Acta Geodyn. Geomater.Vol.1, No.3 (135), 59-67, 2004

DEFORMATION ANALYSIS OF THE UPPER PART OF THE EARTH CRUST IN THE SNIEZNIK MASSIF (POLISH AND CZECH SIDES BETWEEN 1993 AND 2003)*

Stefan CACOŃ [1)]*, Otakar ŠVÁBENSKÝ [2)*], Bernard KONTNY [1)], Josef WEIGEL [2)], O. JAMROZ [1)], Kazimierz ĆMIELEWSKI [1)], Jarosław BOSY [1)], Jan KAPŁON [1)] and Radovan MACHOTKA [2)]

[1)] *Department of Geodesy and Photogrammetry, Agricultural University of Wroclaw, Grunwaldzka 53, 50-357 Wrocław, Poland, tel/fax: +48 71 32-05-617*
[2)] *Institute of Geodesy, Brno Technical University, Veveří 95, 662 37 Brno, Czech Republic, tel: +420 541 141 111, fax: +420 549 245 147*
[*] *Corresponding author's e-mail*: cacon@kgf.ar.wroc.pl

(*Received* March 2004*, accepted* June 2004)

ABSTRACT
The Śnieżnik Massif has complicated geological and tectonic structure. The continuing crust movements, proved on the grounds of geological, geodetic (precise levelling) and satellite (GPS) investigations, confirm present-day mobility of this area. During the past decade (1993-2003) geodynamic research based on repeated satellite (GPS) measurements in a network of 27 points located on both sides of the border has been realized in the Śnieżnik area.
Two joint (Czech-Polish) GPS observation campaigns (1993 and 2003) and a number of GPS measurements in Polish (16 points) and Czech (11 points) networks have been performed by scientists from the two partner Institutes. The results of above-mentioned investigations, particularly the 1993-2003 cycle, are the subject of analyses and interpretations presented in this paper. These are supplemented by the results of researches realized independently by the teams on both sides of the border.

KEYWORDS: Śnieżnik Massif, GPS, deformation analysis, cluster analysis

1. INTRODUCTION

The Śnieżnik Massif is an exceptional region in the geography of Europe. It is here, where the watershed of three seas: the Baltic Sea, the North Sea and the Black Sea is found. Complicated geological structure and tectonics, as well as on-going tectonic movements in the massif, have been an important factor contributing to the organization of present-day geodynamic investigation in the region. The action started in year 1992 when a research network on the Czech and Polish sides of the Śnieżnik Massif was established. The network, made up by 27 points, constitutes part of a 4-segment control and measurement system, which has allowed integration of various measurement techniques used in epoch observations (Cacoń, Kontny, 1994). Satellite GPS technique is supplemented with geodetic (precise levelling, Total Station) and gravimetric measurements, as well as relative observations with the use of crack gauge and inclinometer.

In this paper the main attention is drawn to: processing, analysis and interpretation of the results of satellite GPS measurements realized in 1993 and 2003 by partnership groups of scientists from the Department of Geodesy and Photogrammetry at the Agricultural University of Wrocław (Poland) and the Institute of Geodesy at Brno Technical University (Czech Republic). It should be underlined that the research object "Śnieżnik Massif" has formed, in a way, an investigation area for testing, analyses and interpretations of the methodology for integrated satellite, geodetic and other measurements used in regional and local geodynamic investigations. The outcome of these studies, produced also independently by the partner Czech and Polish groups, have been presented in numerous symposium and scientific conference publications and papers.

2. DESCRIPTION OF THE RESEARCH OBJECT

The metamorphic of Śnieżnik is characterised by heterogeneous geological composition with predominance of S-N elongated outcrops of Strońska series mica schists accompanied by Śnieżnickie gneisses (Don, Opletal, 1996). The distinct boundary of these formations runs from the Kleśnica river valley through the Stroma and Śnieżnik mountaintops towards the Morava valley in the Czech Republic. Crystalline limestone pockets can be found in the schists. The dense network of various age faults running both longitudinally and latitudinally divide the structures being discussed here into smaller blocks shifting in different directions and with various intensities (Fig. 1).

* The studies have been realised within the COST-625 „3D Monitoring of Active Tectonic Structures" Programme

