basin

The maximum drilled thickness of sedimentary infill of the Orava Basin is 950 m, including 922 m of fresh-water Neogene molasses (Watycha 1976; see also Fig. 6B). The thickest Quaternary sediments (117 m) are confined to the Wróblówka Graben, in the northern part of this basin (Watycha 1973). The Quaternary basin fill comprises glaciofluvial sediments deposited during the three mountain glaciations in the Tatra Mountains.

Neotectonic history of the Orava Basin can be reconstructed from the analysis of deformed planation surfaces of Neogene age, structural studies of fractured pebbles within Neogene fresh-water molasses and Quaternary terrace alluvium, as well as from geomorphic studies of tectonically-induced changes of the drainage pattern.

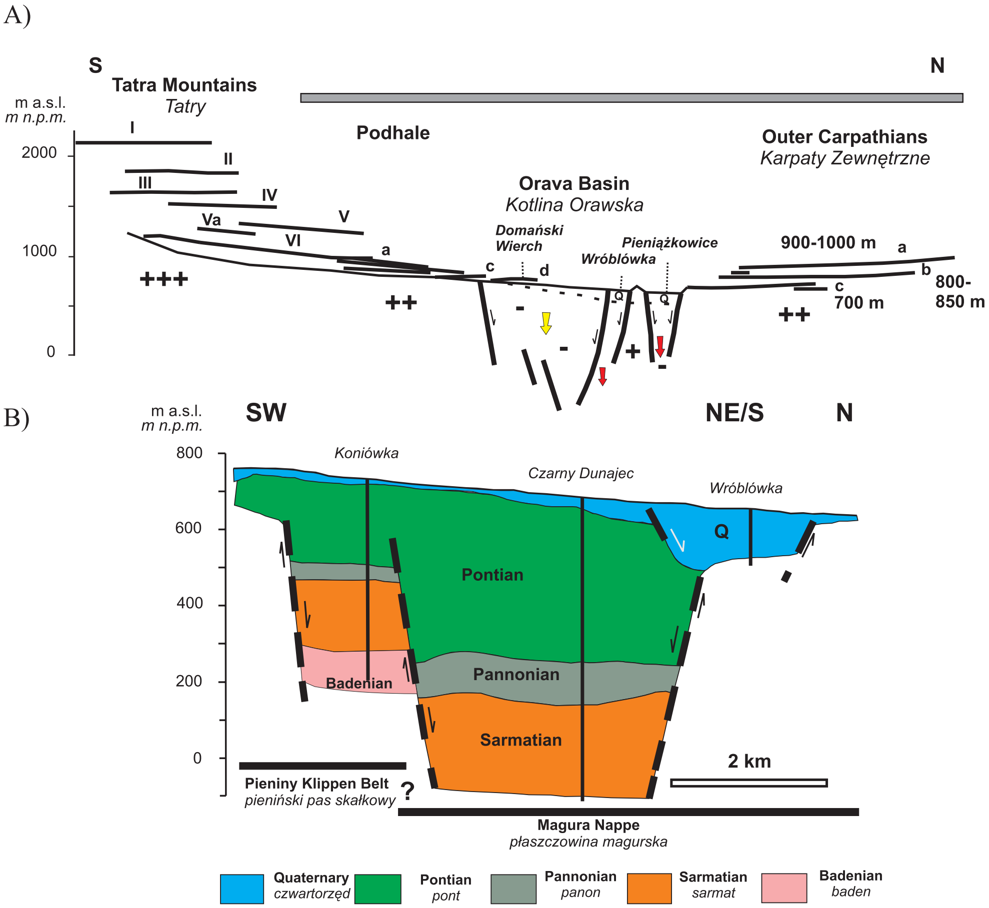


Fig. 6. A) Pattern of planation surfaces in a simplified section across the Tatra Mts, Orava Basin and southern portion of the Outer Carpathians (based on Baumgart-Kotarba 1983, 1991–1992; modified). Arrows denote Neogene and Quaternary (shown in red) subsidence (–); the number of "+" signs reflects relative intensity of uplift. Shaded bar marks the position of KO transect. See text for explanation of the age of planated levels (I–VI, a–d). B) Section across the Orava Basin along transect KO (based on Pomianowski 2003; modified). Mediterranean equivalents of the Central Paratethys Neogene stages: Langhian and early Serravallian = Badenian, late Serravallian = Sarmatian, Tortonian = Pannonian, early and middle Messinian = Pontian. Thick vertical lines denote boreholes

Fig. 6. A) Powierzchnie zrównania na uproszczonym przekroju przez Tatry, Kotline Orawską i południową część Karpat Zewnętrznych (według Baumgart-Kotarbowej 1983, 1991–1992; zmodyfikowane). Strzałki wskazują neogeńską i czwartorzędową (kolor czerwony) subsydencję (–); znak „+" oznacza względną intensywność wypiętrzania. Zaszrafowany pasek wskazuje lokalizację profilu KO. Porównaj tekst odnośnie do wieku kolejnych spłaszczeń (I–VI, a–d). B) Przekrój przez Kotlinę Orawską wzdłuż profilu KO (według Pomianowskiego 2003; zmodyfikowane). Międzynarodowe odpowiedniki pięter wyróżnianych w Paratetydzie Centralnej: lang i wczesny serrawal – baden, późny serrawal – sarmat, torton – panon, wczesny i środkowy messyn – pont. Pogrubione linie pionowe oznaczają wiercenia

Planation surfaces in the Tatra Mts (Klimaszewski 1988), Podhale region and Beskidy Mts (Baumgart-Kotarba 1983, 1991–1992, Kukulak 1993), dated to the Serravallian (late Badenian – Sarmatian; levels I through V) and early Tortonian (Pannonian; levels VI and a), Messinian (Pontian; level b), late Zanclean and Piacenzian (late Dacian and Romanian; level c), and early Pleistocene (level d) are tilted towards the centre of subsiding Orava Basin (Fig. 6A). The axis of subsidence migrated in time from the Domański Wierch and Czarny Dunajec area in Neogene times to the Wróblówka and Pieniążkowice grabens in the Quaternary, from the south to the north (Figs 5, 6). The southern part of the Orava Basin is occupied by the Domański Wierch fan (Fig. 7 on the interleaf), which is composed of a nearly 500 m thick sequence of terrestrial gravelstones, intercalated by sands, clays and lignites (Oszast 1973, Birkenmajer 1979). The southern part of the fan is dated to the late Serravallian (Sarmatian; Birkenmajer 1979), whereas the northern one, more than 220 m thick, represents early and middle Pliocene (Oszast & Stuchlik 1977), Villafranchian-type molasses, composed of paraconglomerates that comprise nearly exclusively sandstone cobbles transported from SW, SSE and ESE, from the Central Carpathian Palaeogene flysch strata.

Numerous pebbles are fractured (Fig. 7); these were examined at sites Stare Bystre and Miętustwo A and B (*cf.* Zuchiewicz 1994, Tokarski & Zuchiewicz 1998). The first site is situated in the northern, Pliocene part of the fan, within a 10 m thick package of gravelstones exposed in a N80°E oriented scarp. Vertical fractures of planar surfaces are limited here to singular clasts and cluster into two sets that intersect each other at an angle of 20–25°, the bisectrix of which strikes N35–40°E. The second site is located in the southern part of the fan, within a 70 m thick sequence of gravelstones of attitude 70/20N. These sediments are exposed in a scarp oriented N140–160°E. Vertical and subvertical fractures show both planar and undulating surfaces, and form a single set striking NNE. Fracture orientation is similar in both localities. Moreover, the fractures are aligned obliquely to the scarps where fractured pebbles were measured; hence, the present-day morphology does not seem to have controlled their pattern. Site Stare Bystre reveals two sets of shear fractures conjugate under small dihedral angle, whose bisectrix (NNE) denotes the position of the maximum principal stress. According to Aleksandrowski (1985), the stress field of similarly oriented $\sigma 1$ did exist in that part of the Carpathians in Middle Miocene times. Recent studies of breakouts in the Outer West Carpathians point to analogous position of the recent maximum compressive stress (Jarosiński 1998).

The stress field characterized by horizontal, NNE-oriented maximum stress was also suitable for the formation of Quaternary transversal faults, detected on the margins of the Orava Basin by Pomianowski (1995). On the other hand, the origin of Neogene and Quaternary longitudinal faults is difficult to explain. This controversy can be resolved by assuming repeated permutations of the stress field axes in the time-span considered. Such a conjecture is supported by the character of fractures occurring at site Miętustwo B (Fig. 7D). These fractures form two sets, I and II. The set I includes vertical and subvertical, NNE-oriented fractures, parallel to those observed at sites Stare Bystre and Miętustwo A. The set II, in turn, is represented by vertical and subvertical fractures that strike WNW, i.e. subparallel to some of the longitudinal normal faults bounding the Orava Basin.

The origin of fractures in the Domański Wierch series is probably associated with the activity of a transversal fault, identified by gravity studies of Pomianowski (1995) in the basement of the fan.

