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REVIEW

GEODYNAMIC STUDIES IN THE PIENINY KLIPPEN BELT IN 2004-2015

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ABSTRACT

The Pieniny Klippen Belt (PKB), which is situated in Southern Poland, is one of the main fault zones on the boundary of the Outer and Inner Carpathians. The geodynamic investigations which have been carried out since 1960s indicate that PKB demonstrates neo-tectonic activity. In 1990s, the Dunajec river dam and the water reservoirs in Czorsztyn and Sromowce Wyzne have been built. This has created a new aspect in investigations related to the effect of tectonic movements on the dam. In 2001, after few years break, the investigations were revived. Current the measurements are performed annually, in the beginning of September and contain GNSS and gravimetric measurements. The results of horizontal displacement in the PKB area based on GNSS measurements as well as gravity changes obtained from absolute measurements in 2004-2015 are presented and discussed in this paper.

1. INTRODUCTION

Structurally, the Pieniny Klippen Belt (PKB) corresponds to one of the main discontinuity zones in the Earth's crust extending along the Inner-Outer Carpathian border (Birkenmajer, 1974, 1986). It is located at the boundary between two major structural units: the Outer Carpathians lying in the north, with the Magura Nappe (MN) directly adjacent to the Klippen Belt, and the Inner Carpathians in the south (Zuchiewicz, 1995; Jurewicz, 2005). The structural phenomenon of the Belt results from its complicated tectonic genesis. Its tectonics is particularly complicated, resulting from the processes taking place during the Alpine orogeny. The belt constitutes a structure of folds and horsts. The sediments of the Klippen Belt were created mainly during the Jurassic and the Cretaceous periods in an oceanic basin constituting the northern part of the Western Tethys. The upper Cretaceous compression from the south caused refolding, scaling and boudinage of the nappe structures (Birkenmajer, 1974).

For a long time, the peculiar geological structure of the Klippen Belt has been an object of interest for scientists engaged in geodynamic research. The intense geological studies of the Klippen Belt, in particular in the Czorsztyn area, commenced as early as before the Second World War. Those studies were connected mainly to the initial plans of constructing a dam on the Dunajec river and creating an artificial lake within this area. The following part of the paper presents an outline of the geodynamic studies conducted within the area of the belt before and after the construction of the dam in Czorsztyn, particularly the examination of the horizontal movements and the results of absolute gravimetric measurements conducted after 2001.

2. THE SCOPE OF GEODYNAMIC RESEARCH IN THE PIENINY KLIPPEN BELT

In the beginning of the 1960s a network of precise levelling benchmarks was established within the area of the planned investment, where levelling surveying was conducted three times a year by the National Geodetic Enterprise from Warsaw for several years. Based on the established levelling network, a geodynamic polygon was created in 1969 and the levelling network was extended as far as to the Kacwin village near the border with Slovakia, so that the levelling line would intersect the southern contact of the Pieniny Klippen Belt with the Podhale Flysch (PF) (Czarnecka, 1988, 1992). In the beginning of the 1970s, two series of levelling surveys were conducted within the area of the Pieniny geodynamic polygon, along with the measurements of the inclination of the terraces of Dunajec and its tributaries, as well as the shallow seismic refraction surveying and electrical resistivity imaging in order to detect the stress concentration zones within the substrate and to locate the fault zones. In the years 1978-1995 the studies were continued by the employees of the Institute of

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Geodesy and Geodetic Astronomy of the Warsaw University of Technology (Ząbek et al., 1988, 1993; Margański, 1997). As part of that research, ten observation epochs of height differences were performed using the precise levelling method in a levelling network, along with precise measurements of the distance in a horizontal network and the measurements of the differences in the gravitational force. Furthermore, in the 1990s absolute gravimetric measurements were realized in one station along with satellite GPS surveying in cooperation with the Slovak University of Technology in Bratislava.

As a result of this research work (Ząbek et al., 1988, 1993; Margański, 1997; Barlik, 1998), diversified vertical movements of block-like nature were detected, originating from the deep substrate of the southern contact of the Pieniny Klippen Belt with the Podhale Flysch. Those movements exhibited an oscillatory nature, their estimated magnitude ranging between 0.5 and 1.5 mm/year. The horizontal movements were far from regular, changing both their magnitude and direction with every year. The maximum values of those movements reached 10 mm over a 17-year period, with a slight tendency of the belt to move eastward relative to the Magura Nappe. Shortening of the distance in the meridian of the research field was also observed. Gravimetric measurements conducted in the area of Czorsztyn and Niedzica indicated quasi-periodic changes in the gravitational acceleration, amounting to approximately 20 μGal. On the other hand, in the Niedzica station during the 17-year period the change in the value of acceleration amounted to approximately 0.1 mGal.

In 2001, after a six-year break, the studies within the Pieniny geodynamic polygon were resumed. In the meantime, a dam on the Dunajec river was constructed near the Niedzica castle, and an artificial lake (The Czorsztyn reservoir) was created along with the lower reservoir in Sromowce Wyżne. A new element important to the studies was therefore introduced, connected to the impact of the movements of Earth's crust on the safety of operation of the river dam. The examinations therefore had to take into account the impact of water masses in the reservoirs on the results of geodetic surveying used in geodynamic research.