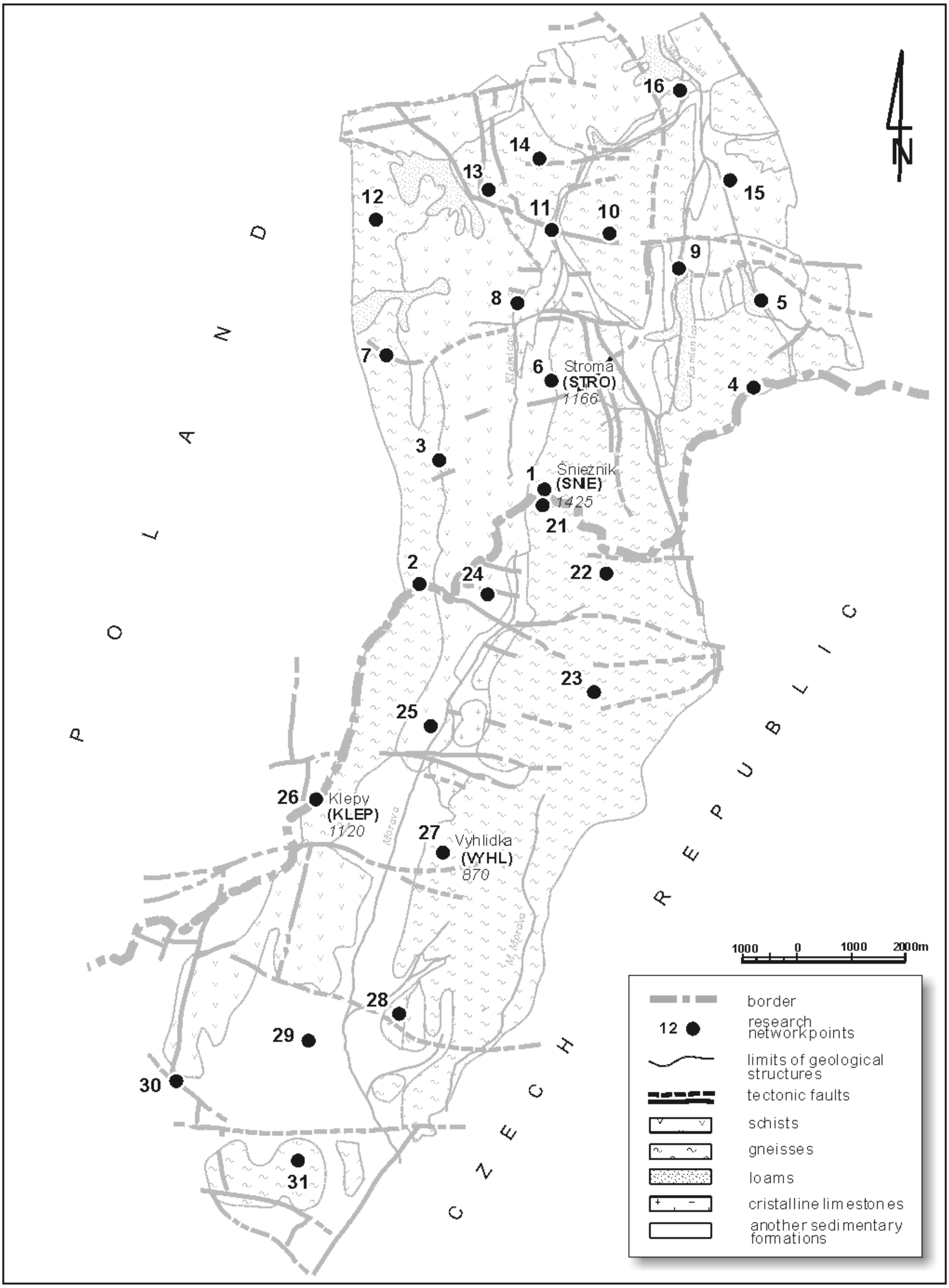

Fig. 1 Points of the geodynamical network "Śnieżnik" against the background of geological structures

Table 1 Measurement instruments used in the 2003 campaign

CZECH PART		POLISH PART	
Receiver	**Antenna**	**Receiver**	**Antenna**
LEICA SR299	**LEICA INTERNAL**	**ASHTECH Z-XII P3**	**ASH700718B**
LEICA SR399	**LEICA INTERNAL**	**ASHTECH UZ-12**	**ASH701975.01Agp**
LEICA SR530	**LEICA AT502**	**ASHTECH Z-XII3**	**ASH700936D_M**
TRIMBLE 4000SSI	**TRM22020.00+GP**	**ASHTECH UZ-12**	**ASH701945B_M**
TRIMBLE 7400MSI	**TRM22020.00+GP**	**TRIMBLE 4700**	**TRM33429.00+GP**

