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PERIODIC GRAVITY CHANGES IN THE YOUNG TECTONIC MOVEMENT INVESTIGATION OF SELECTED AREA IN THE POLISH WESTERN CARPATHIANS

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ABSTRACT
Two geodynamic test transects across the Polish segment of the Western Carpathians, crossing the Orava Basin in the west (KO) and the Pieniny Klippen Belt and Magura Nappe along the Dunajec River valley in the east (DD), are presented. Multidisciplinary studies conducted along these transects included gravimetric, geodetic, geologic and morphostructural investigations. Gravimetric and geodetic results appear to suggest recent subsidence of the Orava Basin, particularly intensive in the Wróblówka Graben, 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 (already suggested by the results of geomorphic and morphotectonic studies), 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, towards the west and SW as well east and SE, respectively, can result from general uplift of the area comprised between these transects, i.e. the Gorce Mts.

KEYWORDS: gravity measurement, geodynamic processes, temporal gravity changes, West Carpathians, Poland

INTRODUCTION

The project was realized at the Department of Geophysics of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków, Poland. The studies were carried out during 36 months in the years 2003 to 2006, and included gravity and geoelectric measurements, as well as geodetic investigations. On this basis, the phenomena accompanying geodynamic and geomorphological processes were registered. Geologic works constitute an integral part of the research project.

The investigations were carried out along two transects crossing the Orawa Basin (KO), and the Pieniny Klippen Belt and Magura Nappe along the Dunajec River valley (DO). Both transect cross those areas of the Polish Western Carpathians which show diversified Quaternary movements (Fig. 1.1).

Geophysical and geodetic observations, as well as geologic and morphostructural studies were conducted in three measurement series, i.e. in summers of 2004, 2005 and 2006.

Geophysical measurements were made at permanently stabilized geodynamic measuring stations, which were placed below the expected freezing point, i.e. ca. 2 m below the ground surface.

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.

Gravity measurements were the basic research method in view of time changes of the Earth's gravity field.

In summer 2004, a sequence of relative gravity observations was made along both measuring profiles at points spaced ca. 1 to 2 km. Gravity measurements at geodynamic points and the relative gravity forces in both profiles were used for gravimetric modelling.

An attempt was made at interpreting the obtained gravity results, i.e. relating time changes of gravity force and geodynamic processes in the Earth's crust.

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

1. MEASURING SITES

The studied objects are placed on two transects (Fig. 1.1): KO (Orava Basin), along the line Dzianisz - Czarny Dunajec - Wróblówka - Spytkowice - Wysoka, and DD (Dunajec River valley), starting in the south at Sromowce Niżne, along the Dunajec River water-gap between Krościenko and Zabrzeż; reaching in the north the Łącko and Młyńczyska region.

