

GEODYNAMICAL INVESTIGATIONS IN THE PIENINY MOUNTAIN IN 1994 - 2010

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1. ABSTRACT

Geodynamical investigations in the Pieniny Mountain (south of Poland) were carried out since the 1960s. They contained leveling, gravimetric measurements and distance observations in horizontal network. The results revealed vertical and horizontal movements of the crust and periodic changes in gravity. In 1994-1995 horizontal network was adapted to perform GPS observations and they were carried out with leveling, gravimetric and EDM observations. In 1990s, the Dunajec river dam and the water reservoirs in Czorsztyn and Sromowce Wyżne have been built. This has created a new aspect in investigations related to the effect of tectonic movements on the dam. Taking that into account, the study was revived, after six year break, in 2001. The investigations, which contain GPS, gravimetric and leveling observations, have been carried out every year. In this paper the result of horizontal displacement obtained from GPS measurement as well as gravity changes in 1994-2010 period are presented and yields linear trend in north-east direction less than 1 mm/year.

2. INTRODUCTION

In terms of structure, the Pieniny Klippen Belt (PKB) is one of the main fault zones of the earth's crust on the boundary of the outer and inner Carpathians (Birkenmajer 1974, 1986). Located on the border of two major structural units – the Outer Carpathians to the north, inclusive of the Magura Nappe (MN) that is directly adjacent to the klippen belt, and the Inner Carpathians to the south (Zuchiewicz 1995). The phenomenon of the belt's structure stems from its complex tectonic origins. The tectonics are extremely complicated and are derived from processes occurring during the alpine orogenesis. The belt has a fold-horst configuration. The klippen belt deposits were mainly formed over the space of the Jurassic and Cretaceous in the oceanic basin making up the northern part of the Western Tethys. The Upper Cretaceous compression from the south is responsible for the folding, flaking, and boudinage of the nappe structure (Birkenmajer 1974).

The interesting geological structure of the klippen belt has been the subject of inquiry on the part of scientists involved in geodynamic research for a long time. Concentrated geological studies of the klippen belt, especially the Czorsztyn area, were commenced

prior to World War II. These studies were primarily linked with the first plans to build a dam on the Dunajec River and the creation of a reservoir in this region. The further part of this paper presents geodynamic research conducted in the area of the belt in the years 1994-2010.

3. HISTORICAL BACKGROUND OF GEODYNAMIC STUDIES IN PKB

A precision leveling network of height benchmarks was established in the beginning of the nineteen-sixties in the area of the planned project. The Państwowe Przedsiębiorstwo Geodezyjne in Warsaw conducted leveling measurements three times a year for several years. It was on the basis of the leveling network established in 1969 that a geodynamic traverse was created, where the leveling network was extended all the way to the village Kacwin on the Slovakian border so that the leveling line cut through the southern contact of the Pieniny Klippen Belt and the Podhale Flysch (PF) (Czarnecka 1988, 1992). At the start of the nineteen-seventies, the area of the Pieniny geodynamic traverse was subject to two series of leveling measurements – measurements of the slopes of the terraces of the Dunajec River and its tributaries as well as shallow seismic refractive profiling and electric resistivity imaging aimed at identifying zones of concentrated stress and the locations of fault zones. The years 1978–1995 saw the work continued by the staff of the Institute of Geodesy and Geodetic Astronomy of the Warsaw University of Technology (Ząbek, et al. 1988, 1993; Margański 1997). In this research ten elevation observation epochs were performed using the precision leveling method on the leveling network with precision measurements of distances on the horizontal network and measurements of differences in the concentration of gravitational forces. Moreover, the nineteen-nineties saw the performance of absolute gravimetric measurements at one station and GPS satellite measurements in collaboration with the Slovak University of Technology in Bratislava.

It was thanks to this research work (Ząbek, et al. 1988, 1993; Margański 1997; Barlik 1998) that varied vertical movements of block character, having their source in the deep substrate of the southern contact of the Pieniny Klippen Belt and the Podhale Flysch, were discovered. These movements demonstrated oscillation. Their magnitude was estimated at 0.5 to 1.5 mm/year. Horizontal movements were far from regular. They changed both their value and direction from year to year. The maximum achieved value for these movements over a seventeen-year period was 10 mm, with a small tendency for shifts of the belt in the eastern direction with respect to the Magura Nappe. Moreover, a shortening of the distance of the meridian of the examined field was noted. Gravimetric studies conducted in the Czorsztyn and Niedzica region indicated quasi-periodic variations in the acceleration of gravity in the area of 20 μ Gal. However, the change in the acceleration of gravity at the Niedzica station was almost 0.1 mGal over a seventeen-year period.