As part of the research project of the Ministry of Science and Higher Education no. 9 T12 E 009 19, the following control networks have been surveyed: elevational, horizontal and gravimetric. Geophysical examinations were also resumed, i.e. shallow seismic surveying and electrical resistivity imaging. An analysis of the results of the 2001-2003 measurements proved above all else that notice able changes took place in the relative height of the Klippen Belt with respect to the Podhale Flysch and the Magura Nappe. Once the reservoir had been filled, Czorsztyn and Niedzica descended by almost 7 mm (Olszak and Szpunar, 2004). Figure 2 shows the height differences between the PKB and the adjacent structures. Detailed results of the work conducted during that period can be found in the monograph edited by Czarnecki (2004). Some results of tectonic activity covering

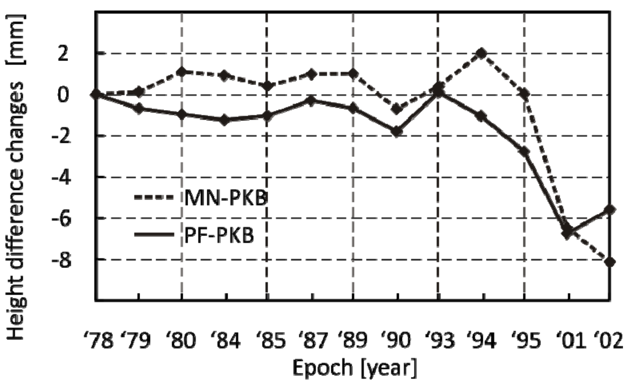

Fig. 2 The height differences between: PKB – MN (CR01) and PKB – PF (CR05) in 1978-2002.

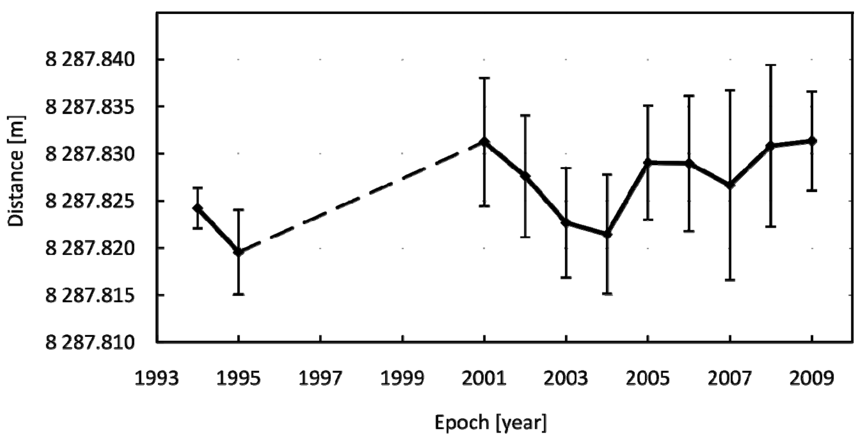

Fig. 3 The distance between the mean points at MN and PF in 1994-2009 (Pachuta et al., 2010).

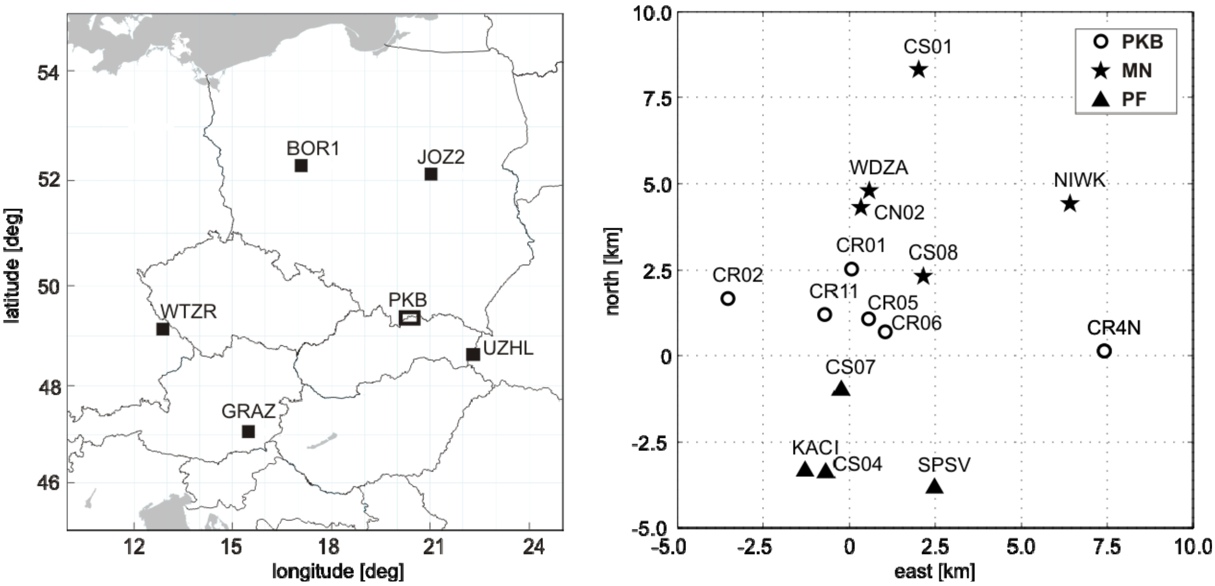

Fig. 4 Map of datum definition sites (left) and points of the PKB geodynamic test field (right).

period from 1992 till 2000 can be also found in Perski (2008).

Once the project was concluded, the scope of work was limited to annual GNSS satellite surveying in the points of the horizontal network and to gravimetric measurements in selected absolute stations. Figure 3 shows the distance differences between the MN and the PF (between the chosen mean points which represent the units) determined in 1978-2009 (Pachuta et al., 2010).