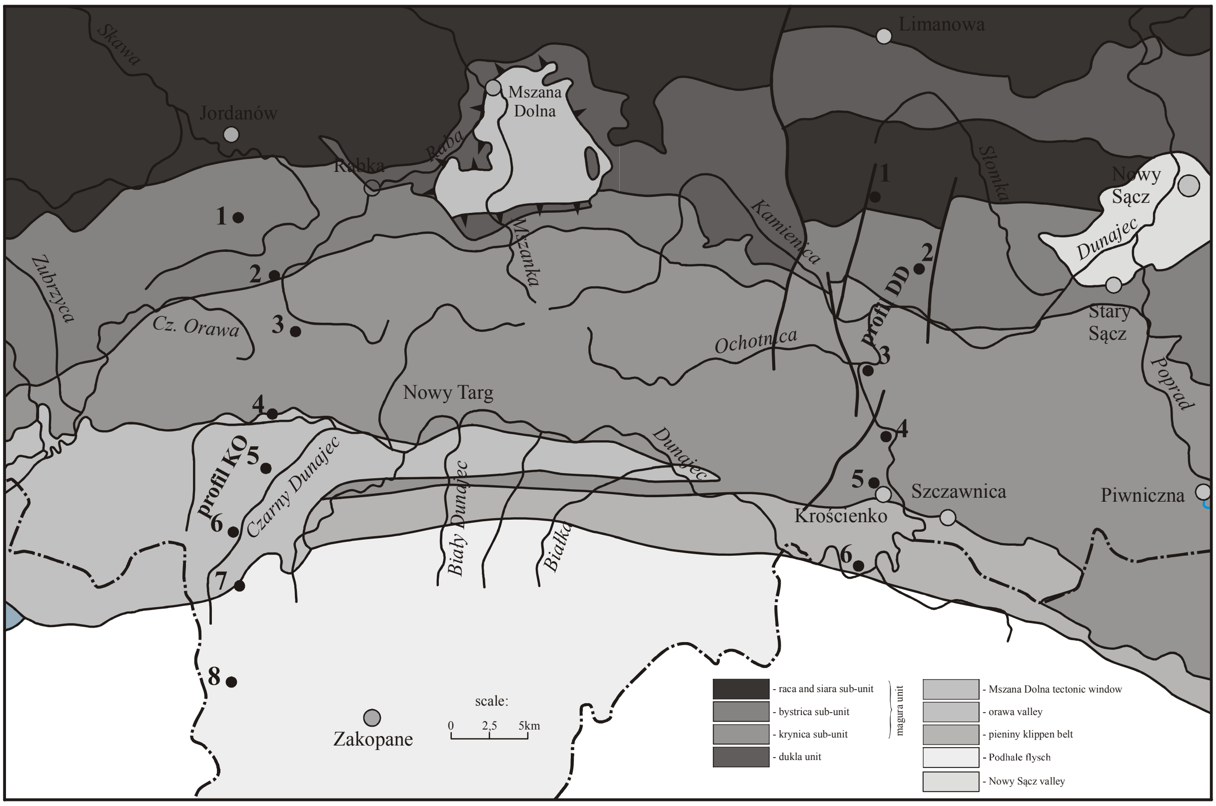

Fig. 1.1 Locality of geodynamic gravity transects across the Polish Western Carpathians.

The profiles, oriented roughly N-S, enabled for location of measuring stations in geodynamically different geological structures. When designing the course of profiles and determining places of measuring stations, both profiles were elongated northwards so as to place the last measuring stations within both subunits of the Magura Nappe, i.e. the Krynica and Bystrica subunits. In this way, the profiles changed their original length from 15 km to ca. 25 km for the profile DD, and from 25 km to ca. 40 km for the profile KO.

These profiles are crossing geological structures of different age and tectonic style; they also exhibit different neotectonic trends (Żytko et al., 1989; Zuchiewicz, 1995, 1998).

Profile KO crosses the boundary between the Inner and Outer Carpathians, showing contrasting trends of young (Pliocene-Quarternary) tectonic movements. The Wróblówka Graben, situated in the southern portion of profile KO, indicates the late Pleistocene, or even Holocene, subsidence. Minor uplift tendencies are observed in the southern part of the Magura Nappe, i.e. in the northern segment of the profile (Baumgart-Kotarba, 1991; Baumgart-Kotarba et al., 2001). The measuring stations were sited on the following geologic 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 subunit, and two in the Bystrica subunit of the Magura Nappe.

Profile 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 through the Lubań-Radziejowa Range (in the northern part of profile DD) crosses one of longitudinal neotectonic elevations that has been uplifted by ca. 150 m in Quaternary times (Starkel, 1972; Zuchiewicz, 1984, 1991, 1998). One station of profile DD is situated in the southern part of the Pieniny Klippen Belt, three in the Krynica subunit, and two in the Bystrica subunit of the Magura Nappe.

Measuring stations in the form of downhole earth benchmarks were stabilized in the analysed profiles (Łój et al., 2005). To cover uniformly the profiles with measuring stations, and to meet the principle that the stations should be located in different geological structures, the distance between these points was chosen at ca. 5 km. Their position was selected in such a way, so as to eliminate the potential influence of the near-surface factors on the stability of these points. This signifies that in the selected areas:

- Stable basement formations were close to the surface (enabling contact of the station with the basement)
- The near-surface formations will not flow down, causing station of observation drift.

2. BENCH MARKS AND STABILIZATION OF MEASURING POINTS

The determination station was specially designed, providing its stability during gravity measurements, and geodetic works with GPS (Fig. 2.1).

The measuring stations were made in situ in compliance with the above assumptions.

It was especially important for the stabilization process to accurately level out the fixed disc, as each deflection from the horizontal could hinder the measurements.

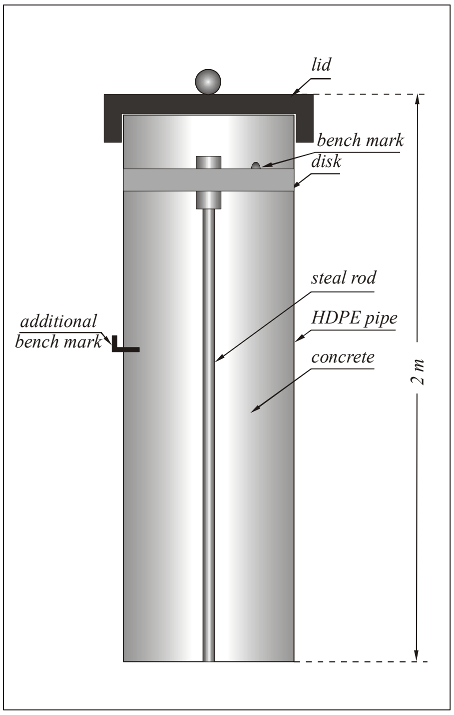

Fig. 2.1 Scheme of a measuring point design.

Gravity and geodetic measurements with the use of GPS were performed on the stabilized points of terrain. 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 bar, screwed into the disc, were made. During the measurement the bar were fastened to the satellite antenna (Łój et al., 2005). 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 the case of gravity measurements performed with various types of gravimeters, a base on which the equipment could be safely disposed had to be constructed. It was a universal stator having a circular base. Its radius corresponded to the inner diameter of the pipe. The stator was finished off with a slotted steel plate, enabling disposal of the measuring equipment – gravimeters on original stators (Łój et al., 2005).