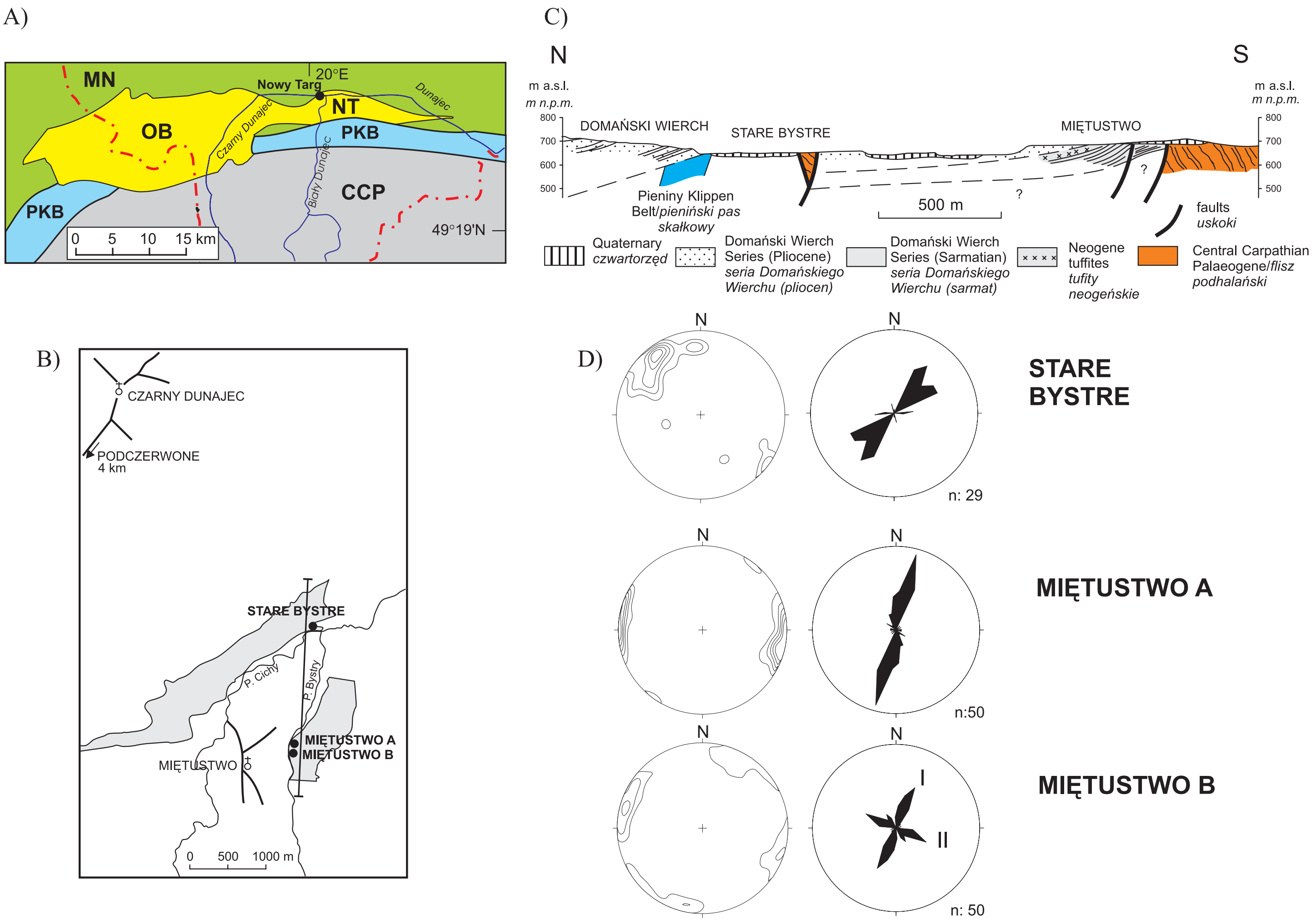


Fig. 7. Location of Neogene conglomerates with fractured clasts in the Orava Basin (based on Tokarski & Zuchiewicz 1998, modified): A) position of the Orava Basin in the West Carpathians (after Żytko *et al*. 1989); letter symbols: MN – Magura Nappe, OB – Orava Basin, NT – Nowy Targ Basin, PKB – Pieniny Klippen Belt, CCP – Central Carpathian Palaeogene; B) outcrops of the Domański Wierch series (after Birkenmajer 1979) with location of the studied exposures; C) section across the Domański Wierch series (based on Birkenmajer 1979); D) plots of fractures within pebbles in the studied exposures (lower hemisphere stereograms on the left, rose-diagrams on the right)

Fig. 7. Lokalizacja wychodni zlepieńców neogeńskich ze spękanymi klastami w Kotlinie Orawskiej (wg Tokarskiego & Zuchiewicza 1998, zmodyfikowane): A) położenie Kotliny Orawskiej w Karpatach Zachodnich (Żytko *et al*. 1989); symbole literowe: MN – płaszczowina magurska, OB – Kotlina Orawska, NT – Kotlina Nowotarska, PKB – pieniński pas skałkowy, CCP – paleogen centralnokarpacki (flisz podhalański); B) odsłonięcia serii Domańskiego Wierchu (wg Birkenmajera 1979) z lokalizacją badanych stanowisk; C) przekrój przez serię Domańskiego Wierchu (wg Birkenmajera 1979); D) stereogramy spękań w klastach badanych stanowisk (z lewej – odwzorowanie półkuli dolnej siatki równopowierzchniowej, z prawej – histogram azymutalny)

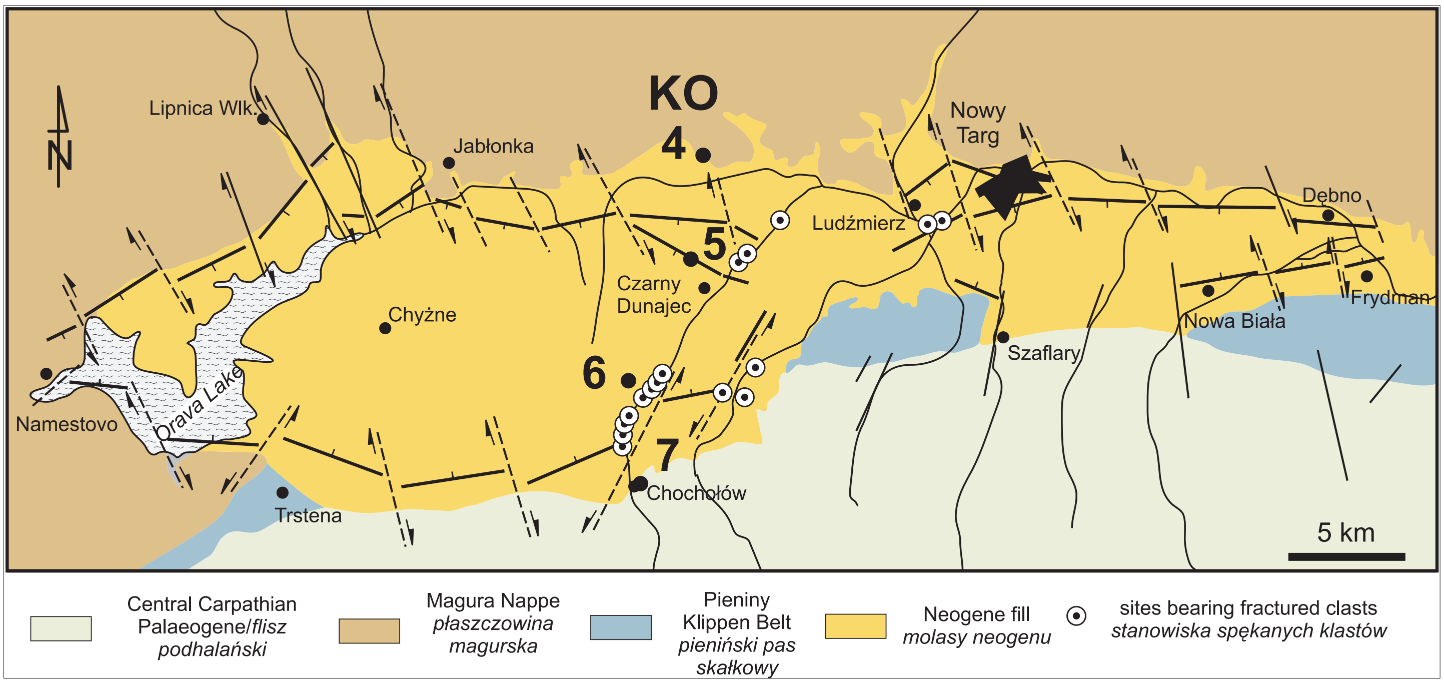


Fig. 8. Geological sketch-map of the Orava – Nowy Targ Basin (based on Pomianowski 2003, modified), showing location of sites of Holocene alluvium bearing fractured clasts (after Tokarski *et al*. 2007). Numbers refer to benchmarks of transect KO

Fig. 8. Szkic geologiczny Kotliny Orawsko-Nowotarskiej (wg Pomianowskiego 2003, zmodyfikowany), z lokalizacją stanowisk holoceńskich aluwiów zawierających spękane klasty (wg Tokarskiego *et al*. 2007). Cyfry oznaczają punkty pomiarowe profilu KO

Fractured clasts are also common within Late Pleistocene and Holocene terrace alluvium, particularly at sites located on both normal and strike-slip faults near the southern margin of the basin, i.e. in areas affected by relatively frequent historical seismicity (Tokarski *et al*. 2007; *cf*. Fig. 8 on the interleaf).

In the remaining part of the Orava Basin, the results of seismic soundings (*cf*. Baumgart-Kotarba 1996, 2000, Baumgart-Kotarba *et al*. 2001, 2004) 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 Graben, smaller ones are confined to a more northerly situated Pieniążkowice Graben (Figs 5, 6). Orientation of young grabens (W-E) points to N-S-oriented extension during the last episode of neotectonic mobility of the area.

Repeated precise levelling surveys in the area (Makowska & Jaroszewski 1987, Makowska 2003) point to diversified uplift of the Tatra Mts., Pieniny Klippen Belt and the southern portion of Magura Nappe, and variable subsidence of the Orava-Nowy Targ Basin (Fig. 9). Recently obtained results of PSInSAR (Persistent Scatterers SAR interferometry) processing of 51 ERS-1/2 SAR scenes, covering a period of 1992–2000 years, showed relative 1 mm/year uplift of the Zakopane area in respect to Nowy Targ, and suggested recent activity of some faults (*cf*. Perski 2008).