4. HORIZONTAL MOVEMENT STUDIES

Geodesic measurements aimed at studying horizontal movements in the area of the Pieniny Klippen Belt have been conducted by the Warsaw University of Technology ever since 1978. The first horizontal network was established for the purpose of studying changes in distances, although certain angles were also measured for the purpose of reduction. The network consisted of eight points laid out so as to investigate the

locations of the stations in the Pieniny Belt with respect to the Podhale Flysch (Jędras) and the Magura Nappe (Frydman, Lubań, and Wdźar).

Four points were stabilized in the Pieniny Klippen Belt – Zielone Skałki, Czorsztyn, Niedzica, and Trzy Korony. Seven measuring cycles were performed between 1978 and 1989. No clear trends were noted with respect to changes in length. Only the Trzy Korony point demonstrated a small tendency for movement in the eastern direction amounting to 0.5 mm/year (Ząbek, et al. 1993).

GPS measurements were included in the horizontal network in 1994-1995. Several new points were stabilized in the PKB, as were reference points in the Magura Nappe and Podhale Flysch. Three points were established on the Slovakian side in collaboration with the Slovak University of Technology in Bratislava (Pachuta, et al. 1995; Czarnecki 2004; Walo, et al.. 2003).

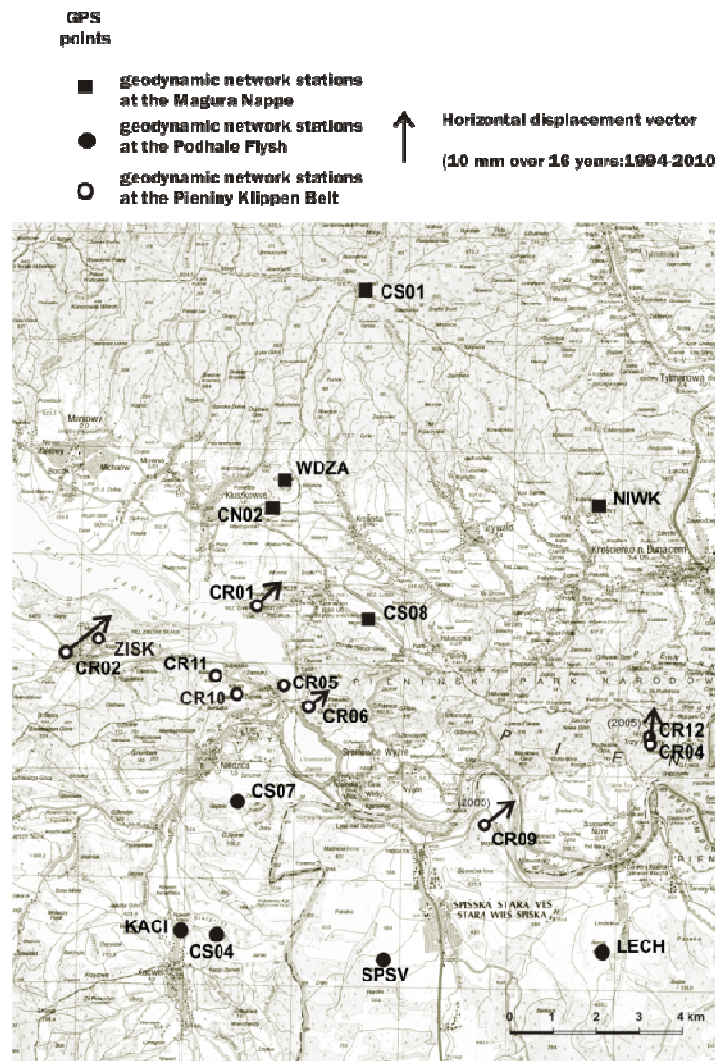


Fig. 1. Velocity vectors at selected points in the PKB.

After a six-year break, research into horizontal movements was restarted in 2001. The horizontal network was somewhat modernized in terms of use of GNSS satellite

measurements (Figure No. 1). From that moment on, it became the primary technique used in the study of horizontal movements of points in the Pieniny geodynamic traverse. As of 2001, satellite observations have been performed annually at the beginning of September. They are conducted at selected points over three-day observation sessions (the Wdżar and Niwki points located within the Magura Nappe structure and the points in Kacwin and Stara Spiska Wieś stabilized in the Podhale Flysch). The remaining points of the horizontal network of the Pieniny geodynamic traverse are observed in six-hour sessions. The coordinates of the horizontal points defined on the basis of observations from a single measurement epoch are characterized by mean errors in the area of $\pm 2\text{--}3$ mm.