3. INVESTIGATIONS

Investigations were conducted along two profiles: (a) crossing the Central Carpathian Palaeogene basin (Podhale Flysch), Orava Basin with the Wróblówka Graben, and Krynica and Bystrica subunits of the Magura Nappe at Spytkowice; and also (b) from the Pieniny Klippen Belt near Sromowce Wyżne, along the Dunajec River water-gap which passes through the Krynica subunit of the Magura Nappe, and finally the region north of Łącko, within the Bystrica and Rača subunits of this nappe (Fig. 1.1).

Geomorphological and morphostructural analysis, aiming at quantitative characteristics of tectonically-controlled landforms, consisted in re-ambulation of the existing geomorphological maps of the area, as well as in construction of maps od relief energy, river valley density, and selected physiographic parameters of small-scale drainage basins. Different methodological approaches pertaining to such studies have already been described by Zuchiewicz (1980, 1995, 1999) and Krawczyk and Zuchiewicz (1989). Moreover, base-level maps of different orders (Zuchiewicz, 1981; Rączkowski et al., 1985) were re-examined for a comparison of the former with the base of the Magura Nappe. An attempt was also made to distinguish topolineaments identified on a digital elevation model.

To determine horizontal changes of stations' location on the profiles during successive measurement series, static GPS measurements were made at the following assumptions:

- duration of an observation session at the basic points of the profiles – 48 hrs,
- duration of an observation session at the additional points – at least 12 hrs,
- registration interval (time of calculations) – less than 30 seconds,
- height of satellite observations over the horizon (cutting angle) – 10˚.

Geodynamic profiles 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 analysed profiles were "tied up" to the national gravity network at an accuracy better than ±5 cm.

On the basis of measurements the following parameters were calculated: the geodetic coordinates and their mean errors after being compensated in the Euref'89 system, horizontal coordinates in the national system 2000 as well as distances between stations on profiles and mean errors of their determining. These parameters may form basis for inferring on the possible movements of the stations. In view of the obtained values of distance mean errors, which are less than a millimeter in the case of the distance between the neighboring stations on a profile, it can be assumed that the comparison of the results of the successive observation epochs shall enable detecting station drifts in time between the epochs at a level of 3 to 5 mm.

Gravity measurements in each of the profiles were performed three times on the yearly basis in 2004 to 2006. Assuming such a research methodics results from the necessity of knowing gravity field changes, in view of the expected small values of time anomalies of gravity force, and first of all, their trend in a function of time. In the future, this should enable planning of suitable time intervals, adjusted to the specific geodynamic conditions registered in the above mentioned profiles.

Gravimetric observations were conducted with two types of astatized gravimeters:

- two quartz gravimeters with automatic record of data by Canadian SCINTREX - CG-3 and CG-3M
- metal gravimeter La Coste & Romberg, model G, for which the read-outs were made by the interpolation method with an external volt meter,

The devices used for field works measure gravity with the accuracy to 0.01 mGal.

Owing to the fact that various types of gravimeters were used for geodynamic investigations, first they were calibrated, i.e. scale coefficients were determined for each device. These coefficients were calculated as a weighted average with its weight 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 equal 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 yearly gravity measurements.

To provide high accuracy of gravimetric observations, the measurements will be made with the double chain method (Łoj et al., 2005).

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 are obtained. The scale coefficients enabled comparing value obtained from various gravimeters between the same stations.

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

On this basis the gravity values could be calculated in the analysed stations thanks to the knowledge of the value for the Nowy Targ station, and the gravity values between stations in the research area.

4. RESULTS OF GEODETIC INVESTIGATIONS

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

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

Significant observations were made on the basis of an analysis of the geodetic results in the part referring to the horizontal coordinates. The position of vectors of horizontal displacement in geodynamic stations in Figs. 4.1 and 4.2 are presented.

In KO profile, only horizontal, south-directed (SSW or SSE) movements are observed at stations located in the Orawa Basin. In the remaining stations located on three different geologic units, the directions of changes of geodynamic stations are different (Fig. 4.1).

In DD profile (Fig. 4.2) no distinct direction of changes of observation stations was be found. This refers to both the entire profile and the geological units marked in the figure.

Attention may be drawn to the fact that in the profile KO the southern direction prevailed, whereas in the profile DD the northern and eastern trends were observed. The latter direction may be found at all stations of the Krynica subunit of the Magura Nappe. It is also worth noting that the only station located on the Krynica subunit crossed by KO profilealsoreveals the E-NE.

5. RESULTS OF GRAVIMETRIC INVESTIGATIONS

Gravimetric observations at all geodynamic stations were performed 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. Gravimetric observations were planned to be made with three gravimeters. However, the results of only two gravimeters were at our disposal: La Coste&Romberg model G No. 986, and Scintrex Autograv CG-3 No. 4511.