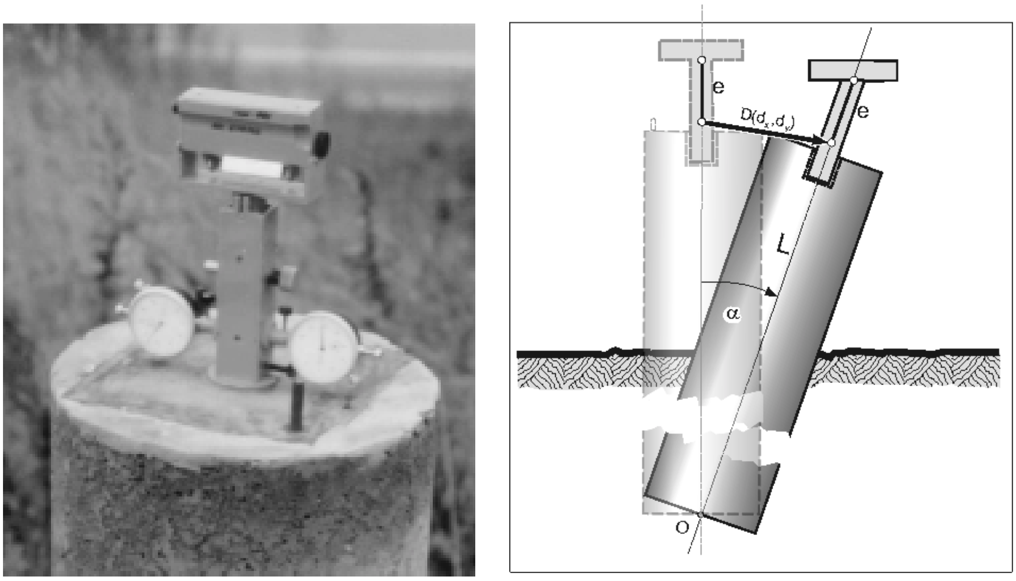

Fig. 2 General inclinometer observation characteristics

The "Śnieżnik" network is made up of 27 points arranged on an area of approx. 100 km sq. – on the Polish (16) and Czech (11) sides of the massif (Cacoń et al., 1996). The points have been stabilised with reinforced concrete pillars fitted with mounts for forced centring of measurement instruments. The location of measurement stations has been correlated with geological and tectonic composition, as well as morphology of the area (Fig. 1.). The pillars have been set directly on crystalline rock outcrops and in cases when this was not possible on foundations placed below ground freezing level. It is worthy to note that two points of the "Śnieżnik" network, Stroma (6) and Vyhlidka (23), stabilised on crystalline rock outcrops, have been included in the regional, international, geodynamic investigations of the Sudety Mts. within the "SUDETY" network (Schenk et al., 2002).

3. GENERAL MEASUREMENT PRINCIPLES

3.1. SATELLITE GPS MEASUREMENTS

The GPS measurements of the entire "Śnieżnik" network (Fig. 1.) were performed in years 1993 and 2003. In year 1993 the measurements were carried out with identical apparatus consisting of 5 Ashtech MD-XII receivers and ASH700228D antenna sets from the 7th to 10th of September in 1h sessions. Static method was used and each point was measured at least in two sessions. In 2003 measurements were realized simultaneously on all of the points in two 10h sessions on the 16th and 17th of May but with various measurement instruments from Ashtech, Leica and Trimble (Table 1).

3.2. OBSERVATIONS OF THE STATIONS' SELF-MOVEMENTS

Measurements with self-developed inclinometer (Cacoń and Ćmielewski, 1992) were realized to evaluate stability of the observation stations in years 1993 and 2003. With the help of this instrument, placed in the centring bush of the pillar's mount, current horizontal position of the centre mark can be determined (Fig. 2.). The points 1 (Śnieżnik) and 21 (Králický Sněžník) were excluded from measurements because of atypical construction (adopted stations). Comparison of the results from successive obser-