A group of reference points on the tectonic structure of the Magura Nappe (MN) and the Podhale Flysch (PF) were assumed in order to determine the horizontal movements of points in the PKB. The mutual stability of the group of points within the given structure was examined in the first phase. The stability criterion applied was the non-exceeding of changes in length among the points over successive observation epoch of a value three times the mean error for that change. Median points representing tectonic units of the Magura Nappe and Podhale Flysch were defined following verification of the stability of the reference points. Figure No. 2 presents changes in the distances between those units as calculated with respect to the median points, inclusive of errors in their determination. The results received from measurements from twelve observation epochs do not indicate any clear tendency with respect to movement between the southern part of the Magura Nappe and the northern part of the Podhale Flysch in the area around the reservoirs. Changes in distances did not exceed 1 cm. However, it should be borne in mind that the reservoir on the Dunajec River was filled between the 1995 and 2001 measurement epochs. This allows the hypothesis that this resulted in a temporary mutual increase in distance between the Magura Nappe and Podhale Flysch.

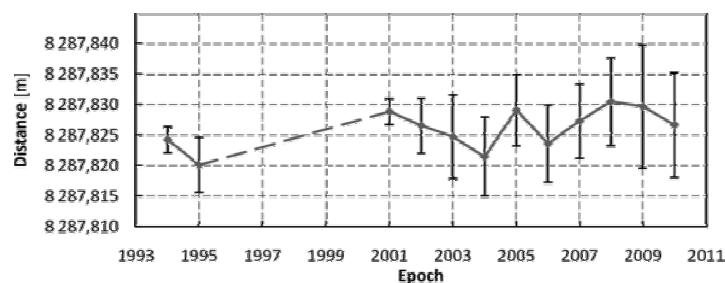


Fig. 2. Distance changes between PF and MN over the period 1994-2010.

Changes in the locations of points within the PKB were determined with respect to median points located within the MN and PF areas. Graphs presented in Figure No. 3 depict changes in point coordinates with reference to median points at MN and PF over successive measurement epochs for which observations were conducted over the years 1994–2010. Change of distance between measurement points and median points (with linear regression) are shown in Figure no. 4 (distance from PF is shown with opposite sign). A certain tendency may be noted on the graphs with respect to the changes in point locations in the north and northeast direction, which achieved a value in the area of 15–20 mm over a sixteen-year period. Only point CR05 (on the Niedzica castle tower) showed no tendency in change, where its coordinates oscillate within ± 10 mm limits. Such an effect may be caused by the stabilization of the point. The graphs only depict

changes for points whose measurement period encompasses no less than five successive measurement epochs.