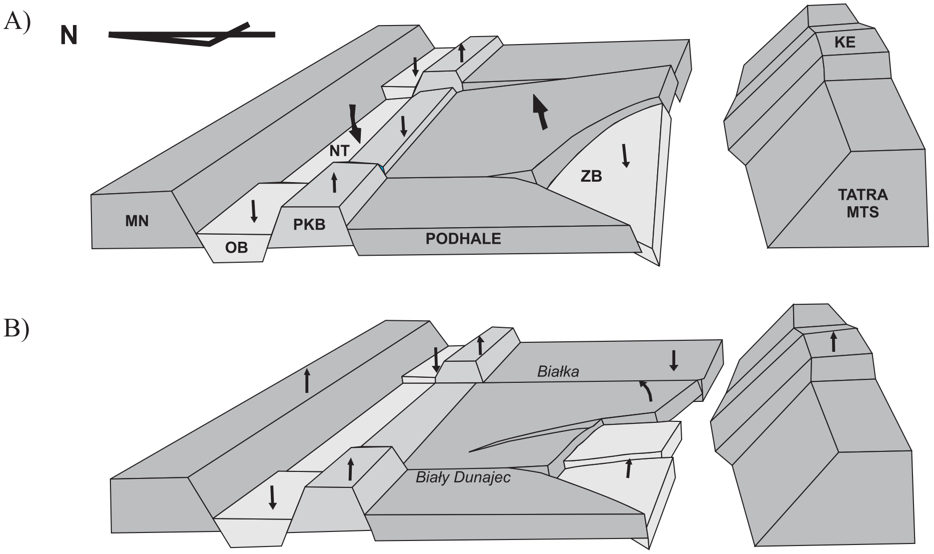
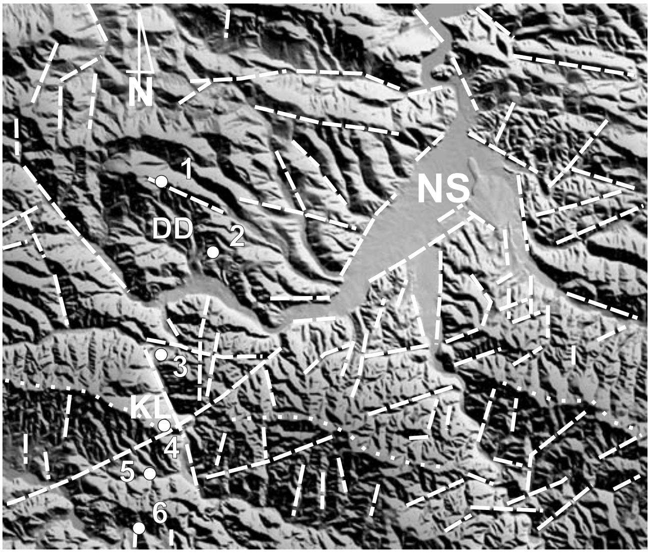


Fig. 9. Recent dynamics of the Podhale–Tatra region inferred from repeated precise levelling (based on Makowska & Jaroszewski 1987, Makowska 2003; modified): A) hypothetical model preceding present-day situation; B) present-day situation. Letter symbols: MN – Magura Nappe, OB – Orava Basin, NT – Nowy Targ Basin, PKB – Pieniny Klippen Belt, ZB – Zakopane Basin, KE – Koszysta Elevation

Fig. 9. Współczesna dynamika rejonu tatrzańsko-podhalańskiego na podstawie wyników powtarzanej niwelacji precyzyjnej (według Makowskiej & Jaroszewskiego 1987 oraz Makowskiej 2003; zmienione): A) hipotetyczny obraz poprzedzający sytuację współczesną; B) sytuacja współczesna. Oznaczenia literowe: MN – płaszczowina magurska, OB – Kotlina Orawska, NT – Kotlina Nowotarska, PKB – pieniński pas skałkowy, ZB – Kotlina Zakopiańska, KE – elewacja Koszystej

Medial portion of the Pieniny Klippen Belt and Magura Nappe cut by the Dunajec River

The Dunajec River valley in the studied transect forms two antecedent water-gaps, dissecting the Pieniny Klippen Belt in the south and the Krynica and southern part of Bystrica slices of the Magura Nappe in the north (Figs 3, 4, 10). The latter water-gap dissects the Beskid Sądecki Mts range, rising above 1,200 m a.s.l. The "Beskid Sądecki" water-gap includes two deeply cut meanders which are separated by a rectilinear valley, parallel to a fault line. This area is situated at a place of intersection of NNW, NE, and N-S striking topolineaments (Fig. 10).



NS - Nowy Sącz Basin, KL - site Kłodne
NS - Kotlina Sądecka, KL - stanowisko Kłodne

Fig. 10. Digital elevation model based on SRTM level 2 data of the medial segment of the Polish Carpathians, dissected by the Dunajec River valley. Dashed lines mark the most prominent topolineaments; dotted line denotes axis of the Beskid Sądecki neotectonic elevation. Numbers refer to benchmarks of transect DD

Fig. 10. Numeryczny model terenu bazujący na danych SRTM level 2 środkowego segmentu Karpat polskich, rozciętego doliną Dunajca. Linie przerywane oznaczają główne topolineamenty; linie kropkowane wskazują oś elewacji neotektonicznej Beskidu Sądeckiego. Cyfry oznaczają punkty pomiarowe profilu DD

The gorge is 15 km long and up to 700 m deep, its width changing from 75–100 m within the meanders to 450–500 m in other segments. The river-bed is cut into solid bedrock and its long profile is ungraded and of exceptionally high gradient, compared to the upstream and downstream valley reaches (*cf.* Fig. 4). The eastern valley sides are steep (50–66%) and dissected by a network of short (up to 1.5 km) and high-gradient (> 200 m/km) minor tributary valleys and ravines (Fig. 11).

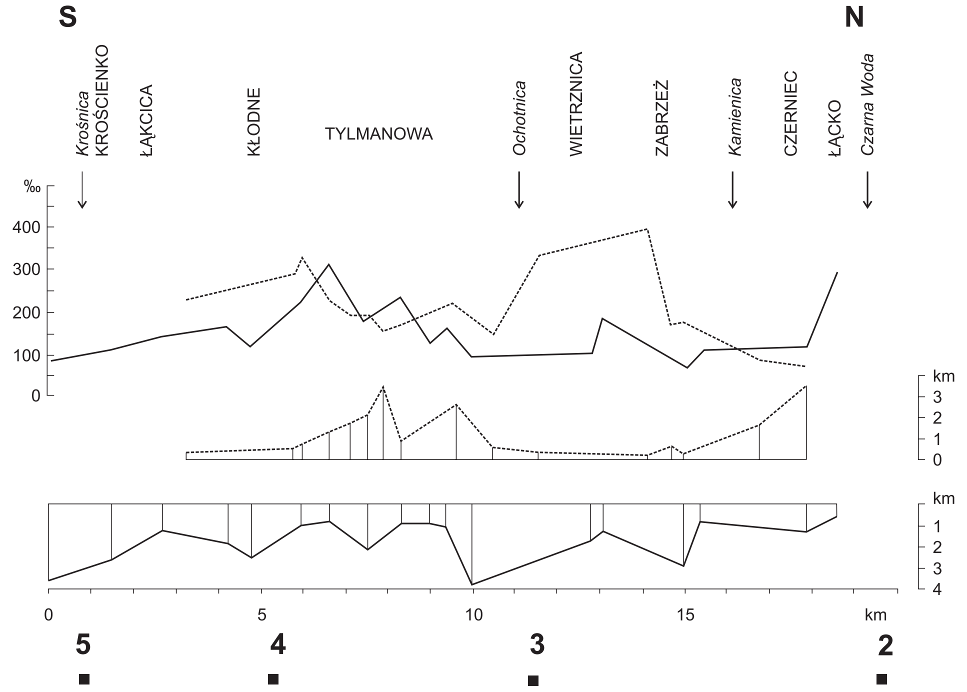


Fig. 11. Stream gradients of the left (dashed lines) and right-hand (solid lines) small-size tributaries of the Dunajec River in the Beskid Sądecki gorge segment. Two lower diagrams portray lengths of the analyzed streams. Bold numbers represent benchmarks of DD transect. See figure 13 for location

Fig. 11. Spadki lewo- (linie przerywane) i prawobrzeżnych (linie ciągłe) dopływów Dunajca w przełomie przez Beskid Sądecki. Dwa dolne diagramy obrazują długości analizowanych potoków. Pogrubione cyfry oznaczają punkty pomiarowe profilu DD. Lokalizacja na figurze 13

Outlets of tributary valleys are usually hanging above the present-day river bed, up to 10–15 m. Headwater parts of some of these tributaries represent hour-glass valleys. The surrounding ridges bear traces of four pre-Quaternary planated surfaces that rise 900 m, 770–830 m, 500–590 m, and 450–500 m a.s.l. (Fig. 12 on the interleaf).

The eastern valley sides are mantled by weathering debris and loams, while the western ones are dominated by a flight of straths and complex-response terraces (Fig. 13 on the interleaf, Fig. 14), the alluvial covers of which were deposited during the Pleistocene glacial stages: Praetiglian (150–155 m to 154–161 m), Menapian or Elsterian-1 (75–84 m to 78–96 m), Elsterian-2 (51–55 m to 52–65 m), Saalian (26–41 m to 29–41 m), Wartanian (17–24 m to 20–31 m), and Weichselian (10–11 m to 16–18 m), as well as in the Holocene (6–10 m, 4–5 m, 2–3 m). The thickness of terrace alluvium is between 3–4 m and 10–14 m (*cf.* Zuchiewicz 1984, 1995 and references therein). These covers are composed of poorly rounded and poorly sorted, both Outer Carpathian flysch (sandstones, siltstones, rare conglomerates) and Tatra-derived (granites, quartzites) gravels and cobbles. Limestones shed from the Pieniny Klippen Belt can only be found within the youngest, i.e. Weichselian and Holocene alluvium; limestone clasts of older fluvial series became completely dissolved.