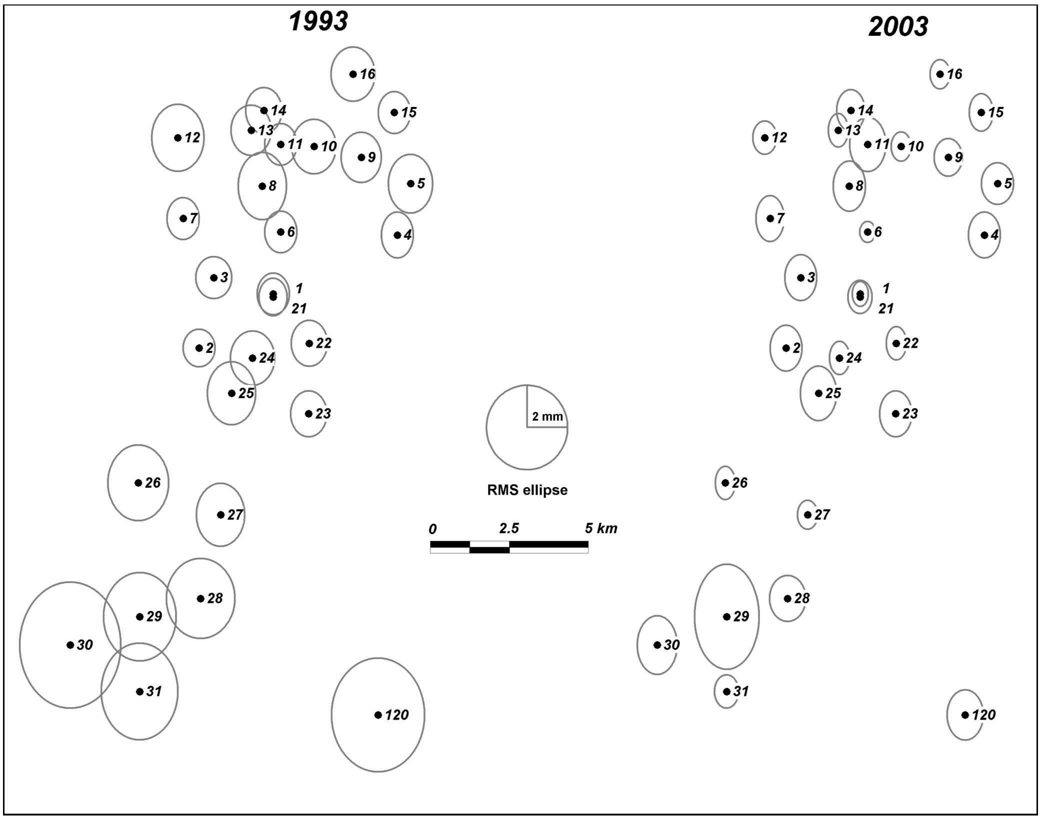

Fig. 3 The results of ŚNIEŻNIK network processing in the years 1993 and 2003 (error ellipses)

vations allowed calculations of the centre marks changes in a horizontal coordinate system N, E. The principles of determining components d_x, d_y were presented by Jamroz (2000).

4. PROCESSING OF SATELLITE GPS MEASUREMENT RESULTS FROM THE 1993 AND 2003 CAMPAIGNS

The results of satellite GPS measurements have been processed with Ashtech Office Suite v.2.0 software (AOS, 1999) using antenna phase center models from NGS (Mader, 1999).

The networks have been adjusted as quasi-free, adopting STRO point coordinates from solution of the SUDETY network (Schenk et al., 2002) in the ITRF2000 system (Altamimi et al., 2002). The estimation of position determination accuracies for "Śnieżnik" network points is shown as error ellipses for horizontal components (Fig. 3.).

The results indicate tangible increase of accuracy for the 2003 network solution in relation to the 1993 network. Global indicators, in the form of maximum RMS errors for particular components (topocentric coordinates), confirmed also higher accuracy of the vertical component in year 2003 (Fig. 4).

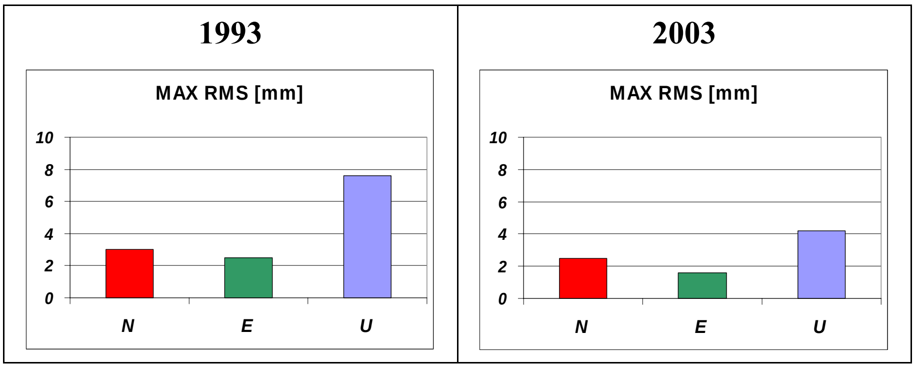

Fig. 4 Estimation of the accuracy of GPS observations in the ŚNIEŻNIK network in the year 1993 and 2003 (maximum errors of coordinate components)

Table 2 Length and azimuth of horizontal displacements of the ŚNIEŻNIK network points

POINT	GPS				Clinometer			Resultant change	
	D[mm]	**Azimuth [g]**	**RMS of D [mm]**	**RATIO**	**D [mm]**	**Azimuth [g]**	**RMS of D [mm]**	**D [mm]**	**Azimuth [g]**
1	3.7	315.7	0.9	4.1	-	-		3.7	316
2	**2.3**	**355.3**	**1.2**	**1.8**	1.8	308.0		1.5	14
3	13.6	303.6	1.1	12.0	24.8	398.2		27.2	231
4	6.8	311.0	1.1	6.0	2.7	316.7		4.1	307
5	17.4	327.2	1.4	12.2	2.0	150.0		19.3	330
6	**3.1**	**194.3**	**1.1**	**2.8**	1.3	236.1	0.1	2.2	171
7	15.6	186.7	1.5	10.6	9.9	58.6		21.8	214
8	**3.1**	**196.4**	**2.0**	**1.6**	2.3*	244.2*		2.1	141
9	12.6	321.1	1.3	10.0	11.4	282.0		7.3	392
10	4.4	269.8	1.3	3.4	1.2	268.2		3.1	271
11	5.9	66.8	1.3	4.7	10.3	173.2		12.3	5
12	13.5	190.2	1.8	7.6	12.8	99.9		17.3	243
13	Mechanical damage to the point								
14	26.6	212.0	1.5	18.0	14.3	182.9		15.1	240
15	13.5	260.6	1.1	12.2	5.2	276.4		8.5	251
16	9.4	221.1	1.4	6.7	19.4	64.5		27.4	251
21	**1.0**	**27.7**	**1.1**	**0.9**	-	-		1.0	27
22	9.0	262.4	1.1	8.0	0.0*	0.0*		9.0	263
23	6.0	362.5	1.5	4.1	0.0*	0.0*		6.0	363
24	**2.7**	**79.4**	**1.2**	**2.2**	0.0*	0.0*	0.1	2.8	79
25	**2.4**	**46.7**	**1.7**	**1.4**	0.0*	0.0*		2.4	46
26	27.4	224.3	1.9	14.5	28.6*	214.8*		4.3	337
27	5.4	321.4	1.3	4.0	0.3*	150.0*		5.7	323
28	5.2	321.7	1.9	2.7	13.1	242.4		12.4	16
29	3.8	19.1	3.2	1.2	4.1	267.7		7.3	44
30	4.1	275.5	2.8	1.5	4.3	236.2		2.6	360
31	6.4	113.9	2.0	3.2	6.1	80.8		3.3	191