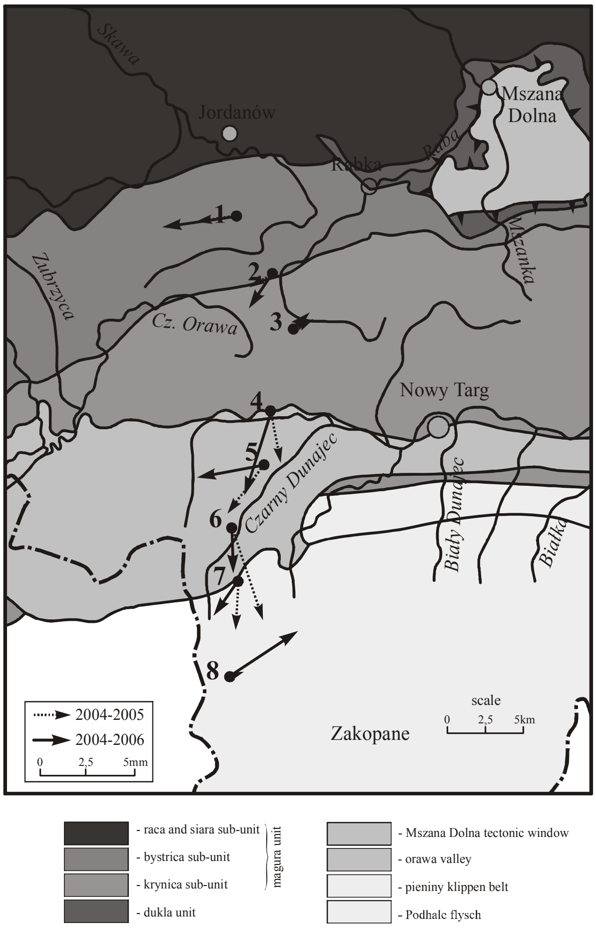

Fig. 4.1 Direction of geodynamic station changes along profile KO.

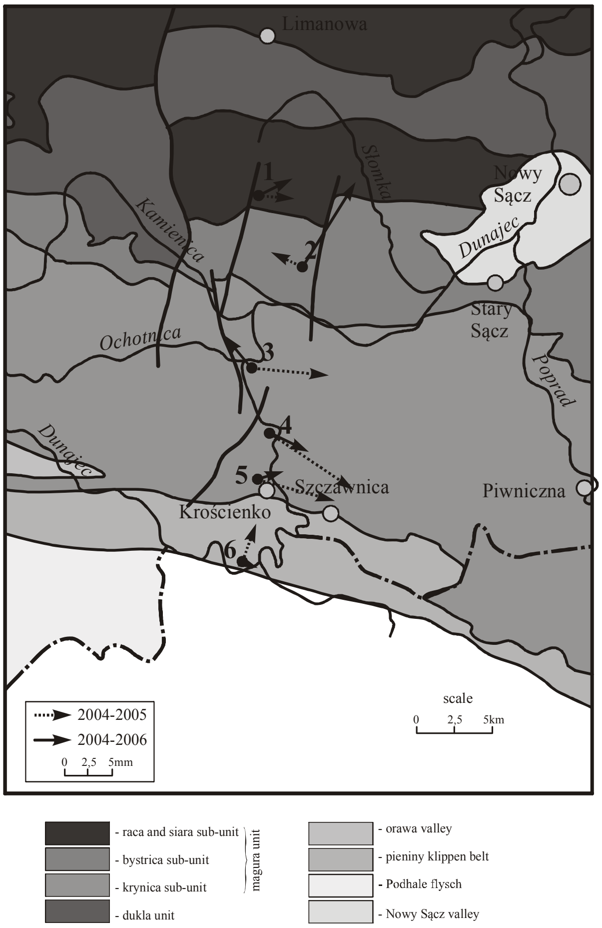

Fig. 4.2 Direction of geodynamic station changes along profile DD.

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 that relative errors of scale coefficients of both gravimeters did not exceed 2×10^{-4}. Hence, it can be concluded that the error of less than 3 μGal 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 obtained gravity error was analysed 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 profiles in Fig. 5.1. Taking into account the error of specific devices, it has to be underlined that the trends of gravity changes at measuring stations are similar only at the initial stations of the profiles. In both profiles, the gravity value at initial stations decreased in 2005 compared to that of 2004. The magnitude of this decrease ranged from 0.01 mGal (for the gravimeter LCR) to 0.045 mGal (for the gravimeter CG-3) in profile KO. In profile DD, in the similar span of temporal changes Δg between 2005 – 2004, bigger differences were observed with the LCR gravimeter. The discrepancy between the indications of both gravimeters intensified at the end stations of both profiles. However, its value was less than 0.03 mGal.

The discongruence of trends and gravity changes between 2005 and 2004 in the indications of both gravimeters should be explained by a more prominent