3. GNSS NETWORK: DATA AND PROCESSING

Since 2004, horizontal movements of the geodynamic units have been determined in the points of the GNSS network. This network consists of 15 GNSS stations, including 6 stations stabilised inside the PKB, 5 stations within the MN and 4 stations within the PF (see Fig. 4). The whole test area is additionally supplemented by 4 GNSS stations situated in the Tatra Mountains. The points of the GNSS network were stabilised in the form of brass bushes in the native rock, enabling forced centring of the GNSS antennas (Fig. 5 – left). Some of the points have also been adapted from the points of the triangulation network established in the years 1978-1995 (Fig. 5 – right) and used for precise measurements of distance in the years 2001-2003.

The GNSS measurements have been conducted for the points of the horizontal network every year in early September according to the uniform schedule of observations from 2004 until the present day. Only in 2005 there were missing observations for some points of the network. The duration of an observation session for four basal points (NIWK and WDZA within the MN as well as KACI and SPSV within the PF) equals 72 hours. For the remaining points the duration of the session ranges between 6 and 12 hours. Until 2008, the satellite surveying was based solely on the GPS system; since 2009 the observations have been conducted in two systems: GPS+GLONASS. The observations are performed mainly by two types of surveying sets: a Trimble 4007 receiver with the

Fig. 5 Examples of GNSS network point stabilization.

Table 1 GNSS processing parameters.

Parameters	Value
Session scheme	Daily
Baseline creation strategy	Max. number of common obs.
Ambiguity resolution strategy	200-2000 km: QIF 20-200 km: L5/L3 < 20 km: L1&L2
A priori troposphere model	GMF (dry only) (Böhm et al., 2006)
Time resolution of ZTD	1 hour
Mapping function of ZTD	GMF (wet)
Troposphere gradient	Chen/Herring (24 hours) (Chen and Herring, 1997)
High order ionosphere	Yes
Orbit, ERP and clock	CODE (GNSS) (Dach et al., 2015b)
Antenna phase center	IGS08 (Schmid et al., 2016)
Ionospheric model	Global CODE

Trimble Micro-Centered L1/L2 + GP antenna and the Leica GX1230GG receiver with the LEIAX1202GG antenna. The individual antennas are assigned to specific points in order to eliminate the error of the antenna phase-centre offset. The sampling interval of the GNSS signal is 30 seconds, and the elevation cut-off angle equals 5 degrees.

The processing of GNSS observations for the whole network was computed using the Bernese GNSS Software 5.2 (Dach et al., 2015a). The measurements were processed in one-day sessions, based on the double differences of the observations for all the independent vectors. The template for the processing of the observations complied with the standard procedure for the development of a regional GNSS network included in the Process Control Files RNX2SNX.PCF of the Bernese GNSS Software 5.2 (Dach et al., 2015a). The basic parameters for the processing of the network with the used GNSS products are presented in Table 1. The final coordinates of the network points were determined by a minimum constraint solution for the translation parameters in the IGb08 system (Rebischung et al., 2015) per measurement epoch. 5 stations defining the IGb08 system distributed uniformly around the test area were adopted as the fiducial sites (see Fig. 4 – left). Table 2 comprises a statistical summary of the errors in the estimation of the unknowns (coordinates of points and the parameters of the tropospheric delay) and of the definition of the reference frame for the individual daily solutions. The maximum value of a typical a posteriori RMS error did not exceed 1.8 mm, which indicated high accuracy of the estimation of the network point coordinates. The Chi^2 value of the statistical test was accepted for all the sessions. The error of reference frame definition also constitutes the verification of the network solution quality, calculated based on the residua for the fixed points obtained from the Helmert transformations, along with the repetitiveness of solutions from the daily sessions during the given year. The average value of RMS for the horizontal components equalled approx. 2 mm (with a maximum of 4 mm), and the average value of four-day repetitiveness amounted to approx. 1 mm (with a maximum of 4 mm). The above results indicate a high accuracy of the network solution. This accuracy is constant for all the documented epochs, which is also very important from the standpoint of the correct estimation of the velocity vectors of the measurement points.

4. HORIZONTAL MOVEMENTS

Based on the coordinates of the GNSS network stations per survey epoch, vectors of horizontal velocity were determined for the points of the geodynamic network. The horizontal coordinates of the points for an average observation epoch in a given year were determined as a weighted mean of the daily solutions for the given year with the weights inversely proportional to the squared average RMS errors for the individual components of the coordinates. Based on them, the linear trends of changes in the components of coordinates in a topocentric system were determined along the north-south and east-west directions together with their mean errors. Residual values of the linear trends were determined upon subtracting the speed of the Eurasian Plate assessed based on the ITRF2008-PMM geodetic plate model (Altamimi et al., 2012). Residual changes in the horizontal components of the coordinates of the GNSS network points, for the points located respectively in the PKB, MN and PF units, are presented in the Figures attached to the paper (see Figs. 8, 9 and 10). Table 3 includes a list of the residual station velocities and their mean errors for the individual points and the average velocities for three tectonic units. The residual horizontal velocity vectors are also presented in Figure 6.

All the time series of the coordinate changes are characterised by high consistency and visible linearity. The residua for the individual epochs amount to an average of ±5 mm, their maximum values not exceeding ±20 mm. The points located inside the PKB are characterised by very similar residual velocities

Table 2 Summary of GNSS network processing results.