* observations realized in years 1992-2003

5. CALCULATION OF THE HORIZONTAL DISPLACEMENT OF POINTS IN THE 1993-2003 PERIOD

5.1. DISPLACEMENTS FROM GPS MEASUREMENTS

The horizontal displacements of the SNIEZNIK network points, calculated, as changes of coordinates acquired from GPS measurements were determined in a local, topocentric system defined by a reciprocally stable reference points. The group of points, meeting the reciprocal stability criterion for the mutual congruency test, located on a single crustal block has been adopted as reference points (Kontny, 1999). These are points: 2, 6, 8, 21, 24, 25, for which residual displacement vectors (congruency fitting deviations) do not exceed triple estimation error values. The calculated horizontal displacement vectors for SNIEZNIK network points in the 1993-2003 period are given in Table 2 (lengths and azimuths of vectors). The points selected as references are marked in bold. Several centimeters' of displacement for point 13, resulting from mechanical damage of the observation pillar construction, excluded the point from further analyses.

5.2. STABILITY ASSESSMENT OF POINTS FROM INCLINOMETER OBSERVATIONS

The results of clinometric measurements (Table 2) indicate self-motion of observation pillars for points: 3, 7, 9, 11, 12, 13, 14, 16 on the Polish side of the network and for points: 26, 28, 29, 30, 31 on the Czech one. The observed, several centimeters' of relative movement of point 13's head has been caused by mechanical damage to the pillar. The point was excluded from further analyses, similarly as in the case of GPS measurements. Inclinations of stations 9, 11 and 16 should be linked with the effects of the 1997 flood (Jamroz, 2000).