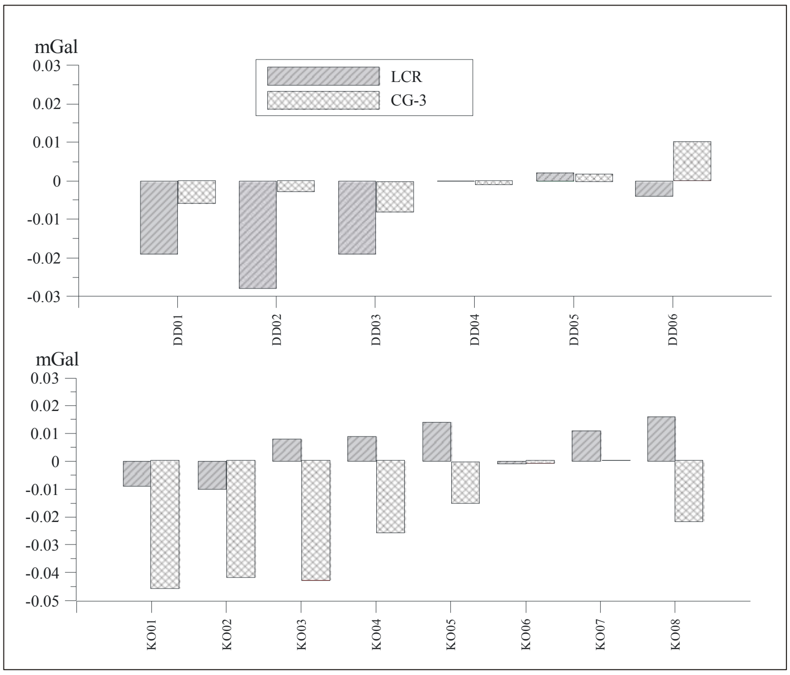

Fig. 5.1 Time Temporal changes of the gravity field for profiles DD and KO in the time interval of 2005 – 2004.

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 condition was observed during the measurements. These changes negatively affected the accuracy of observations made with the gravimeter LCR. For this reason, the time interval 2006 - 2004 was assumed for further analysis of temporal changes of gravity values along the profiles. In both these measuring periods, similar atmospheric conditions occurred.

The results are presented in Figs. 5.2 and 5.3. These figures also include a list of temporal changes in the discussed interval 2005 – 2004. The presented differences Δg between years 2006 and 2004 are analogous for both gravimeters in both profiles.

In profile KO, between stations KO01 and KO07, a uniform trend of temporal changes Δg in the period 2006 – 2004, calculated for both gravimeters, can be observed (Fig. 5.2).

A very reliable distribution at geodynamic stations is the mean value of changes Δg in the time interval 2006 – 2004 (Fig. 5.2), calculated on the basis of observations performed with both gravimeters. The highest changes Δg are at stations KO01 – KO05, reaching a value of -0.03 mGal. This is in contrast to the registered height changes (Fig. 5.2d), and means that a drop of Δg value in the time interval 2006 – 2004 corresponds to an increase of ordinate Z. The dependence is observed for the northern half of profile KO. In other parts of the profile no such dependence was observed. This difference of time indications of gravity changes is certainly connected with geological conditions. The northern part of profile KO crosses the Magura Nappe, whereas its southern counterpart, between stations KO05 and KO08, transects two different units: the Orava Basin and Central Carpathian Palaeogene basin (Podhale Flysch).

As far as profile DD is concerned (Fig. 5.3), the gravity values decreased between 2005 and 2004, especially in the initial, northern part of the profile, 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 whole section, as compared to the year 2004.

It should also be noted that the registered trends of temporal Δg changes, measured by both gravimeters along DD profile in the period 2006 – 2004, are of the same shape. Accordingly, the calculated average value from both gravimeters has the same trend (Fig. 5.3c).

Unlike profile KO, the temporal Δg value changes between 2006 and 2004 are congruent with the decreasing trend of the ordinate Z (Fig. 5.3d). This is especially well visible at stations DD02 – DD03, where changes of Δg and ordinate Z significantly stand out in the entire profile DD.

The hitherto-conducted studies of temporal changes of gravity in Poland relied on measurements in geodynamic test areas. No attention was paid to the methodology of work, oriented to the possibility of determining the depth of deposition of potential sources of temporal disturbances of the gravity field.

In September 2004, a detailed gravity profile imaging along the geodynamic profiles KO and DD (at stations spaced ca. 1 km apart), was made.