Session		Summary of parameter estimate		Summary of datum definition			
				RMS of datum transformation		4 days repeatability	
Year	DOY	A posteriori RMS of unit weight [mm]	Chi²/DOF	North component [mm]	East component [mm]	North component [mm]	East component [mm]
2004	250	1.15	1.32	3.01	3.61		
	251	1.28	1.64	2.97	2.87		
	252	1.47	2.16	4.06	3.00		
	253	1.26	1.58	3.20	3.27	0.97	0.87
2006	247	1.45	2.10	3.71	3.15		
	248	1.40	1.96	3.38	3.05		
	249	1.24	1.53	2.73	3.66		
	250	1.24	1.53	2.68	3.83	1.08	1.10
2007	246	1.16	1.34	2.37	3.94		
	247	1.17	1.36	2.53	3.84		
	248	1.31	1.72	3.01	3.56		
	249	1.17	1.37	2.39	4.23	1.02	0.76
2008	245	1.20	1.44	2.53	4.04		
	246	1.18	1.39	2.94	3.81		
	247	1.25	1.56	2.64	4.07		
	248	1.30	1.68	2.38	4.06	1.38	0.67
2009	250	1.09	1.20	1.12	1.41		
	251	1.13	1.28	0.98	1.41		
	252	1.16	1.36	1.36	1.19		
	253	1.26	1.59	2.64	4.15	0.51	0.66
2010	249	1.18	1.39	2.32	2.35		
	250	1.23	1.51	1.88	1.91		
	251	1.26	1.59	2.13	2.31		
	252	1.41	1.99	1.76	2.37	0.68	0.85
2011	248	1.52	2.31	1.03	0.62		
	249	1.53	2.34	0.82	1.06		
	250	1.55	2.42	0.87	0.89		
	251	1.36	1.85	0.84	1.06	0.95	1.19
2012	247	1.49	2.21	0.85	0.47		
	248	1.44	2.08	1.12	0.55		
	249	1.68	2.81	1.09	0.62		
	250	1.42	2.03	1.09	0.43	2.02	1.70
2013	245	1.65	2.71	0.74	0.90		
	246	1.76	3.10	1.28	0.80		
	247	1.52	2.31	0.94	0.38		
	248	1.43	2.05	0.93	0.93	4.24	1.53
2014	245	1.37	1.87	1.02	3.57		
	246	1.47	2.17	1.51	3.63		
	247	1.40	1.95	1.58	3.70		
	248	1.44	2.06	1.66	4.08	0.88	0.63
2015	250	1.31	1.70	1.79	3.96		
	251	1.31	1.73	2.19	4.32		
	252	1.27	1.62	1.44	3.84		
	253	1.28	1.65	1.69	4.32	1.00	0.73

within the range of ±0.2-0.4 mm/year. Only two stations: CR4N (the summit of the Trzy Korony mountain) and CR11 (a rock outcrop) stand out due to their much higher velocities exceeding 2 mm/year in the south-eastern direction. The resultant velocity for the whole tectonic unit determined as an average for all the points equals -0.4 mm/year and 0.6 mm/year, for the northern and eastern components respectively.

The points located within the MN tectonic unit were characterised by velocities amounting to

Table 3 Summary of residual horizontal velocity.

Station	Unit	Residual velocity		Residual velocity errors	
		North [mm/year]	East [mm/year]	North [mm/year]	East [mm/year]
CR01	PKB	0.1	-0.2	±0.6	±0.3
CR02		-0.2	-0.3	±1.0	±0.4
CR4N		-0.3	2.5	±0.4	±0.3
CR05		-1.1	-0.4	±0.4	±0.2
CR06		0.4	0.2	±0.2	±0.3
CR11		-1.1	1.8	±0.5	±0.4
Mean:		**-0.4**	**0.6**		
NIWK	MN	-0.8	0.4	±0.1	±0.3
WDZ		-0.3	0.5	±0.5	±0.3
CN02		0.0	0.5	±0.7	±0.5
CS01		0.2	1.2	±0.2	±0.5
CS08		-0.8	0.0	±0.4	±0.4
Mean:		**-0.3**	**0.5**		
KACI	PF	-0.2	0.6	±0.2	±0.1
CS04		-0.9	-0.2	±0.3	±0.4
CS07		-0.9	-2.2	±0.2	±0.4
SPSV		0.0	0.2	±0.3	±0.2
Mean:		**-0.5**	**-0.4**		

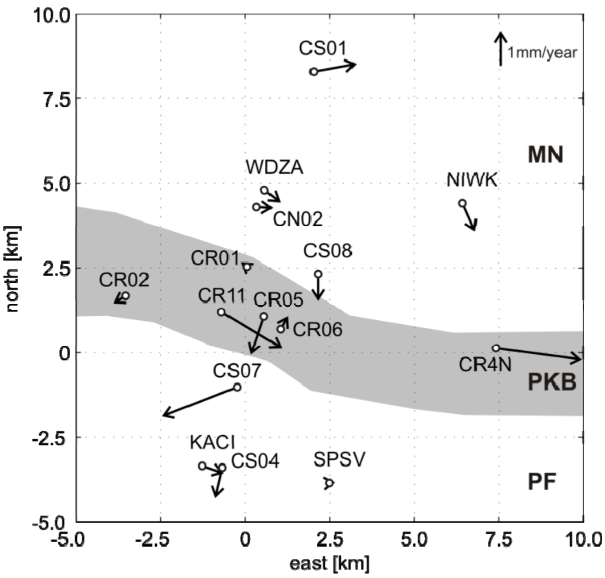

Fig. 6 Map of the residual horizontal velocity vectors.

±0.2-0.8 mm/year for the northern component and 0.0-0.5mm/year for the eastern component. Only the northern most CS01 point (the summit of the Lubań Mountain) stood out due to the higher velocity in the eastern direction, amounting to 1.2 mm/year. The resultant average velocity for the MN unit equals -0.3 mm/year for the northern component and 0.5 mm/year for the eastern component. For the PF unit, very similar residual velocities were also obtained, amounting to ±0.2-0.9 mm/year, along with similar average resultant velocities equaling - 0.5 mm/year and -0.4 mm/year. For this unit, only the CS07 point featured a slightly higher velocity amounting to 2.4 mm/year in the south-western direction.