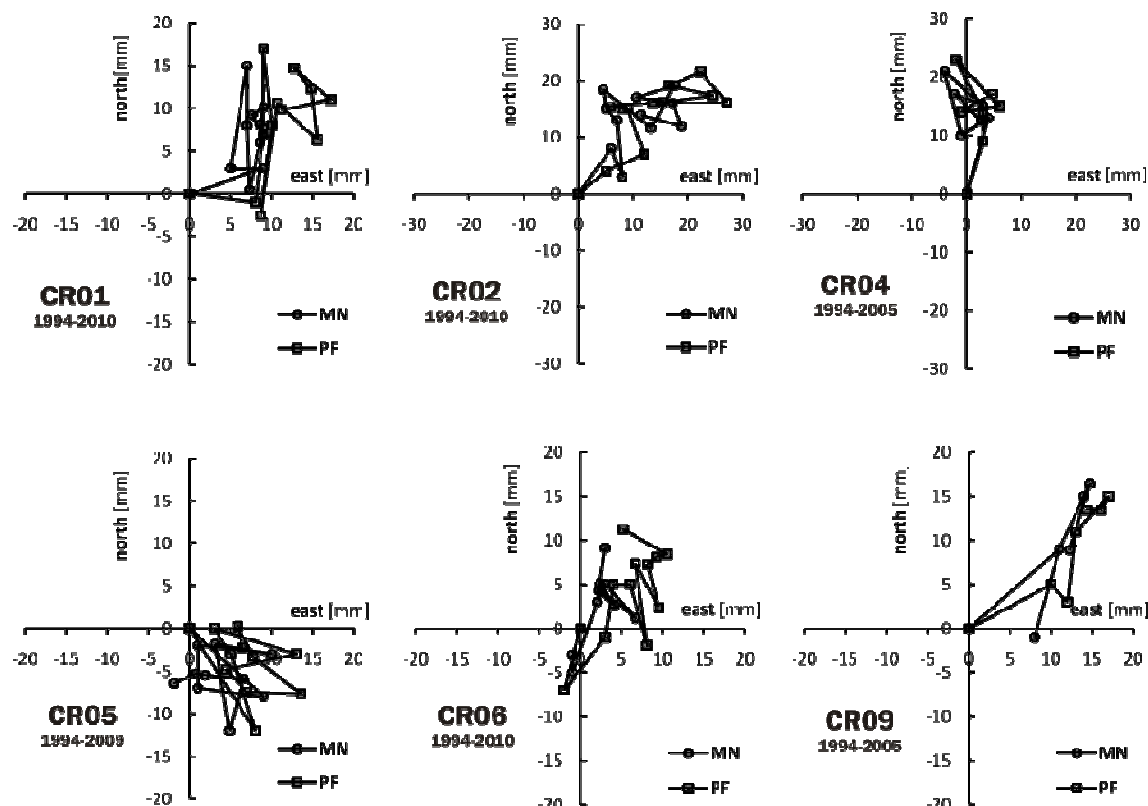


Fig. 3. Points movements within the PKB.

5. GRAVIMETRIC STUDIES

The gravity measurements were added to geodynamic studies in 1978 (Ząbek, et al. 1988, 1993). It was then that four stations located near the leveling datum points of the network monitoring vertical movements were stabilized. Reference points were selected so that they would be in various tectonic units at a distance of up to 30 km from the traverse. Stations of the National Gravimetric Network in Łąck and Krościenko, a point in Kacwin in the Podhale Flysch, and the National Gravimetric Network station in Nowy Targ were selected. Gravimetric research was expanded over successive years. It may be subdivided into four periods: 1978–1990 (eight measurement cycles), 1993–1995 (three measurement cycles at the end of June and beginning of July – Barlik, Knap 1993, Barlik 1998), 2001–2003 (three measurement cycles in the first half of September), and 2007–2009 (absolute measurements of g values at three points).

All relative measurements were performed using static gravimeters, first a Worden gravimeter and subsequently a LaCoste & Romberg gravimeter (Pachuta 2003). The smallest changes in gravity were found at the Zielone Skalki and Wdżar stations. A permanent tendency for changes in gravity appeared at the Niedzica station. There it reached 0.127 mGal over the past fifteen years. However, the bulk of this value stemmed

from the influence of the earth volume of the dam and of the water in the upper and lower reservoirs on the Dunajec River.

The year 2008 saw the incorporation of three absolute gravity stations into the unified gravimetric reference system as established for Polish geodynamic traverses (Szpunar, et al. 2010). It was within the framework of this work that locations were