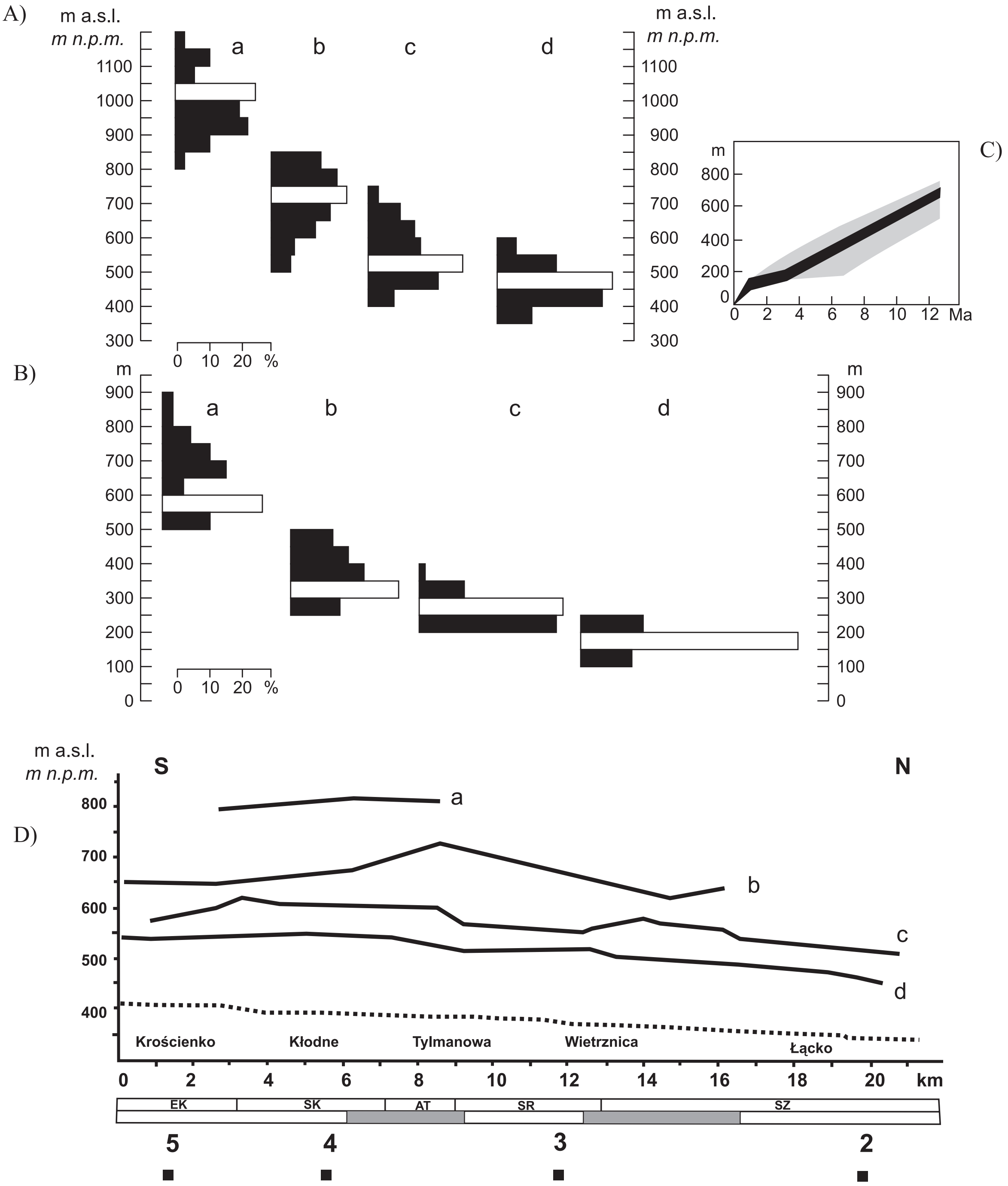


Fig. 12. Diagrams showing elevation of preserved fragments of planation surfaces in the central part of the Dunajec River drainage basin (based on Zuchiewicz 1995, modified and supplemented). Planation surfaces: a – "Beskidy" level (middle – late Serravallian), b – "intramontane" level (early – middle Tortonian), c – "foothills" level (Piacenzian), d – "riverside" level (Early Pleistocene). A) elevation above sea level; B) elevation above present-day river bed; C) rates of erosional dissection with confidence intervals shown in grey; D) long profiles in the Dunajec River gorge segment in the Beskid Sądecki Mts. Tectonic units (based on Tokarski 1975): EK – Krościenko Elevation, SK – Kłodne syncline, AT – Tylmanowa anticline, SR – Rzeka syncline, SZ – Sobel-Zabrzeż anticline. Shaded bars mark zones of disturbance within long profiles of planation surfaces. Bold numbers represent benchmarks of transect DD

Fig. 12. Diagramy obrazujące wysokości zachowanych fragmentów powierzchni zrównania w środkowej części zlewni Dunajca (wg Zuchiewicza 1995, zmienione i uzupełnione): a – poziom beskidzki (środkowy – późny serrawal), b – poziom śródgórski (wczesny – środkowy torton), c – poziom pogórski (piacent), d – poziom przydolinny (wczesny plejstocen). A) wysokość nad poziom morza; B) wysokość nad współczesnym poziomem koryta rzeki; C) tempo rozcięcia erozyjnego wraz z przedziałami ufności (kolor szary); D) profile podłużne w beskidzkim przełomie Dunajca. Jednostki tektoniczne (według Tokarskiego 1975): EK – elewacja Krościenka, SK – synklina Kłodnego, AT – antyklina Tylmanowej, SR – synklina Rzeki, SZ – antyklina Sobla – Zabrzeży. Odcinki zaszrafowane wskazują strefy zaburzeń profili podłużnych powierzchni zrównania. Cyfry pogrubione oznaczają punkty pomiarowe profilu DD