Based on the average velocities for the units it can be concluded that their relative location over the 11-year research period was stable and did not exhibit any major changes. The three examined units are characterised by negative residual velocities for the northern component with similar values of -0.3-0.5 mm/year. For the eastern component, only the southern PF unit is characterised by a negative velocity, which may indicate the existence of local intraplate movements between the PKB and the PF along this direction, however their magnitude is close to the level of accuracy of determining the residual velocities and it requires additional confirmation.

5. ABSOLUTE GRAVIMETRY IN THE PKB

By January 1996, a total of four series of absolute gravimetric measurements were conducted within the Pieniny geodynamic polygon. Two series were conducted for a point located in the Cultural Centre building in Niedzica and the remaining two - in the cellar of the building of the District Office of Water Management in Niedzica (both points are located within the Klippen Belt). In each measurement series an almost one day-long observation session was conducted, consisting of approximately two and a half thousand rises and falls (the ZZG gravimeter was a symmetrical gravimeter). The resulting values of acceleration are presented in Table 4. The selection of

Table 4 Absolute gravity values measured by ZZG gravimeter.

Station name	Date	Gradient [μGal/m]	Transfer height [m]	g value at h=0 with error [μGal]
Dom Kultury Niedzica	9.10.1993	258±3	0.355	980 855 671.4±13.8
Dom Kultury Niedzica	15.07.1994	258±3	0.358	980 855 649.4±10.9
ODGW Niedzica	29.07.1995	269±3	0.347	980 850 641.1±7.9
ODGW Niedzica	13.01.1996	269±3	0.347	980 850 640.2±4.3

Table 5 Absolute g values measured after 2008 epoch on three stations of modernized network.

Epoch	Name of the station		
	Łącko	Niedzica	Kacwin
2008.40	980892800.4 μGal	980855669.2 μGal	980843150.6 μGal
2011.68		980855662.0 μGal	980843152.1 μGal
2015.69	980892791.7 μGal	980855666.9 μGal	980843150.6 μGal

the location of the absolute determination points was driven mainly by the emerging ability to examine long-term, age-related changes in the acceleration of the absolute value of the gravitational acceleration within the area of the Pieniny Klippen Belt. At the time there were no plans to use these points for calibration and reference of relative gravimetric measurements.

In 2008, three points of the polygon were incorporated into a uniform gravimetric reference system being created for the Polish geodynamic polygons (Walo, 2010). As part of the performed tasks, locations were selected and stabilised with concrete posts for two points located outside of the Pieniny Klippen Belt. The first point was stabilised in the village of Łącko (the Magura Nappe area), and the second one in Kacwin (the Podhale Flysch area). In the PKB area one already existing point was selected in Niedzica, where previous measurements had been performed using an absolute apparatus – the ballistic ZZG (Ząbeket al., 1993).

In the years 2008 - 2015, three observation sessions were conducted using the FG-5 no. 230 gravimeter. A typical observation session consisted of 24 observation series repeated every hour. The ultimate value of acceleration is a mean of the observation series taking into account the following corrections: tidal lithospheric (the Wenzel model with global coefficients), tidal taking into account the movement of sea water masses (model FES2004), barometric as well as the correction due to the location of the pole. The determined value of acceleration is referred to a certain level over the benchmark, which explains the necessity to determine the true value of the gravitational acceleration gradient for the reduction of the measured value to the benchmark level using the real gravitational acceleration gradient and assuming its constancy during the three survey epochs. The results presented in Table 5 also take into account the results of calibration of absolute gravimeters presented as part of ICAG2011 (Francis at al., 2013), therefore the values of g are at a level which is in compliance with what is defined as the European level of reference.

Comparing the results obtained using the ZZG and FG-5 gravimeters it can be concluded that the maximum discrepancies between the determinations reach up to 20μGal. Such major differences result probably from the imperfection in the construction of the ZZG gravimeter (the main problem, which is at the time difficult to solve, was to obtain high vacuum (the lack of an ion vacuum pump), along with the impact of microseismicity on the results of absolute measurements).

An analysis of the absolute observations conducted after 2008 using the FG-5 gravimeter indicates smaller changes in values between the epochs. Because these observations are not accompanied by additional information associated with the environmental conditions, the analysis will use the global effects, resulting from the changes in the global hydrological balance. The variations of the gravitational acceleration resulting from the changes in the global hydrological model were determined based on the Global Land Data Assimilation System (GLDAS) model in the spatial resolution variant $0.25^{o}$and with the temporal resolution of one month (Rodell and Beaudoing, 2013). The calculated gravitational effect according to (Rajner et al., 2012) has been determined taking into account the full ten layers of the GLDAS model. The results of those assessments against the changes in acceleration for three points in the Pieniny are presented in Figure 7.

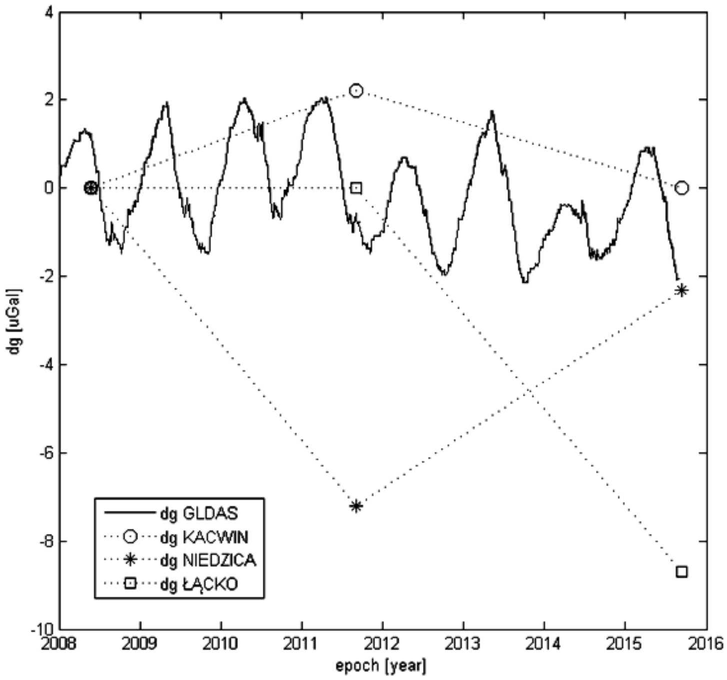

Fig. 7 Global hydrological effect on Niedzica station vs. measured absolute gravity differences with respects of the first epoch (2008.40)