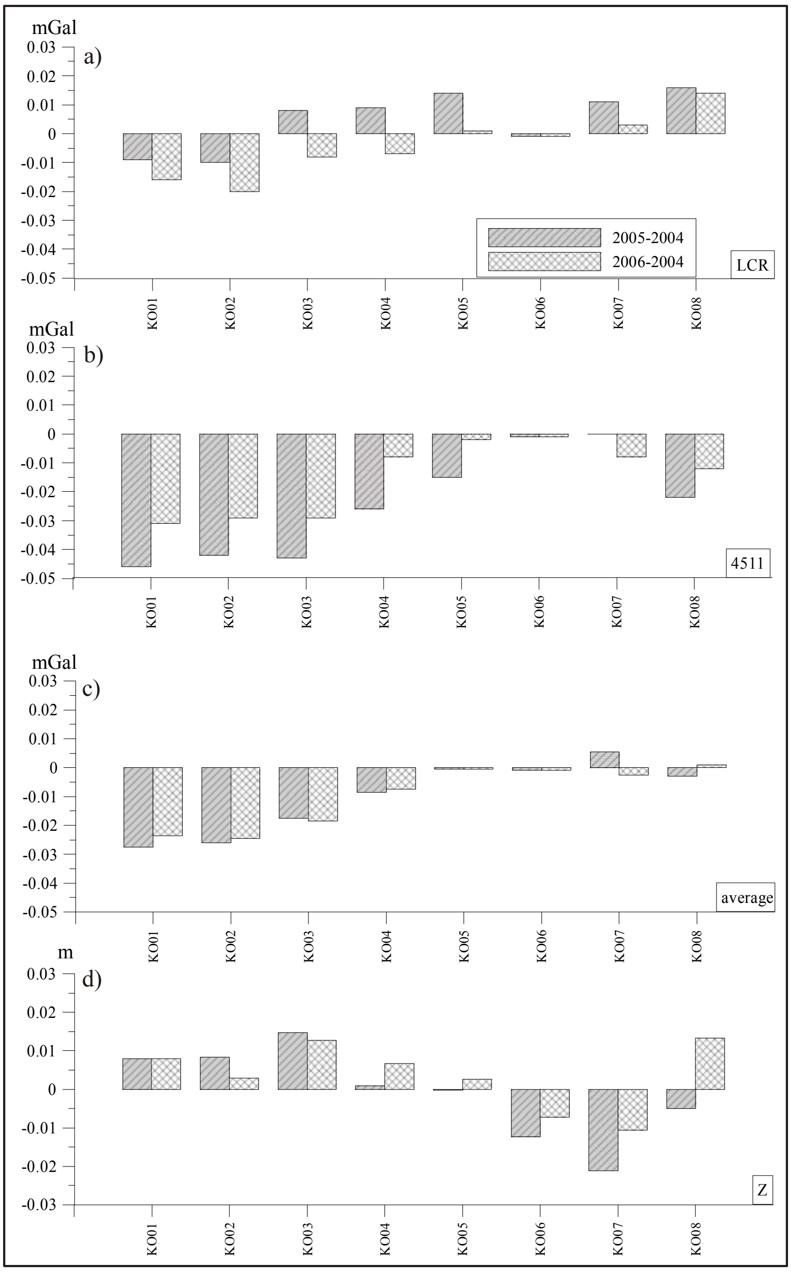

Fig. 5.2 Temporal changes of the gravity and height at stations on the geodynamic profile KO for the time intervals of 2005 – 2004 and 2006 – 2004.

Assuming that the depth of the source of changes of gravity field stays within the thickness of the Earth's crust, the length of the profiles was elongated northwards and southwards for the sake of a detailed image. In these conditions, the entire geodynamic profile could be modelled gravimetrically.

After densifying gravimetric measurements, gravity modelling was made with the use of all available geological data, and gravimetric models were constructed. The results of gravimetric modelling for both profiles are presented in Figs. 5.4 and 5.5.

The analysis of the Outer and Inner Carpathians nappes reveals that they constitute a gravimetrically uniform entity of a comparable average bulk density. The mean bulk density of rock (assumed in Bouguer's reduction), to which model density contrasts were referred, enabled distinguishing two separate zones of different densities in profile KO in the Carpathian Flysch. One of them is the Orava Basin area, the outline of which was based on the works by Pomianowski (1995, 2003). The sediments filling up the Orava Basin have a density lower by ca. 0.3 Mg•m^3 in relation to the Bouguer's reduction