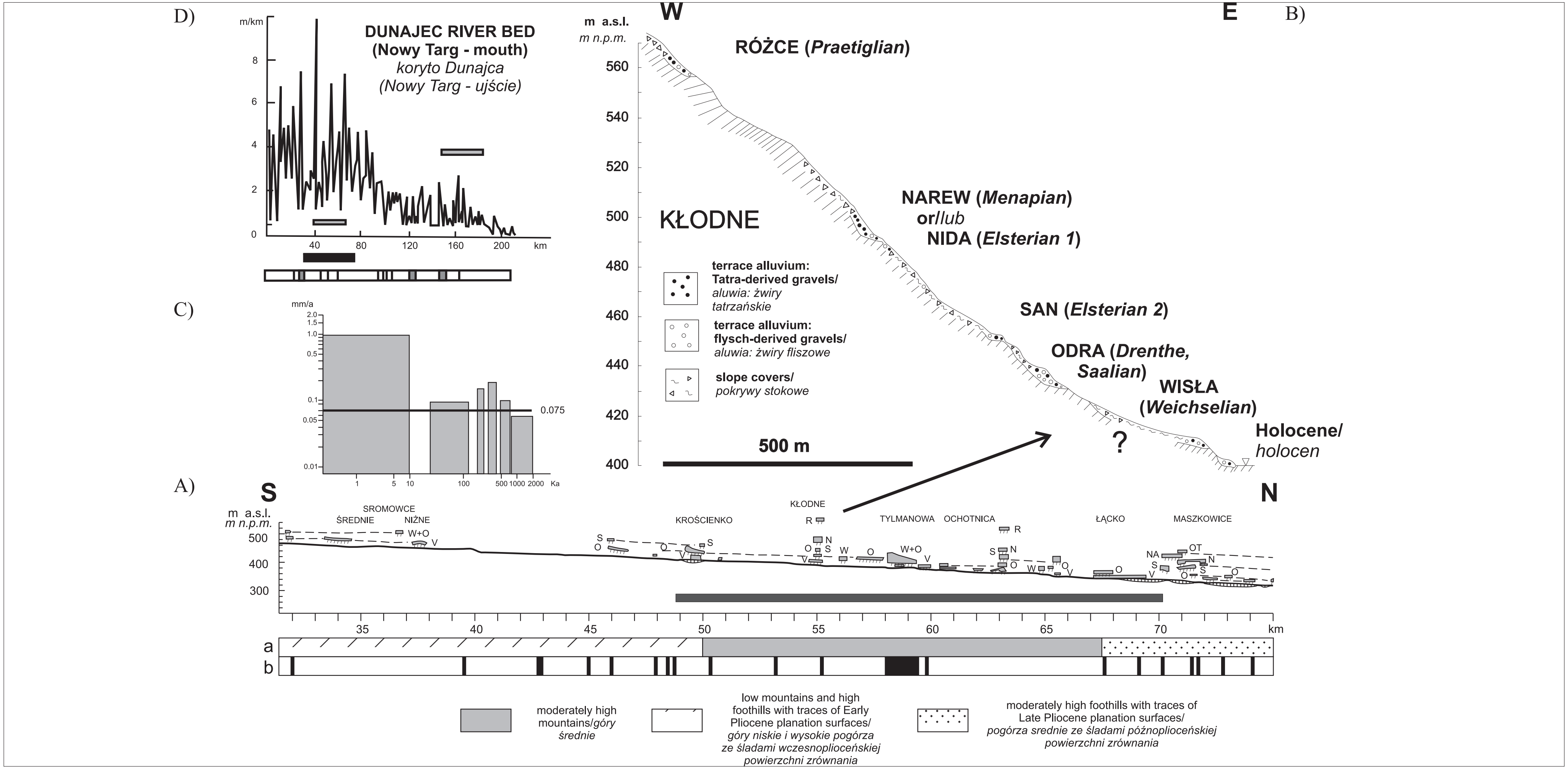


Fig. 13. Fluvial terraces in the Dunajec River valleys in its segment parallel to transect DD. A) Long profile of terraces between Pieniny Mts. and Beskid Wyspowy Mts. Shaded areas denote alluvium, barbed lines – position of straths. Age of terraces (Polish climatostratigraphic stages and their West European equivalents): R – Różce (Praetiglian), OT – Otwock (Eburonian), NA – Narew (Menapian), N – Nida (Elsterian-1), S – San (Elsterian-2), O – Odra (Saalian/Drenthe), W – Warta (Saalian/Warthe), V – Wisła (Weichselian). Thick black bar marks the extent of gorge segment in the Beskid Sądecki Mts, shown in figures 11 and 12; a – types of landscape, b – location of bedrock fault zones cut by the river. B) Cross-section through the Dunajec River straths at site Kłodne, within a meander loop dissecting the highest elevated zone in the Polish Outer Carpathians. C) rates of dissection of straths portrayed in B. D) Slope of the Dunajec River bed between Nowy Targ and mouth. Shaded bars mark segments of abnormally high gradients with respect to the surrounding reaches; black bar indicates river bed segment shown in A. The lower bar shows location of principal fault zones in the bedrock

Fig. 13. Terasy rzeczne w dolinie Dunajca na odcinku pokrywającym się z przebiegiem profilu DD. A) Profil podłużny teras między Pieninami a Beskidem Wyspowym. Pola zaszrafowane oznaczają miąższość pokryw aluwialnych, ukośne kreski – cokoły skalne teras. Wiek teras (jednostki klimatostratygraficzne polskie oraz ich zachodnioeuropejskie odpowiedniki): R – Różce (praetiglian), OT – Otwock (eburonian), NA – Narew (menapian), N – Nida (elsterian-1), S – San (elsterian-2), O – Odra (saalian/drenthe), W – Warta (saalian/warthe), V – Wisła (weichselian). Gruba czarna kreska wskazuje zasięg przełomu przez Beskid Sądecki, pokazany na figurach 11 i 12; a – typy krajobrazu, b – lokalizacja stref uskokowych. B) Przekrój przez terasy skalno-osadowe Dunajca w Kłodnem, w obrębie zakola meandrowego rozcinającego najwyżej elewowaną strukturę neotektoniczną polskich Karpat Zewnętrznych. C) Tempo rozcinania cokołów skalnych teras zobrazowanych przez przekroju B. D) Spadki koryta Dunajca między Nowym Targiem a ujściem. Szrafura wskazuje segmenty o anomalnie wysokich spadkach w porównaniu z odcinkami usytuowanymi bezpośrednio w górę i dół biegu; czarny prostokąt wyznacza odcinek koryta pokazany na diagramie A). Diagram dolny wskazuje położenie głównych stref uskokowych

The Early and Middle Pleistocene covers include a large proportion of angular clasts, pointing to the role of intensive solifluction within glacial stages. All Pleistocene fluvial covers interfinger with solifluction tongues, those dated to the last and penultimate glacial stages being also overlain by slopewash and/or solifluction-slopewash sediments, which are 3–8 m thick. Such interfingering enables for relative dating of the preserved terrace covers, i.e. their assignment to individual glacial stages.

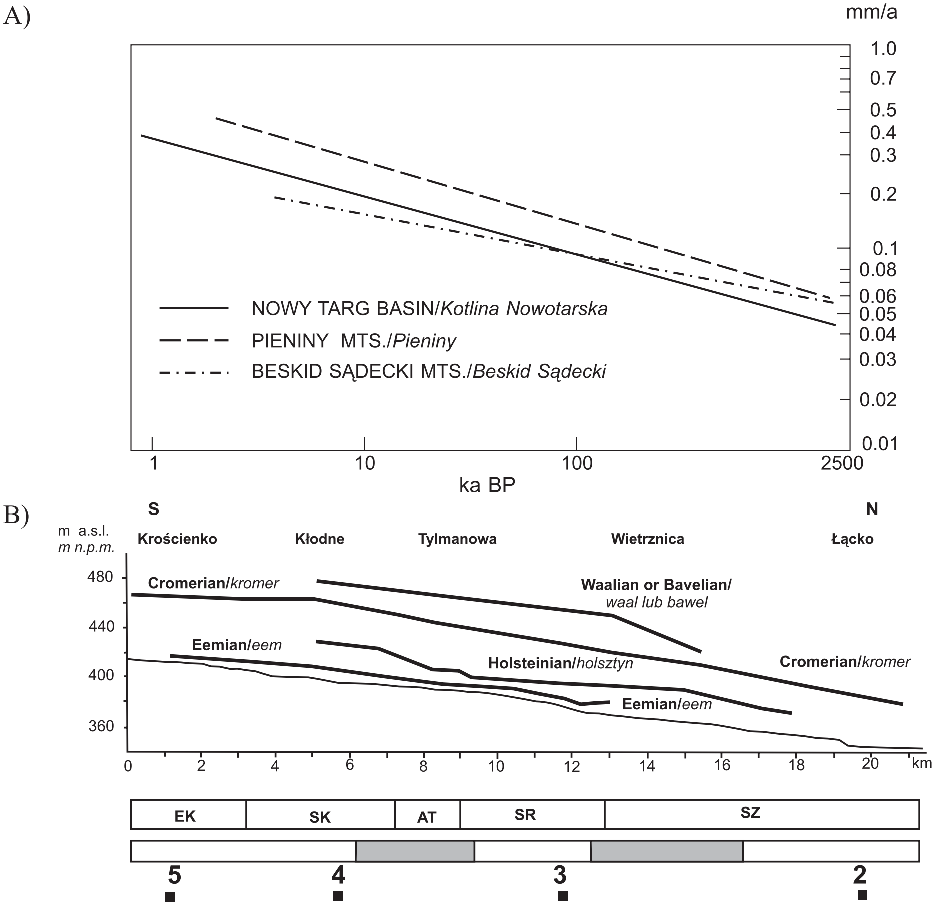


Fig. 14. Straths of the Dunajec River (based on Zuchiewicz 1984, 1998; modified and supplemented): A) rates of erosional dissection of Pleistocene straths within regions of contrasting neotectonic tendencies; B) long profile of straths within the gorge in the Beskid Sądecki Mts (see figure 13 for location). Shaded bars mark zones of disturbance in strath long profiles. Bold numbers represent benchmarks of transect DD. See figure 12 for explanation of tectonic units

Fig. 14. Cokoły skalne teras w dolinie Dunajca (wg Zuchiewicza 1984, 1998, zmodyfikowane i uzupełnione): A) tempo rozcinania erozyjnego cokołów plejstoceńskich teras w obszarach o różnych tendencjach neotektonicznych; B) profile podłużne cokołów terasowych w przełomie przez Beskid Sądecki (lokalizacja na figurze 13). Szrafura wskazuje strefy zaburzeń w profilach podłużnych cokołów. Pogrubione cyfry oznaczają punkty pomiarowe profilu DD. Pozostałe objaśnienia – por. figura 12

Long-profiles of Pleistocene straths (Fig. 14) clearly show increased relative heights of the latter within meander loops. These heights are greatest within the entire Polish segment of the Outer Carpathians; straths of equivalent age within the remaining Dunajec River valley reaches, and those of other Carpathian river valleys are lower even by 30 m in case of the oldest Pleistocene straths (*cf.* Zuchiewicz 1998 and references therein). Deformations of Pleistocene straths combined with intense erosional downcutting appear to indicate Pleistocene surface uplift of the axial part of the Beskid Sądecki Mts, part of the most strongly elevated neotectonic structure in the Polish Outer Carpathians (cf. Starkel 1972, Zuchiewicz 1995; *cf.* also Fig. 4). The amount of fluvial accumulation throughout the Middle and Late Pleistocene in the Dunajec River gorge can be estimated at 555 × 10^6 cubic metres, that removed by erosion attaining *ca.* 652 × 10^6 cubic meters (*cf.* Tokarski *et al.* 2006). The lack of fluvial covers from the Eburonian and – possibly – also Menapian stages points to intense, tectonically-controlled, erosion before the Elsterian; the equivalent-age terrace covers are to be found immediately north of the gorge.

Gravity survey

Gravimetric observations were made at all geodynamic stations with the use of the same measuring method in summer months. This refers both to the time regime and the measuring scheme. The material is based on the results of three years of observations of gravity values at the stabilized geodynamic stations. Gravity surveys were planned to be made with three gravimeters. However, the results of only two gravimeters were at our disposal: LaCoste & Romberg model G No. 986, and Scintrex Autograv CG-3 No. 4511.

Prior to gravimetric observations, calibration measurements were made in both research areas to provide a uniform scale of the determined relative gravity force values. Calibration was made each year in a period directly preceding the gravimetric observations. It should be stressed out that relative errors of scale coefficients of both gravimeters did not exceed 2×10^{-4} mGal. Hence, it can be concluded that the error of less than 3 μGal (1 Gal = $1 \cdot 10^{-8}$ ms^{-2}), was made when determining the gravity at measuring stations. Both devices were calibrated between the stations of the National Gravimetric Network on the route: Myślenice – Nowy Targ – Zakopane.