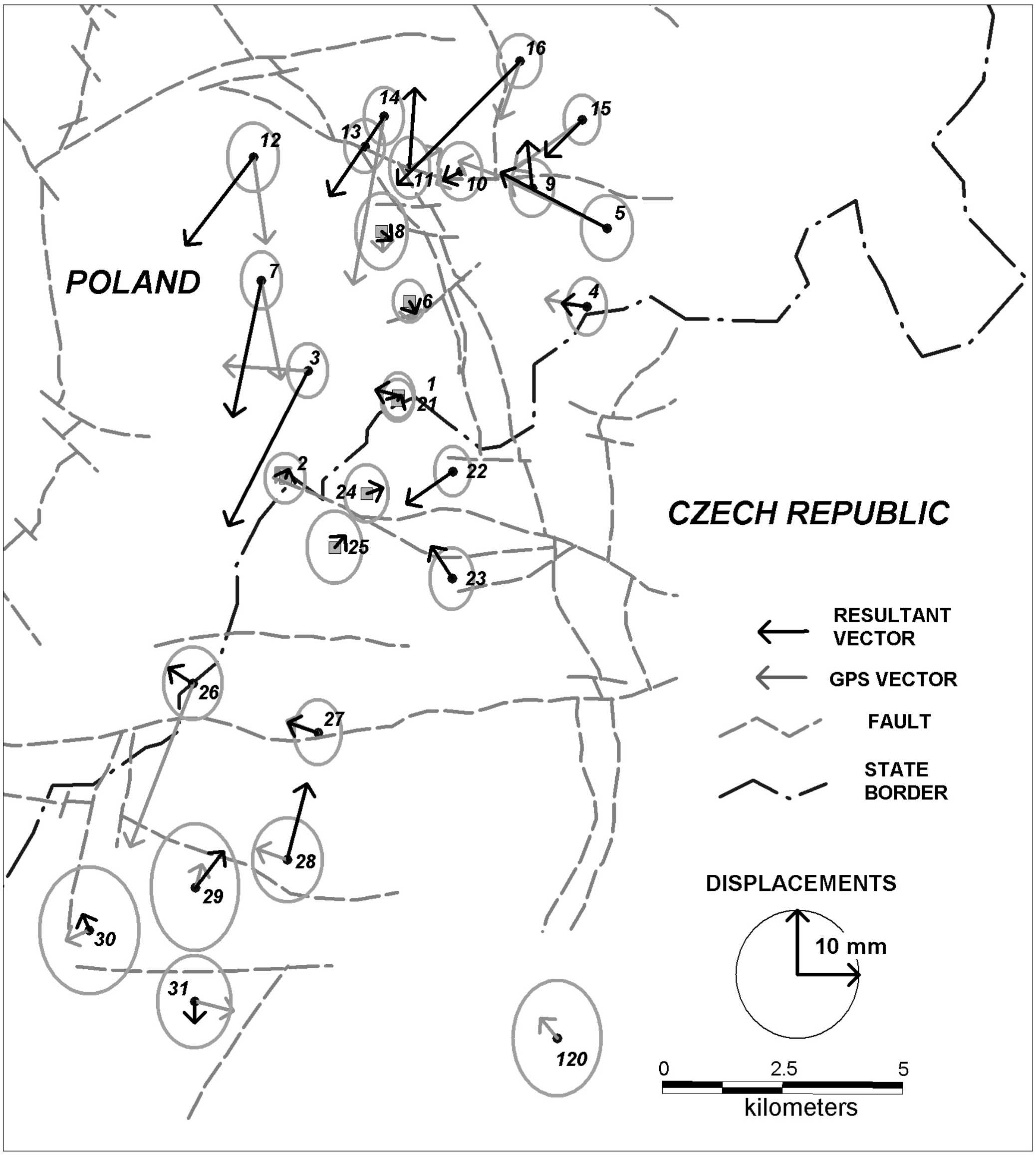

Fig. 5 The resultant horizontal displacements of the ŚNIEŻNIK network points (1993-2003)

The stations 2, 6, 10 and 22, 23, 24, 25 show stability since stabilisation in 1992. Inclination of station 12, located on an outcrop of gneiss rocks and amounting to 12.8 mm towards east, may be caused by disturbance of rock structure during installation of viewing tower on the top of Czarna Góra. Inclinometer observations realized on point 26 indicate that it is not stable. The 28.6 mm change value in the southern direction (consistent with the slope inclination) and "shaking" of the pillar during the actual measurement imply probable separation of its foundation from the bedrock.

5.3. ANALYSIS OF POINT DISPLACEMENTS

The resultant horizontal displacement vectors of research points including components of the stations' inclination changes are presented in Table 2 and in Fig. 5. These show relatively higher movements of certain points in the northern (Polish) part of the network and lower in the southern part (Czech). The displacement values are within 1 to 27.4 mm limits but vector directions are divergent.

The displacements of point 26 (KLEP) were evaluated by comparisons of the results from all the campaigns realized between 1992 and 2003. Time series of single coordinate components in local system (N, E. U) were computed from differences between adjusted spatial coordinates in each campaign. There are obvious problems of lower result confidences in the earlier campaigns (1992 – 1995) caused by shorter observation times and incomplete, at that time, GPS satellite constellation. More inconsistencies could have been introduced by combination of different receivers/antennas as calibration uncertainties. The early analyses had already revealed distinctly outstanding behavior of point KLEP in relation to neighbouring points. The trend was corroborated by the campaigns that followed. Displacements, mainly

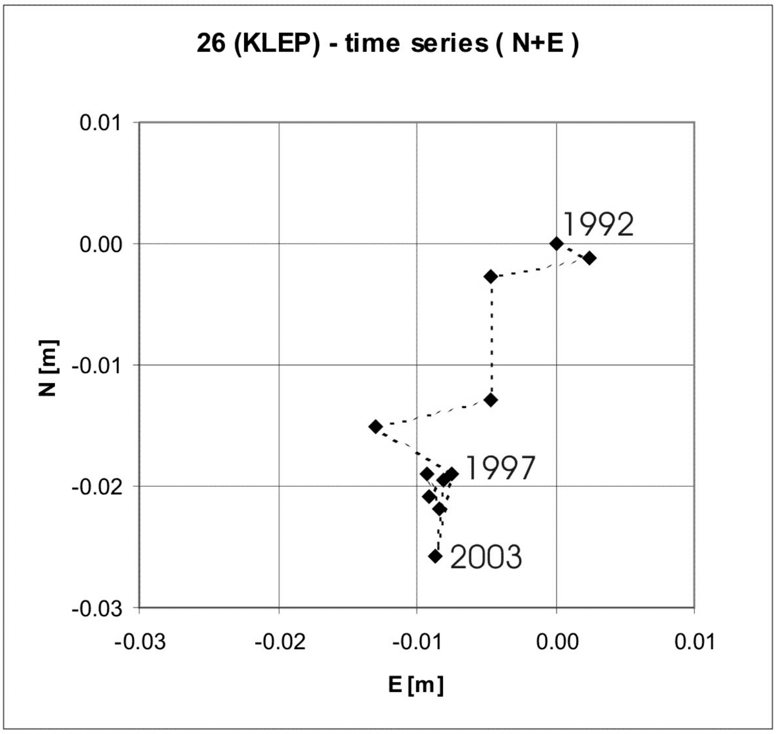

Fig. 6 Time series of horizontal coordinate components (N, E) of point 26 (KLEP) during the 1992-2003 period

in the north-south directions, were accompanied by oscillating vertical movements. The highest values of displacements were registered in the 1992 – 1997 period (Švábenský and Weigel, 1999). In the following years (Švábenský and Weigel, 2000), till present time, the point stabilized and the values of recorded movements decreased. The cause of displacements is not clear and must be investigated in greater detail. Total measured movements reached 26 mm in north-south and 12 mm in east-west directions (Fig. 6).