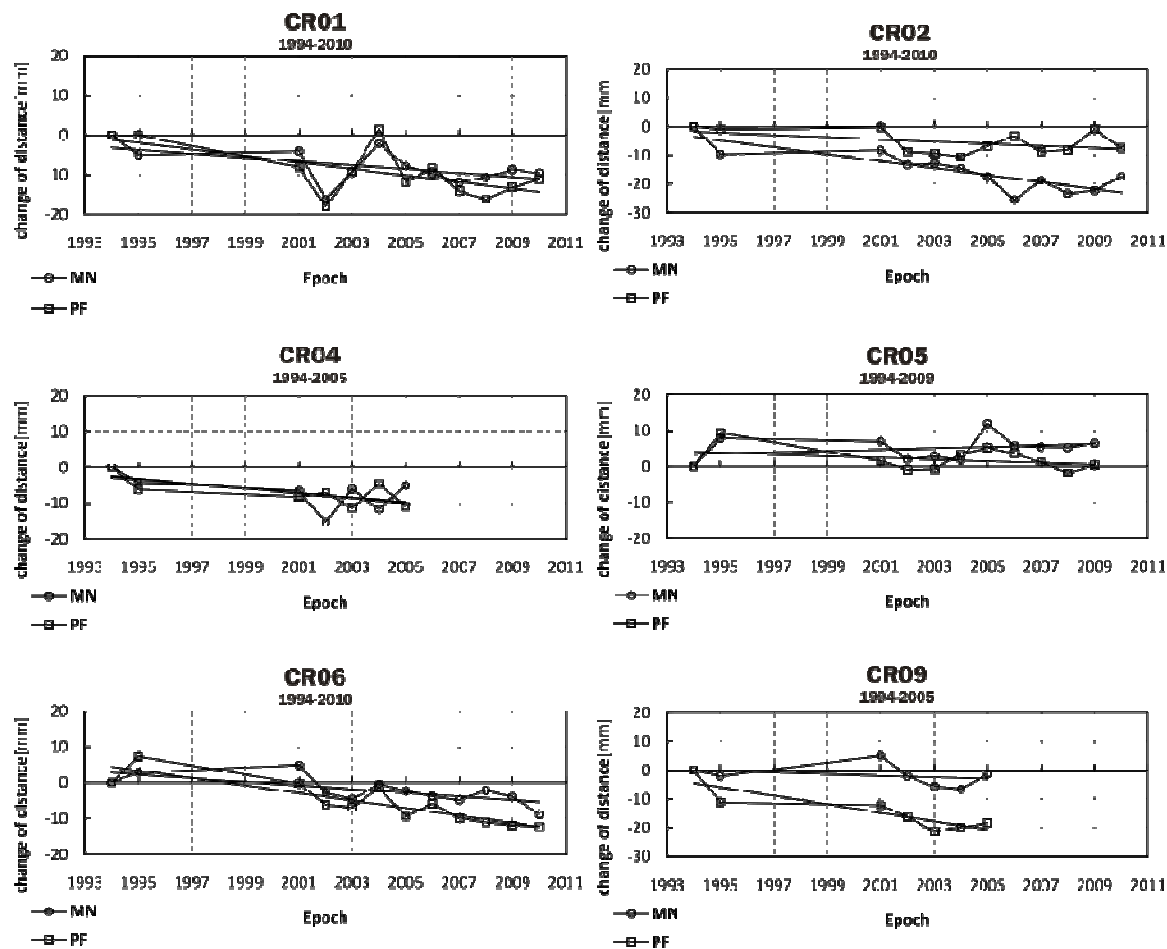


Fig. 4. Distance changes between measurement points and medium points at MN i PF.

selected and two points lying outside of the Pieniny Klippen Belt were stabilized with concrete blocks. The first point was stabilized in the locality of Łącko (the Magura Nappe area), while the second one was in Kacwin (the Podhale Flysch area). The already existing point in Niedzica was selected in the PKB area, where measurements had been conducted earlier using a ZZG absolute-ballistic meter (Ząbek, et al. 1993). Observations were conducted at all points using an FG-5 no. 230 absolute gravimeter spanning twenty-four hour observation sessions.

Table No. 1 contains the values of gravity, reduced to the level of the observation point. The values for the acceleration of gravity were determined using the absolute method. They make up valuable input material for further research and facilitate the interpretation of changes in gravity.

Tab. 1. The gravity at points of geodynamic test field

Point Name	Date	Gradient [$\mu\text{Gal}/\text{m}$]	Height [m]	Gravity [μGal]
Niedzica (PKB)	26.05.2008	268.1 \pm 1.2	1.288	980855669.0 \pm 2.3
Łącko (MN)	27.05.2008	219.6 \pm 2.8	1.288	980892809.2 \pm 4.0
Kacwin (PF)	25.05.2008	263.6 \pm 1.8	1.290	980843159.3 \pm 2.9

6. SUMMARY

The above-presented results of geodynamic research indicate that the Pieniny Klippen Belt demonstrates neo-tectonic activity that is clearly manifested in noticeable changes in elevations and horizontal coordinates. Also documented are changes in gravity in two geological complexes. Horizontal movements in the Pieniny Klippen Belt in the north-eastern direction are less than 1 mm/year and explaining this requires further research.

The authors propose the continuation of research into the current geodynamic activity of the Carpathians, especially the Pieniny Klippen Belt:

- At three stations in order to determine absolute values for the acceleration of gravity (Łącko, Niedzica, and Kacwin) and one each within important geological structures,
- At current GNSS satellite observation points, and
- Along one precision leveling line oriented perpendicular to the PKB contact zones.

Based on the presented results of studies of geodynamic phenomena, the authors postulate a repeating of observations in this region every three to five years.

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