The results of gravimetric observations performed in the years 2004–2006 are presented for two time intervals: 2005–2004 and 2006–2004. After each measurement session, the calculated gravity error was analyzed to maintain the reliability of measurements. The errors of the determined gravity values are below the accuracy of the apparatuses used. Therefore, it can be assumed that the obtained gravity values are congruent with the actual ones.

A preliminary analysis of two series of investigations was presented by Łój *et al.* (2005, 2007) and Porzucek *et al.* (2006). The trend of gravity field changes at the measuring stations was determined and presented for both transects. Taking into account the error of specific devices, it has to be underlined that the trends of gravity changes at measuring stations are only similar at the end-stations of both transects. Gravity values at initial stations of these transects decreased in 2005 compared to that of 2004. The magnitude of this decrease ranged from 0.01 mGal (for LCR gravimeter) to 0.045 mGal (for CG-3 gravimeter) in transect KO (Figs 15, 16). The discrepancy between indications of both gravimeters intensified at the end-stations of both transects. However, its value was less than 0.03 mGal.

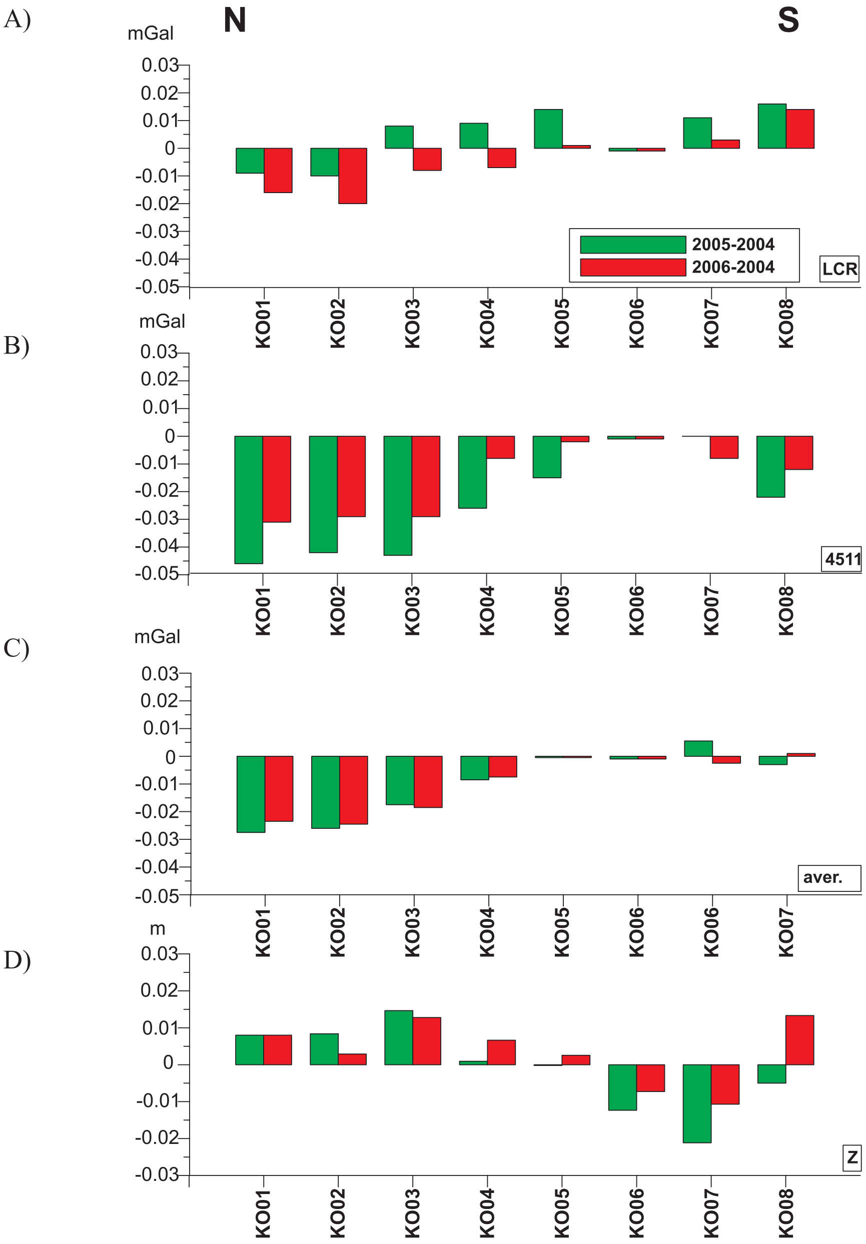


Fig. 15. Temporal gravity changes (in mGal, 1 mGal = $1 \cdot 10^{-5}$ ms^{-2}): A) LaCoste & Romberg; B) Scintrex Autograv CG-3; average (C), and height changes (D) at stations located on transect KO for time intervals of 2005–2004 and 2006–2004. See figure 3 for station distribution

Fig. 15. Czasowe zmiany siły ciężkości w mGal (1 mGal = $1 \cdot 10^{-5}$ ms^{-2}): A) LaCoste & Romberg; B) Scintrex Autograv CG-3, średnia (C) oraz wysokości (D) punktów pomiarowych profilu KO dla interwałów 2005–2004 i 2006–2004. Lokalizacja punktów na figurze 3

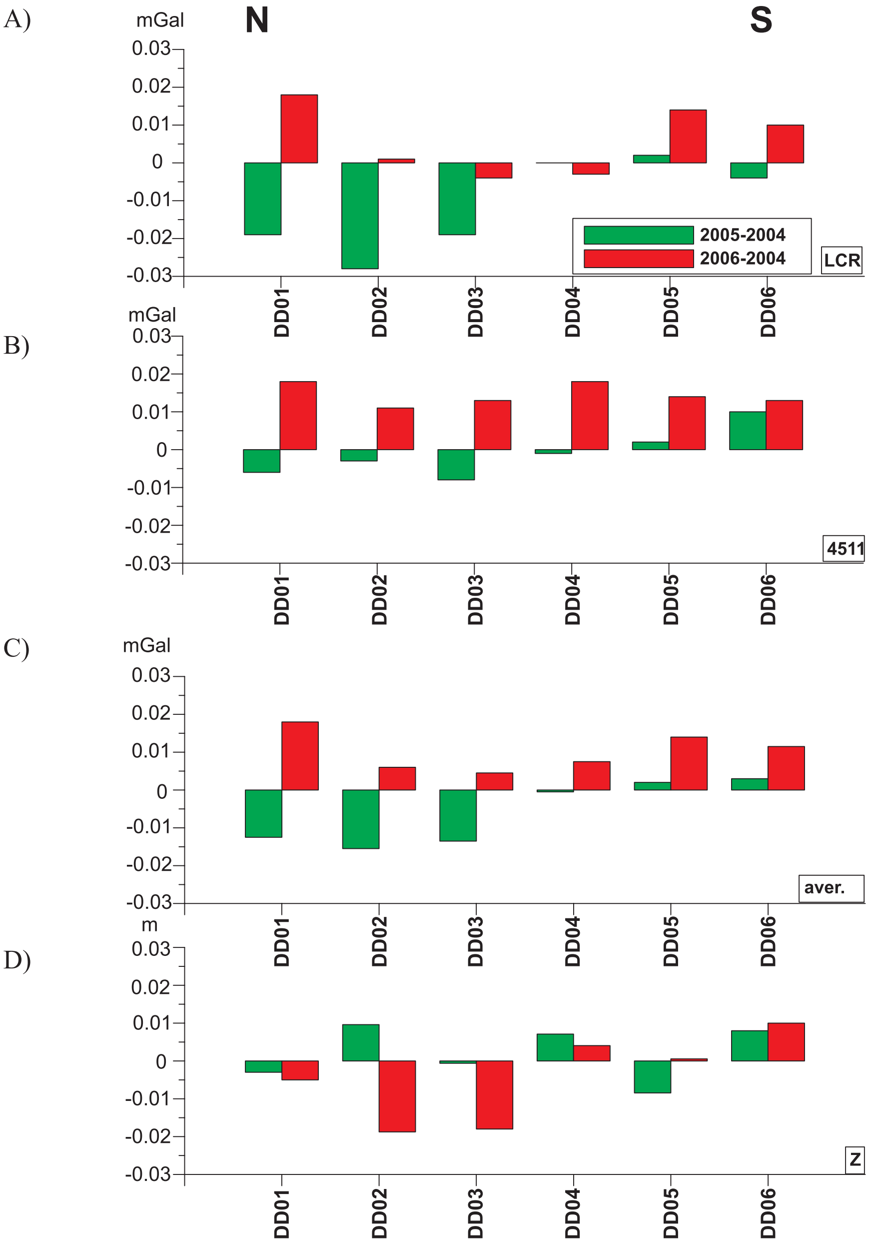


Fig. 16. Temporal gravity changes (in mGal, 1 mGal = $1{\cdot}10^{-5}$ ms^{-2}): A) LaCoste & Romberg; B) Scintrex Autograv CG-3, average (C), and height changes (D) at stations located on transect DD for time intervals of 2005–2004 and 2006–2004. See figure 3 for station distribution

Fig. 16. Czasowe zmiany siły ciężkości w mGal (1 mGal = $1{\cdot}10^{-5}$ ms^{-2}): A) LaCoste & Romberg; B) Scintrex Autograv CG-3, średnia (C) oraz wysokości (D) punktów pomiarowych profilu DD dla interwałów 2005–2004 i 2006–2004. Lokalizacja punktów na figurze 3

Differences in trends and gravity changes between 2005 and 2004 in the indications of both gravimeters should be explained by a more prominent influence of air humidity on the indication of gravimeter LCR than that of CG 3. July 2005 was a very rainy month. A very rapid change of atmospheric conditions was observed during the measurements. These changes negatively affected the accuracy of observations made with gravimeter LCR. For this reason, the time interval 2006–2004 was assumed for further analysis of temporal changes of gravity values along the transects. In both these measuring periods, similar atmospheric conditions occurred.