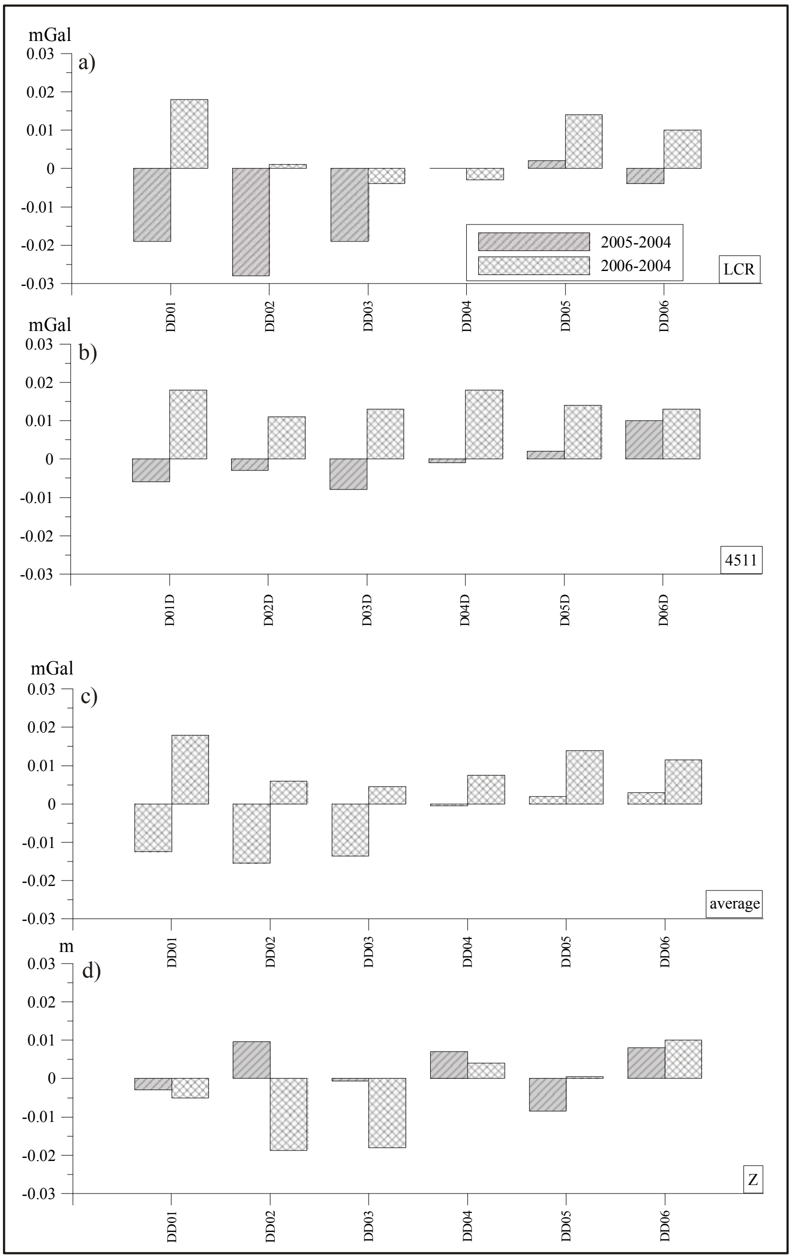

Fig. 5.3 Temporal changes of the gravity and height at stations on the geodynamic profile DD for the time intervals of 2005 – 2004 and 2006 – 2004.

density. Another zone was determined at a distance of ca. 22 km of the profile. Its density is smaller than the ambient density by ca. 0.1 Mg•m^3. It can represent a zone of local density changes of one of the Outer Carpathians units, and can be related with the "thicker zone of the Magura Nappe", and associated with the Fore-Magura unit (Golonka et al., 2005; Fig. 10). Its density could be determined as different from the density of the Magura unit proper.

In the case of both investigated profiles, the main source of measured gravity anomalies are changes in the geological structure of the sub-flysch basement. This basement can be subdivided into two parts separated by the Pieniny Klippen Belt. The thickness of sedimentary successions in the southern part of the basement changes from profile to profile: from -7,500 m b.s.l. for profile KO (Fig. 5.4) to ca. -4,000 m b.s.l. for profile DD (Fig. 5.5). The largest thickness is observed close to the Pieniny Klippen Belt. With the growing distance from the Pieniny Klippen Belt, the basement is elevated, to be uplifted most in the Western Tatra Mts. region, i.e. beyond the area gravimetrically measured.

The highest variability of geological structure is observed in the sub-flysch basement in the northern part of the profile. It has a block-type structure, with

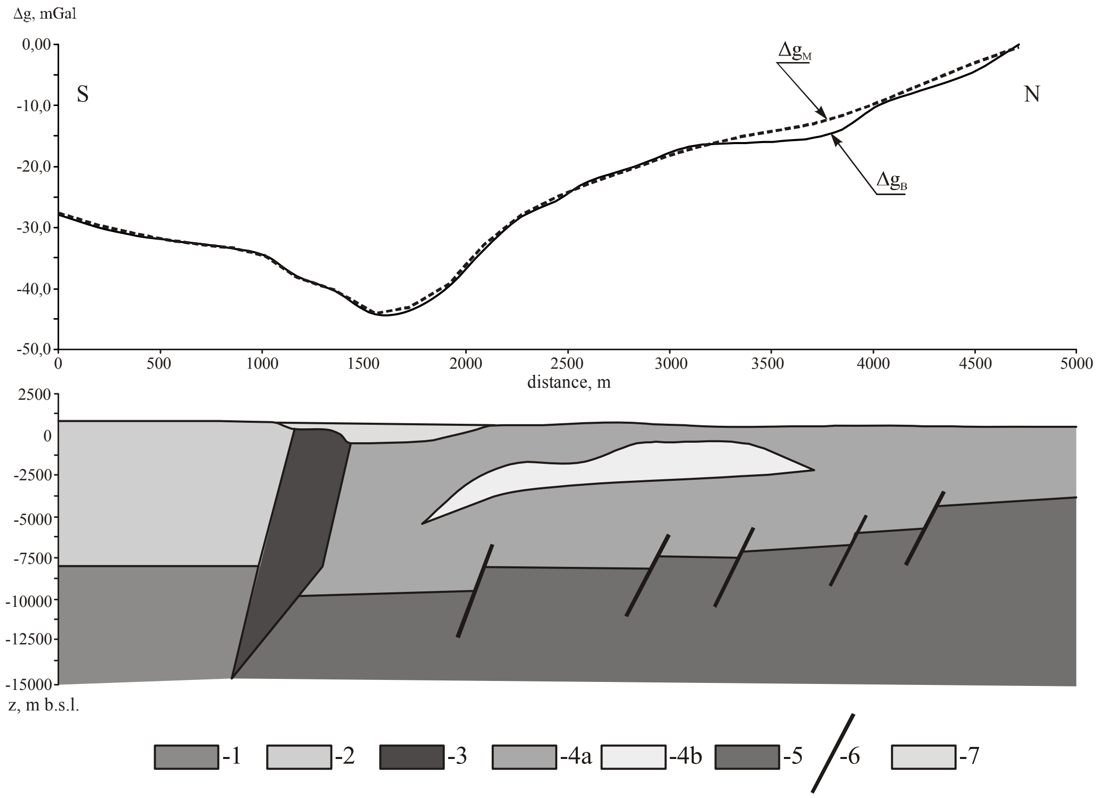

Fig. 5.4 Results of gravimetric 2.5D modelling along profile KO (ΔgB – observation curve, ΔgM – calculation curve), 1 - Palaeozoic and Mesozoic strata of the Outer Carpathians, 2 - Palaeogene strata of the Central Carpathians (Central Carpathian Palaeogene basin), 3 - Pieniny Klippen Belt, 4a - Outer Carpathians Flysch, 4b – Outer Carpathians flysch strata of density smaller by ca. 0.1 Mg•m3, 5 - basement of the Outer Carpathians, 6 - equivalent faults, 7 - Orava Basin,