A comparative analysis indicated a high degree of independence of the station in Kacwin on the changes in the local hydrological conditions. This station is clearly characterised by the lowest changes in acceleration, their magnitudes corresponding to the impact of global hydrology. The remaining stations feature higher changes in acceleration, whose basis is of a geodynamic nature or it constitutes a local hydrogeological effect. The gravimetric point in Łącko exhibits a drop in the value of acceleration resulting most likely from the expansion of the building in which the measurement station is located.

6. SUMMARY

The results of geodynamic examinations presented above indicate that the Pieniny Klippen Belt exhibits minor neotectonic activity which manifests itself mainly by clearly noticeable changes in elevation. Noticeable gravity changes in two geological complexes have also been documented. The horizontal point movements are minor and do not exhibit clear tendencies in terms of their magnitude and direction. Only for the eastern component, the Podhale Flysch (PF) is characterised by negative velocity which may indicate the presence of local intraplate movements between the PKB and the PF. Confirmation of this fact would however require further survey epochs in the future.

In order to examine the contemporary geodynamic activity of the Carpathians, and the Pieniny Klippen Belt in particular, the authors suggest continuation:

- of the absolute gravimetric measurements in three stations for the gravitational force (Łącko, Niedzica and Kacwin), one within each major geological structure,
- of GNSS satellite surveys in the network points existing to date,
- of levelling surveying along one precise levelling line, oriented transversely relative to the contact zones of the PKB.

Based on the presented results of the examinations of the geodynamic phenomena, the authors recommend repetition of the observations within this area every 3 to 5 years. This would enable continuous tracking and a more complete interpretation of the geodynamic phenomena taking place in the PKB area.

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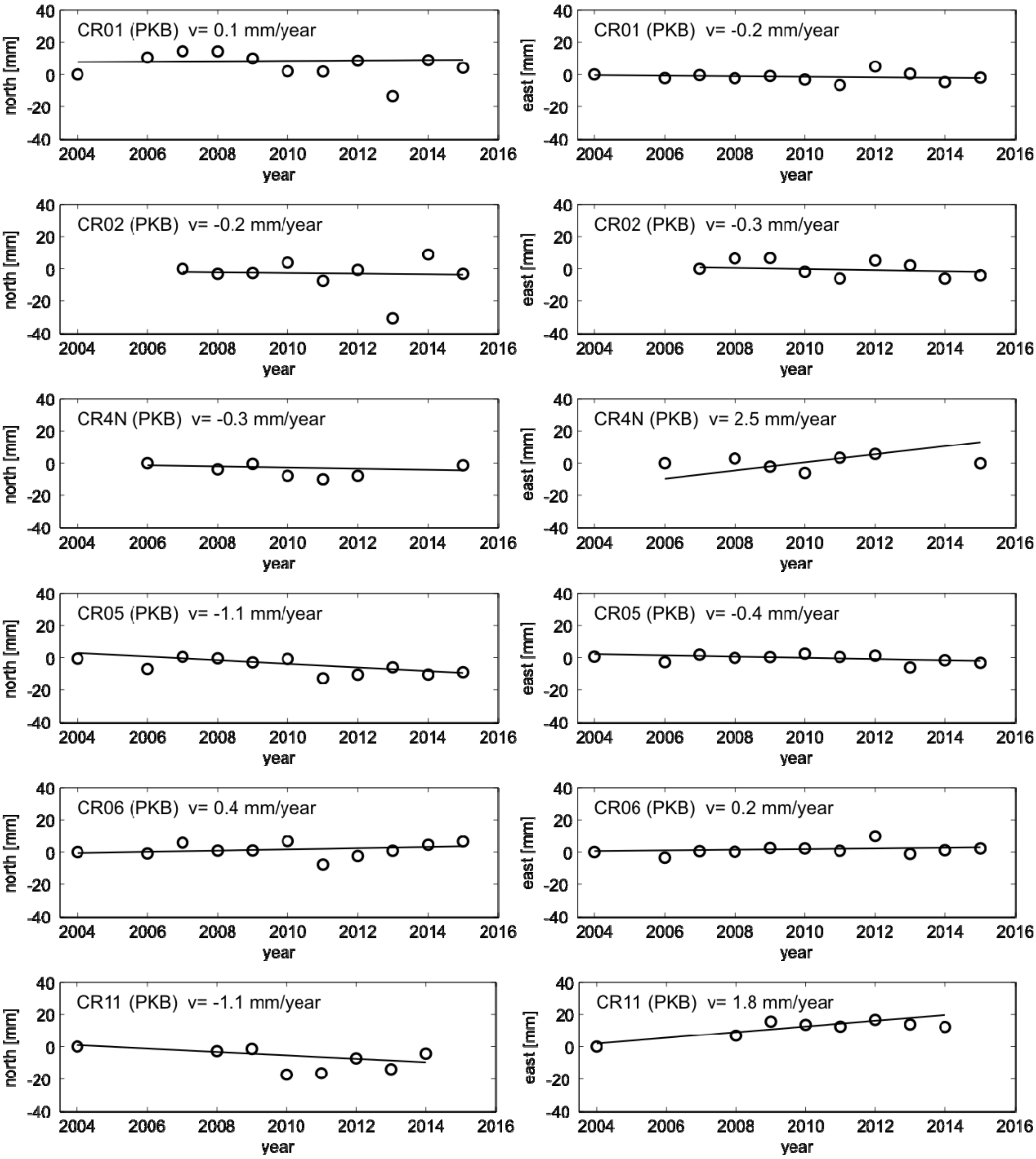

Fig. 8 Residual horizontal velocity for PKB.