The results are presented in figures 15 and 16, which also include a list of temporal changes in the discussed interval 2005–2004. The presented gravity differences (Δ*g*) between years 2006 and 2004 are analogous for both gravimeters on both transects.

In transect KO, between stations KO01 and KO07, a uniform trend of temporal changes Δ*g* in the period 2006–2004, calculated for both gravimeters, can be observed (Fig. 15). Mean values of changes Δ*g* in the time interval 2006–2004, calculated on the basis of observations performed on both gravimeters, present a very reliable distribution. The highest changes Δ*g* were observed at stations KO01 through KO05, reaching a value of –0.03 mGal. This is in contrast to the registered height changes (Fig. 15D), and means that a drop of Δ*g* value in the time interval 2006–2004 corresponds to an increase of ordinate Z. Such a relationship was only observed in the northern portion of transect KO. This difference in time indications of gravity changes is certainly connected with geological structure. The northern part of transect KO crosses the Magura Nappe, whereas the southern part, between stations KO05 and KO08, transects two different units: the Orava Basin and the Central Carpathian Palaeogene Basin.

As far as transect DD is concerned (Fig. 16), the gravity values decreased between 2005 and 2004, especially in the initial, northern part of the transect, but in the interval 2006–2004 the trend of gravity values became reversed. Bearing in mind the accuracy of gravimeters, the gravity values increased by about av. 0.02 mGal along the entire transect, compared to the year 2004. It should also be noted that the registered trends of temporal Δ*g* changes, measured by both gravimeters along DD transect in the period 2006–2004, are of the same shape. Accordingly, the calculated average value from both gravimeters reveal the same trend (Fig. 16C). Unlike transect KO, the temporal Δ*g* changes between 2006 and 2004 are congruent with the decreasing trend of the ordinate *Z* (Fig. 16D). This is especially well visible at stations DD02 – DD03, where changes of Δ*g* and ordinate Z significantly stand out in the entire DD transect.

Geodetic survey

The GPS satellite measurements conducted in 2004, 2005 and 2006 were performed at 14 basic stations of the two N-S-oriented geodynamic transects. In the Dunajec River valley transect (DD), observations were made at 6 stations, and in the Orava Basin transect (KO) at 8 stations (Fig. 17).

The compensation covering mean error of satellite antenna centering equalled to ±0.3 mm and the height measurement error was ±1.0 mm. Moreover, the mean errors of component GPS vectors were multiplied by 10. A typical error of compensated network was ±0.4 – 0.65 mm for transect DD, and ±0.4 – 0.7 mm for transect KO. The χ^2 test, checking the congruence of distribution of corrections after compensation with the normal distribution, was also made.

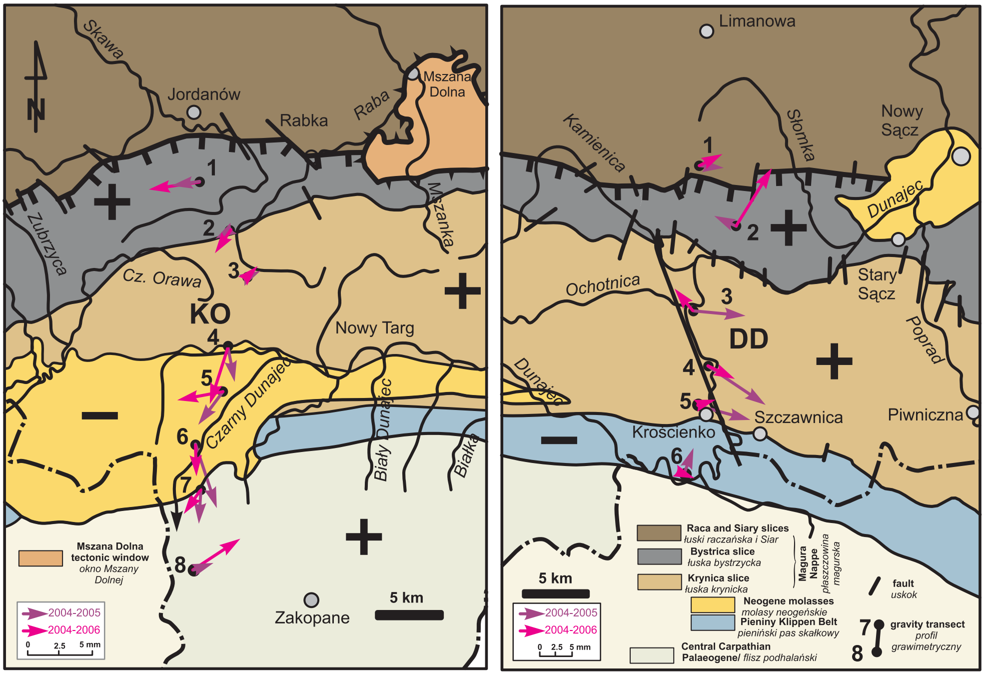


Fig. 17. Directions and rates of horizontal displacements of stations located on KO (left) and DD (right) transects

Fig. 17. Kierunki i tempo ruchów poziomych na stanowiskach zlokalizowanych na profilach KO (z lewej) i DD (z prawej)

In KO transect, only horizontal, south-directed (SSW or SSE) movements were observed at stations located in the Orava Basin. In the remaining stations located on three different geological units, the directions of changes of geodynamic stations were different. In DD transect, no distinct direction of changes of observation stations was found. This refers to both the entire transect and the geological units marked in figure 17.

The southern directions prevailed in transect KO, while in transect DD the northern and eastern trends were observed. The latter direction may be found at all stations of the Krynica slice of the Magura Nappe. It is also worth noting that the only station located on the Krynica slice crossed by KO transect also reveals the E to NE trend.

DISCUSSION

Weather constraints and measurement reliability

Gravimetric investigations were carried out in summer months, in the first decade of July, to provide comparable measuring conditions. Unfortunately, it was not possible to guarantee the identical conditions during all observation sessions. The weather conditions turned out to be the least stable factor. Only two series performed in the years 2004 and 2006 had similar atmospheric conditions, and their influence on the measured gravity forces was irrelevant. The measuring series in 2005 was performed in difficult weather conditions. All the period during which the measurements were made was very rainy and strongly humid. Analysis of the results of gravity measurements in 2005 reveals a discrepancy between values obtained from various apparatuses, whereas the results from the remaining sessions were fully congruent. The discrepancies are most probably a result of the influence of air humidity on the measuring systems used by the gravimeters. Unlike Autograv CG-3, which has a measuring system closed in a tight container, LaCoste & Romberg gravimeter is attached unprotected and exposed to the direct impact of air humidity. This has been confirmed in the literature (El Wahabi *et al*. 2001), analyzing the influence of atmospheric factors, mainly temperature and air humidity on the measured gravity values. It follows from the analyses that air humidity causes a considerable drop in accuracy of gravity measurements. Therefore, the changes of gravity obtained in the time interval 2004–2005 were treated only as a statistical proof that the measurements were performed. Only the results obtained in the time interval 2004–2006 were analyzed.

Geodynamic implications

Gravity changes in transect KO are two-fold in type. Stations KO01 through KO04, located within the Magura Nappe, reveal the same trend of changes. The observed gravity force values decrease with time, whereas the height value is observed to increase at the same stations. The results obtained by both methods may suggest that the region is still being uplifted. The opposite trends of gravity changes are observed at stations KO05 through KO07 in the Orava Basin, where field values relatively decrease compared to those registered in the Magura Nappe. Moreover, a drop in height values is observed at these stations. The most prominent lowering is observed at stations located near the Wróblówka Graben. Thus, it can be concluded that the obtained gravimetric and geodetic results confirm subsidence of the area. Temporal changes of the gravity field observed along transect DD are less dramatic than those of transect KO. The same trend of gravity changes is observed at all stations of transect DD. The gravity value increases with time and the height slightly decreases for the entire transect. The least increase of the gravity value is observed at stations DD02 and DD03, where the biggest lowering of the coordinate Z was recorded.

The results of GPS observations enabled determining trends of drift of certain structures, on which benchmarks were stabilized. The general trend of horizontal shift of stations in the Orava Basin is pointed to the north or NNE, whereas the trends of motion of other geologic units do not share a common direction. The eastward trend prevails in transect DD, while opposite directions are characteristic for transect KO. No traces of recent strike-slip activity of the Dunajec Fault were recorded. The NNE-directed shift of stations situated south of the Pieniny Klippen Belt follows the recent maximum horizontal stress trajectories, obtained by Jarosiński (2006) from borehole breakouts for the Western Carpathians.

CONCLUSIONS

The results of gravity and geodetic surveys appear to suggest that the intramontane Orava Basin reveals recent subsidence, particularly intense in the Wróblówka Graben, confirming conclusions derived from previous geological and geomorphic studies. Data obtained for the Dunajec River transect do not show any particular differentiation among individual benchmarks, what can point to either minor uplift of the entire area, minimal differences between successive slices of the Magura Nappe and the Pieniny Klippen Belt, or both. Horizontal displacements of benchmarks, different for the KO and DD transects, respectively towards the west and SW as well east and SE, can result from general uplift of the area comprised between these transects, i.e. the Gorce Mts., situated within one of the most neotectonically elevated structures of the Outer Carpathians of Poland.

It should be emphasized, however, that such a short time of measurements does not allow for drawing unambiguous and final conclusions on recent tectonic activity of the fold-and-thrust belt of the Outer Carpathians. Our results can only provide input data for future observations.