numerous faults of different dip directions. The depth to the top of the basement changes from about -10,000 m b.s.l. in the zone of contact with the Pieniny Klippen Belt, to about -2,500 m b.s.l. in the northernmost part of the geodynamic profiles. The thickness of sedimentary successions of the sub-flysch basement is related to the presence of faults. These faults dip mostly southwards, towards the contact area with the Pieniny Klippen Belt. Some faults, however, are dipping in the opposite direction. Gravimetric investigations enabled to mark some of the faults existing in the basement, particularly those dipping so steeply that the change of measured gravity value caused by them was above the measurement error level.

Both models also include the Pieniny Klippen Belt, with the characteristic varying dip directions.

The aim of the calculations was to find gravity anomalies with the Bouguer's reduction with the geological structure, and in the future, after obtaining temporal distributions of gravity changes, to determine the place of these changes and the depth of deposition.

SUMMARY AND CONCLUSIONS

The studies of young tectonic activity in Poland usually rely on only one research method, thanks to which the geodynamic physical parameters can be traced. The objective of our project was a complex approach to the problem.

The gravimetric investigations were carried out in the 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.

The measuring series in 2005 was performed in rainy weather season. The analysis of the results of gravity measurements in 2005 reveals a discrepancy between values obtained from various apparatuses. The discrepancies are most probably a result of the influence of the air humidity on the measuring systems used in the gravimeters (El Wahabi et al., 2001). It is a reason of making a gravity results less accurate. Therefore, the changes of gravity obtained in the time interval 2004 – 2005 were treated only as a

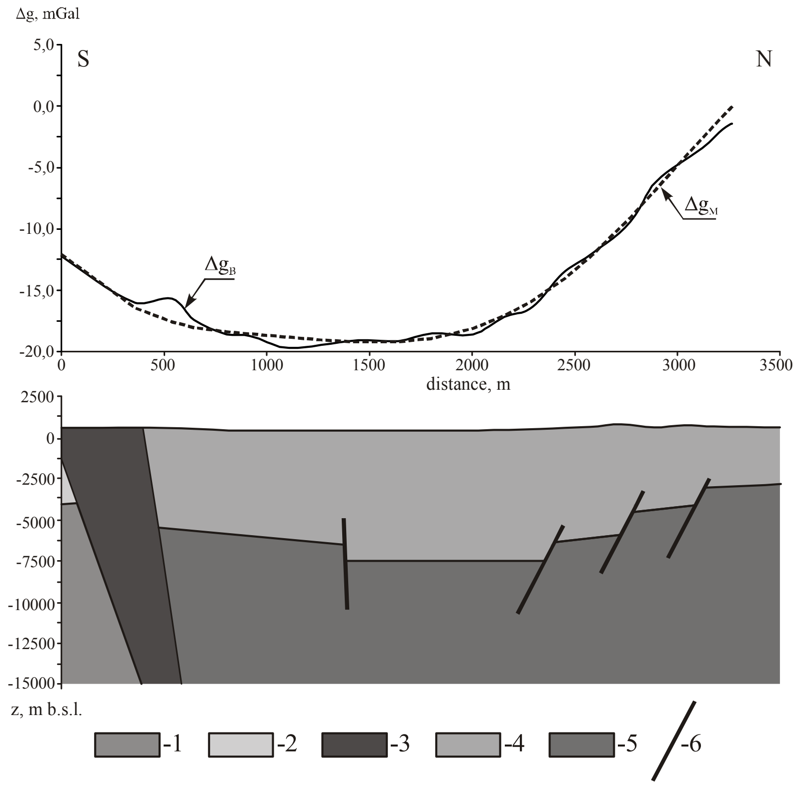

Fig. 5.5 Results of gravimetric 2.5D modelling along profile DD. See Fig. 5.5 for explanation.

statistical proof that the measurements were performed. Only the results obtained in the time interval 2004 – 2006 were analysed.

The data on gravity changes in profile KO are two-fold in type. The stations from KO01 through KO04, located within the Magura Nappe, have the same trend of changes. The opposite trends of gravity changes are observed at stations KO05 – KO07 in the Orava Basin.

Temporal changes of the gravity field observed along profile DD have a less violent course as those of profile KO. The same trend of gravity changes is observed at all stations of profile DD.

The results of geodetic method obtained from the GPS observations enabled determining trends of drift of certain structures, on which the geodynamic measuring stations were stabilized. It can be noted that the general trend of horizontal drifts of stations in the Orawa Valley is meridian-oriented, whereas the trends of drift of other geologic units does not have a common direction. Generally, the horizontal (eastward) trend prevails, though the trends in the opposite direction can be also met.

The results of gravimetric and geodetic measurements appear to suggest that the Orava Basin reveals recent subsidence, particularly intense in the Wróblówka Graben, confirming conclusions derived from geomorphological 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 (already suggested by the results of geomorphic and morphotectonic studies), 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.

It should be emphasized 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 of Poland. Our results can only provide input data for future observations.

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