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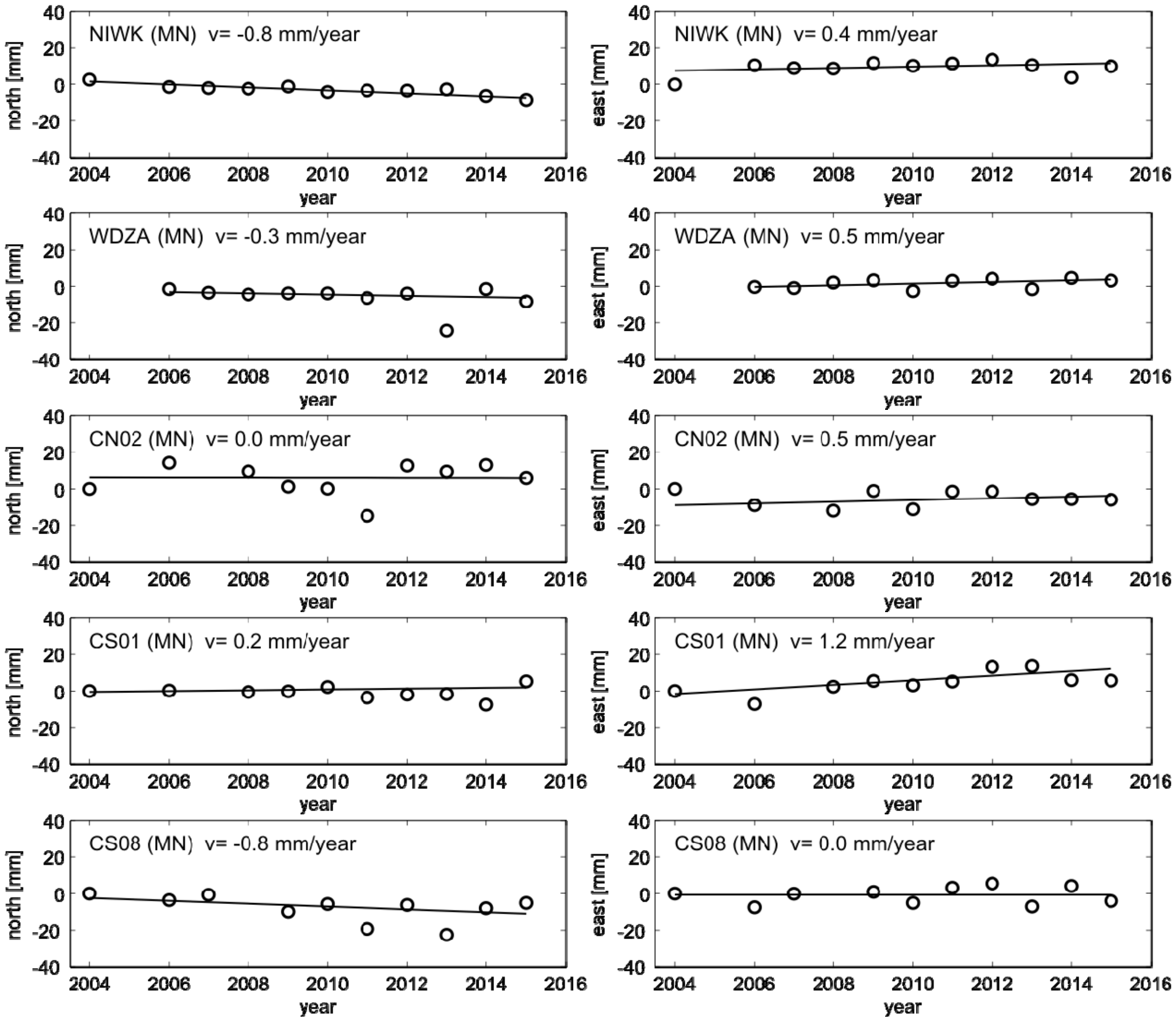

Fig. 9 Residual horizontal velocity for MN.