5.4. INTERPRETATION OF POINT DISPLACEMENTS

The values of point displacements, reduced by the influence of observation pillars' inclinations were used to isolate groups of points with similar character of movement. Cluster analysis, the same as in the paper (Dąbrowski and Jamroz, 2000), was applied. Four-dimensional variable derived from standardized horizontal coordinates and horizontal components of displacements, which guaranteed spatial homogeneity of the selected groups, has been adopted for variable analysis (Kontny et al., 2003). The outcome of grouping is shown as a hierarchical binary tree *(StatSoft, 2004)* – dendrograph (Fig. 7.) and a map of the points making up each group (Fig. 8.).

Four distinctly different groups of points (Fig. 7.) were identified. Spatial arrangement of the groups does not fully correspond with the locations of tectonic structures (Fig. 8.). This is particularly true of points: 3, 7, 12, 14, 16 which are situated on both sides of main tectonic structure in the area – the Bystrzyca - Nove Mesto fault zone – (Don, Opletal, 1996) and demonstrate similar character of movement. Incomplete, as yet, identification of the Śnieżnik Massif tectonic structures may be one of the reasons for this situation. Prospective geological, geodynamic and also other investigations should allow verification of this theory.

6. CONCLUSION

The analysis and interpretation of the research network points' deformations, identified as changes of the uppermost lithosphere layer in the Śnieżnik Massif, basing on the results of two satellite GPS observation cycles in the years 1993 and 2003, yielded a number of cognitive and utilitarian conclusions. From the methodical point of view, observations of self-movements of the research points united with geological structures by means of concrete pillars furnished with heads for forced centring of instruments have proved to be very important. The observations confirmed that despite meticulous realization of the points' stabilization process that was to ensure their stability, in reality has proved to be to some extent ineffective. Thanks to the application of self-developed methodology and instrument for observations of points' self-movements quantitative data was obtained. It allowed the data to be included and separated from the displacement values determined by repeated GPS observations.

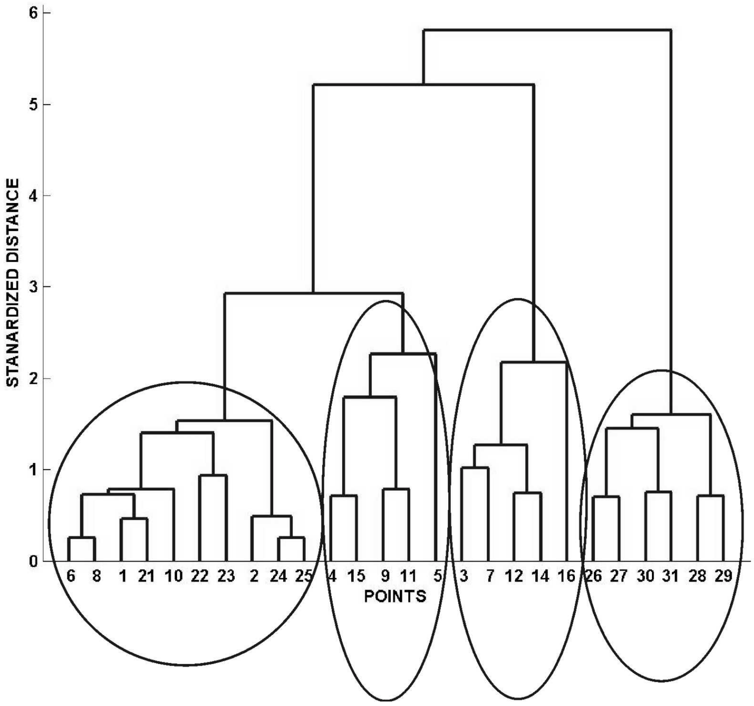

Fig. 7 Hierarchical binary tree (4 parameters: x, y, dx, dy)