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Streszczenie

Badania grawimetryczne i geodezyjne przeprowadzono w dwóch profilach: przecinającym Kotlinę Orawską (KO) oraz biegnącym wzdłuż beskidzkiego przełomu Dunajca (DD); zlokalizowanych na jednostkach geologicznych polskiego segmentu Karpat Zachodnich o zróżnicowanych tendencjach neotektonicznych: fliszu podhalańskim, pienińskim pasie skałkowym, a także wewnętrznych podjednostkach płaszczowiny magurskiej (Fig. 1–4). Profil w Kotlinie Orawskiej, na którym założono osiem punktów pomiarowych, ma długość ok. 40 km (Fig. 5–9). W dolinie Dunajca natomiast obserwacje wykonano w sześciu punktach geodynamicznych na odcinku 25 km (Fig. 10–14). Geodynamiczne punkty pomiarowe stabilizowano w odległościach ok. 5 km od siebie. Uzyskane wyniki odniesiono do częściowo już publikowanych danych geologicznych i geomorfologicznych, odnoszących się do plioceńsko-czwartorzędowej mobilności tektonicznej badanych obszarów.

Obserwacje grawimetryczne we wszystkich punktach badawczych obu profili przeprowadzono w okresie letnim z zachowaniem tej samej metodyki pomiarowej. Dotyczyło to zarówno reżimu czasowego, jak i schematu pomiarowego. Podstawowym materiałem badawczym były wyniki trzechletnich obserwacji wartości względnych siły ciężkości w ustalonych punktach geodynamicznych. Przewidziano, iż obserwacje grawimetryczne wykonane zostaną trzema grawimetrami. Z powodów niezależnych od wykonawców niniejszego projektu pozostały do dyspozycji wyniki tylko z dwóch urządzeń: La Coste & Romberg model G nr 986 oraz Scintrex Autograv CG-3 nr 4511.

Przed przystąpieniem do obserwacji grawimetrycznych na obu profilach badawczych przeprowadzono pomiary kalibracyjne mające na celu zapewnienie jednolitej skali wyznaczanych wielkości względnych siły ciężkości. Kalibrację tę przeprowadzano corocznie w okresie bezpośrednio poprzedzającym obserwacje grawimetryczne. Błędy względne współczynników skali obu grawimetrów nie przekraczały $2 \cdot 10^{-4}$ mGal. Upoważnia to do stwierdzenia, że w wyznaczonych wartościach względnych siły ciężkości w punktach pomiarowych popełniono błąd nie przekraczający 3 μGal. Kalibracje obu przyrządów przeprowadzono na przęsłach podstawowej Krajowej Sieci Grawimetrycznej na trasie: Myślenice – Nowy Targ – Zakopane. Wyniki obserwacji grawimetrycznych, przeprowadzonych w latach 2004–2006. przedstawiono w dwóch interwałach czasowych 2005–2004 i 2006–2004. Po wykonaniu każdej serii pomiarowej przeanalizowano wartości błędu obliczonych wartości siły ciężkości. Pozwoliło to na sprawdzenie wiarygodności wykonanych pomiarów.

Błędy wyznaczonych wartości siły ciężkości lokują się poniżej dokładności wykorzystywanych urządzeń. Można zatem założyć, iż otrzymane w wyniku pomiarów wartości siły ciężkości są zgodne z rzeczywistością.

W granicach błędu poszczególnych przyrządów tendencje zmian siły ciężkości w punktach pomiarowych są podobne tylko w początkowych punktach profili (Fig. 15, 16). Zarówno w profilu KO, jak i DD w początkowych punktach zarejestrowano w 2005 roku spadek wartości siły ciężkości w stosunku do roku 2004. Wielkość tego spadku waha się od 0.01 mGal (dla grawimetru LCR) do 0.045 mGal (dla grawimetru CG-3) w profilu KO. W profilu DD natomiast przy podobnej rozpiętości zmian czasowych g pomiędzy latami 2005 i 2004, większe wartości różnic zaobserwowano grawimetrem LCR. Rozbieżności pomiędzy wskazaniami obu grawimetrów nasilają się w końcowych punktach obu profili. Jednak ich rozpiętość już nie jest tak duża – nie przekracza bowiem wartości 0.03 mGal.

Niezgodność kierunków i wartości zmian siły ciężkości w czasie (pomiędzy 2005 a 2004 rokiem) we wskazaniach obu grawimetrów należy tłumaczyć znacznie większym wpływem wilgotności powietrza na wskazania grawimetru LCR niż CG 3. Przypomnieć bowiem należy, iż w lipiec 2005 roku był wyjątkowo deszczowy. W czasie obserwacji prowadzonych w tym czasie zachodziła bardzo szybka zmiana warunków atmosferycznych. Zmiany tego rodzaju w sposób niekorzystny dla dokładności obserwacji wpływały na prace grawimetru LCR. Z tego też względu do dalszej analizy zmian czasowych siły ciężkości w profilach badawczych przyjęto interwał czasowy 2006–2004. W obu tych okresach pomiarowych występowały podobne warunki atmosferyczne.

W profilu KO zaobserwować można jednolitą tendencję przebiegu zmian czasowych Δg w okresie 2006–2004 od punktu KO01 do KO07 obliczona dla obu grawimetrów (Fig. 15). Wielce wiarygodnym rozkładem w punktach geodynamicznych staje się zestawienie średnich wartości zmian g w interwale 2006–2004 obliczonych na podstawie obserwacji poczynionych oboma grawimetrami. Największe zmiany Δg widoczne są w punktach KO01 – KO05 osiągające wartość –0.03 mGal. Pozostaje ona w opozycji do rejestrowanych zmian wysokości, co oznacza, że spadkowi wartości Δg w interwale czasowym 2006–2004 odpowiada wzrost rzędnej Z. Zależność ta występuje w północnej połowie odcinka profilu KO. W drugiej jego części nie obserwuje się tych analogii. Ta dwudzielność różnych wskazań czasowych zmian siły ciężkości ma niewątpliwy związek z budową geologiczną. Północna część profilu KO położona jest na płaszczowinie magurskiej, natomiast południowa jego część, od punktu KO05 do KO08 na dwóch odmiennych jednostkach – w Kotlinie Orawskiej i na fliszu podhalańskim.

W profilu DD (Fig. 16) w okresie 2005–2004 nastąpiło zmniejszenie obserwowanej wartości siły ciężkości – szczególnie w początkowym, północnym odcinku profilu, natomiast w interwale 2006–2004 zaznaczyło się odwrócenie tendencji zmian wartości pola siły ciężkości. Na całym odcinku obserwuje się, w granicach dokładności grawimetrów, wzrost wartości siły ciężkości w porównaniu do roku 2004, średnio o około 0.02 mGal. W odróżnieniu od profilu KO następuje tu zgodność zmian czasowych (w interwale 2006–2004) wartości Δg z tendencją spadku obserwowanej rzędnej Z. Jest to szczególnie widoczne w punktach DD02 – DD03, gdzie zmiany Δg i współrzędnej Z są wyraźnie wyróżniające się w całym przekroju profilu DD.

Pomiary satelitarne GPS w latach 2004–2006 wykonane zostały na 14 podstawowych punktach dwóch południkowych profili geodynamicznych (Fig. 17). W wyrównaniu przyjmowano średni błąd centrowania anteny satelitarnej równy ±0.3 mm oraz błąd pomiaru wysokości ±1.0 mm. Dodatkowo błędy średnie składowych wektorów GPS przemnożone były przez 10. Błąd typowy sieci po wyrównaniu wyniósł dla profilu dunajeckiego ±0.4–0.65 mm oraz dla profilu orawskiego ±0.4–0.7 mm. Zawsze był też spełniony test χ^2 badający zgodność rozkładu poprawek po wyrównaniu z rozkładem normalnym.

W profilu KO wyraźnie widać, iż w punktach położonych w Kotlinie Orawskiej – KO04 – KO07 obserwuje się ruchy poziome tylko w kierunku zbliżonym do południowego, tj. SSW lub SSE. W pozostałych punktach, położonych na trzech różnych jednostkach geologicznych, kierunki zmian położenia punktów są różne. W profilu DD brak jest wyróżniającego się kierunku zmian położenia punktów obserwacyjnych. O ile w profilu KO przeważał kierunek południowy zmian położenia reperów, to w profilu DD dominuje tendencja do ruchu ku północy i na wschód. Ten ostatni kierunek obserwować można we wszystkich punktach położonych na podjednostce krynickiej płaszczowiny magurskiej.

Wyniki badań grawimetrycznych i geodezyjnych zdają się sugerować tendencje obniżające Kotliny Orawskiej, szczególnie w rejonie rowu Wróblówki, potwierdzając zarazem wnioski płynące z analiz geomorfologicznych. Dane uzyskane dla profilu wzdłuż przełomu beskidzkiego Dunajca nie wykazują większego zróżnicowania między poszczególnymi punktami badawczymi, co może wskazywać na: słabe podnoszenie całego obszaru (sugerowane przez wyniki badań gemorfologicznych i morfotektonicznych), minimalne różnice między poszczególnymi łuskami płaszczowiny magurskiej i pienińskim pasem skałkowym, względnie równoczesne oddziaływanie obu czynników.

Przemieszczenia poziome reperów usytuowanych w obrębie Karpat zewnętrznych, a skierowane ku zachodowi i SW w profilu zachodnim (KO) oraz ku wschodowi i SE w profilu wschodnim (DD), mogą odzwierciedlać wypiętrzanie obszaru ograniczonego profilami, tj. masywu Gorców. Natomiast skierowane ku północy i NNE wektory współczesnych ruchów poziomych dla stanowisk ulokowanych na południe od pienińskiego pasa skałkowego zdają się wskazywać na nadal aktywny nacisk bloku ALCAPA ku NNE.