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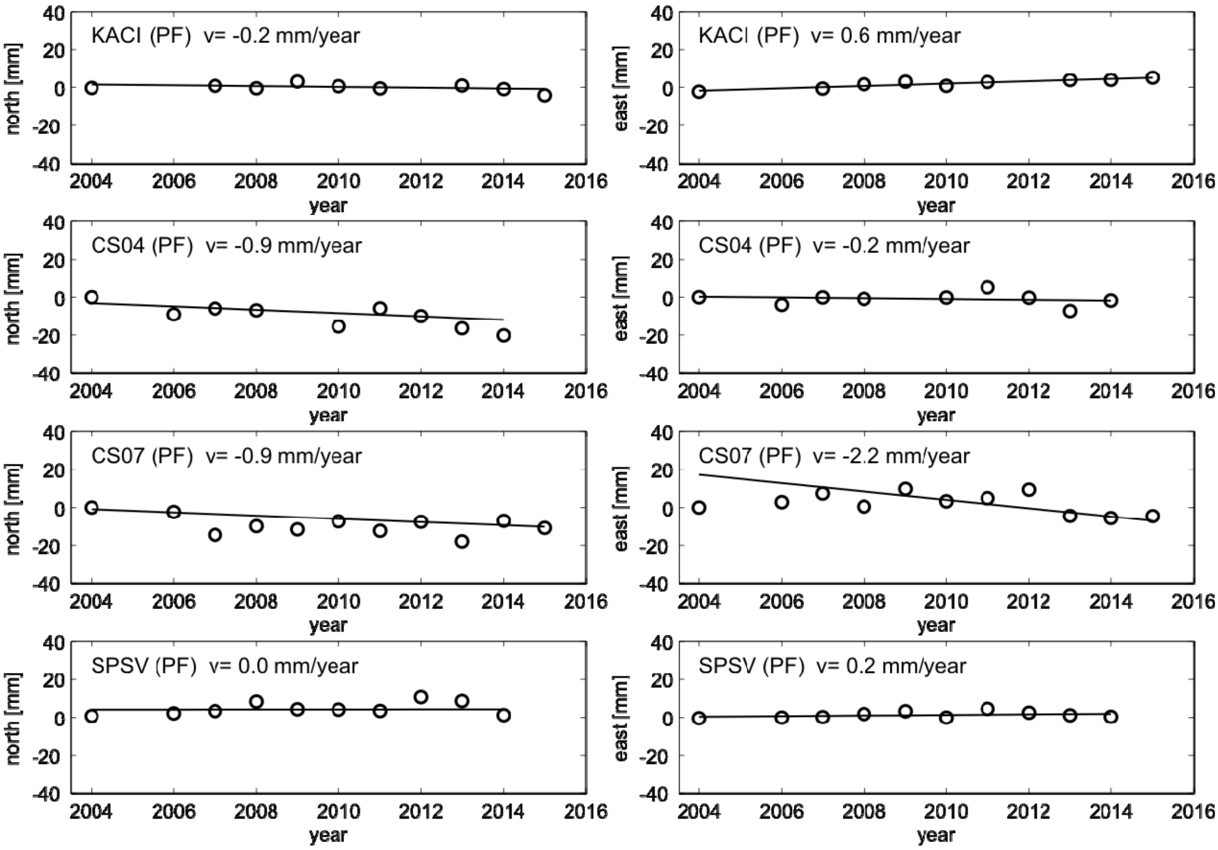

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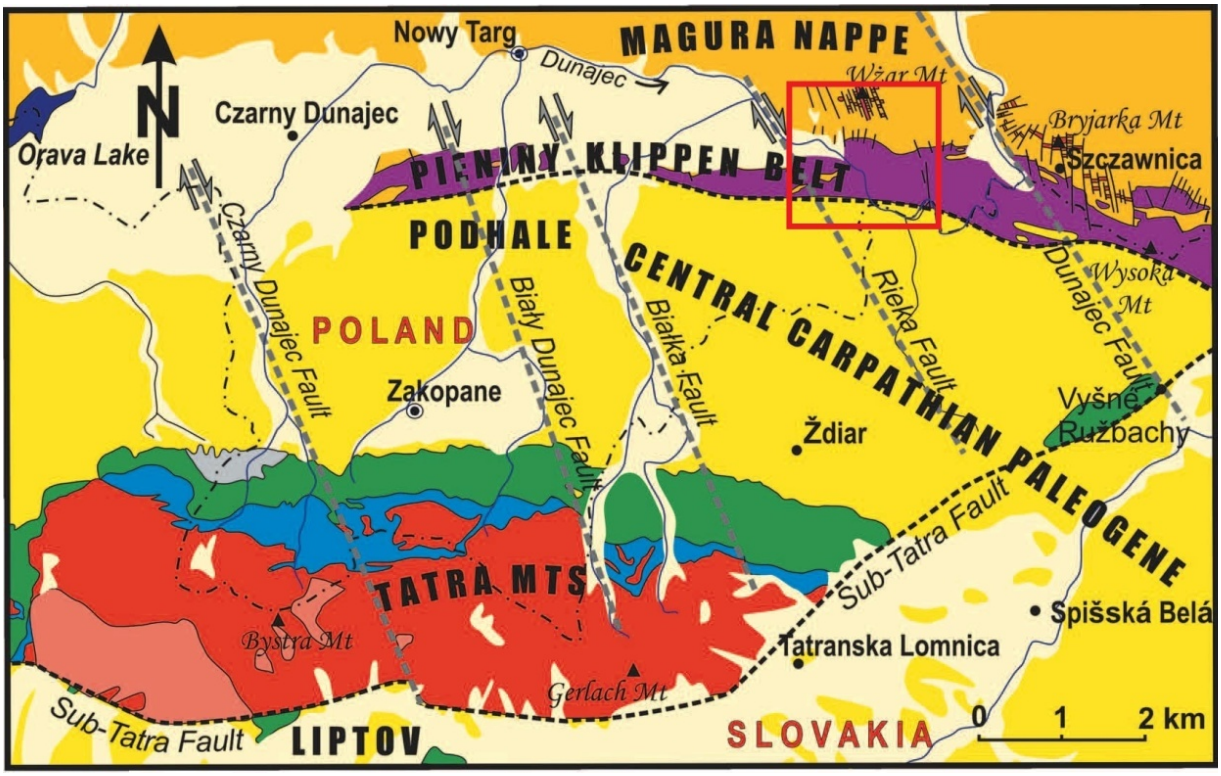

Fig. 1 Localisation of the Pieniny Klippen Belt (Jurewicz, 2005).