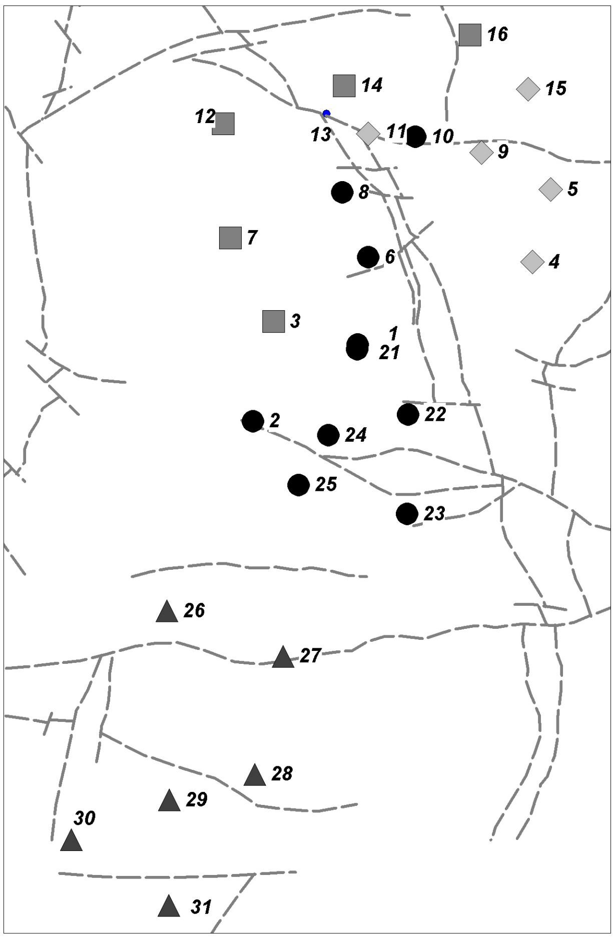

Fig. 8 Result of cluster analysis (4 parameters: x, y, dx, dy)

The horizontal displacements of the Śnieżnik Massif's uppermost lithosphere layer determined for the 1993-2003 period range from 1.0 to 27.4 mm, at the same time displacement vectors are not uni-directional. On these grounds four groups of points were isolated that, in the analysed period, show different character of movement. This may be a sign of the complex deformation character in the Śnieżnik Massif and probably incomplete identification of the region's geological and tectonic composition.

Possible application of the measurement methodology and result processing on other geodynamic objects and in deformation observations of engineering objects (e.g. water dams, underground and opencast mines, etc.) is also well worthy to note.

REFERENCES

Altamimi, Z., P. Sillard, and C. Boucher: 2002, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science application, J. Geophys. Res., 107(B10), 2214, doi : 10.1029/2001JB000561, 2002.

AOS (1999) Aschtech Office Suite User's Manual. Version 2.0 Magellan Corporation USA and Terrasat GmbH,Germany.

Cacoń, S. and Ćmielewski, K.: 1992, Thimble Inclinometer. Utility Model of the Polish Patent Office RP-9544. Bulletin of the Polish Patent Office, Vol. 25 pp .5, (in Polish).

Cacoń, S., Weigel, J., Švábenský, O., Kontny, B. and Jamroz, O.: 1996, Geodynamic structure of the Massif of Śnieżnik and the adjacent areas, [in] The Massif of Śnieżnik – Changes in natural environment, Polish Ecological Agency Publ. (monography), Warsaw (in Polish), pp. 57-70.

Cacoń, S. and Kontny, B.: 1994, Measurement and monitoring system for deformation investigation of lithosphere of natura and engineering objects In Sudety Mountains, Proceed. of 1st Turkish Int. Symp. On Deformation, Sept.5-9, 1994, Stambul , pp.97-104.

Dąbrowski, A. and Jamroz, O.: 2000, Statistical evaluation of the Śnieżnik Massif deformations, Reports On Geodesy No. 7 (53), Warsaw University of Technology, Institute of Geodesy and Geodetic Astronomy, pp. 59-65.

Don, J. and Opletal, M.: 1996, Structure and geological evolution of the Massif of Śnieżnik, [in] The Massif of Śnieżnik – Changes in natural environment, Polish Ecological Agency Publ. (monography), Warsaw (in Polish), pp. 13-26.

Jamroz, O.: 2000, Monitoring of uppermost lithosphere layer changes in the Śnieżnik Klodzki Massif, Sci. Papers of the WUofA, Ser. Geodesy and Agricultural Equipment XVI, No. 379, pp. 51-83. (in Polish).

Kontny, B.: 1999, Reference frame control for deformation measurements of open pit mine, Proc. 9th FIG International Symposium on Deformation Measurements, September 27-30 1999, Olsztyn, Poland, pp. 125-132.

Kontny, B., Bosy, J. and Borkowski, A.: 2003, Correlation between EPN station velocities and the tectonics of Europe, Artificial Satellites, Journal of Planetary Geodesy (in print).

Mader, G.L.: 1999, GPS Antenna Calibration at the National Geodetic Survey. GPS Solutions, Vol. 3, No. 1, pp. 50-58.

Schenk, V., Cacoń, S., Bosy, J., Kontny, B., Kottnauer, P. and Schenková, Z.: 2002, The GPS geodynamic network East Sudeten. Five annual campaigns (1997–2001) Data processing and results. Acta Montana, Ser. A. Geodynamics, No 20 (124), Praha 2002, pp. 13–23.

StatSoft, Inc.: 2004,. Electronic Statistics Textbook. Tulsa, OK: StatSoft. WEB: http://www.statsoft.com/textbook/stathome.html.

Švábenský, O. and Weigel, J.: 1999, Local Geodynamic Network „Sněžník“. Exploration Geophysics, Remote Sensing and Environment VI. 2 (1999), p. 4-7.

Švábenský, O. and Weigel, J.: 2002, 10 Years Monitoring of Sněžník Massif - Changes in Czech Part of the Network. Acta Montana IRSM CAS CR (2002) Series A Geodynamics No. 20 (124), pp. 7-11.