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METHODIC ANALYSIS OF DATA OBTAINED BY MONITORING MICRO-TECTONIC MOVEMENTS WITH TM-71 CRACK GAUGES IN THE POLISH SUDETEN

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ABSTRACT

On the Polish side of the Sudeten more than ten TM-71 crack-gauges, constructed by Kostak, have been installed for micro-movement monitoring since the 70'ties of the 20th Century. The first instruments were installed for monitoring of gravitational movements of rock blocks on Szczeliniec Wielki Massif in the Table Hills Mts. Later the gauges were installed to detect micro-tectonic movements in Bear Cave near Stronie Słaskie, and the last ones in Dobromierz, Zloty Stok, and Janowice Wielkie. Time series of the data obtained with these TM-71 gauges have been analysed regarding:

- Linear trend analysis using Least Squares method and M-estimation (robust method);
- Frequency component analysis using discrete Fast Fourier Transform;
- Temperature dependency analysis with the help of correlation coefficient estimation;
- Detection of episodic movement and analysis of correlation with earthquake occurrence.

Results of the analysis show that series of observations several years long enable estimation of linear trends. At most sites in the Sudeten only slow relative movements (below 0.1 mm/year) are detectable. However, results from one site (Dobromierz) show horizontal movements higher than 2 mm/year. Estimation of periodicity requires longer (more than 10 years) data series without many data gaps. One-year periodicity is dominant due to seasonal temperature variations, longer periods are also detectable (e.g. ca 12 years). Some echoes of earthquakes are also detectable in the time series of the TM-71 data.

KEYWORDS: active faults, monitoring, Sudetic Fault Zone

1. INTRODUCTION

Control-measurement system concept of movement detection published by Cacoń and Kontny (1994) is based on three accuracy levels in measurements. Relative measurements in it constitute its third and the most accurate segment. Such relative measurements in the system can be introduced using extensometers, inclinometers, crack gauges, tilt meters, etc. In the research geodynamic networks established in Lower Silesia, particularly in the Polish part of the Sudeten, such relative measurements are performed using TM-71 feeler or crack gauge of Košťák construction (Košťák, 1991). In the period between 1974 and present, eleven crack gauges of this type were installed in the studied area. The three first and oldest instruments were installed in the Szczeliniec Wielki Massif in Table Hills Mts. to observe rock block movements. Later, such gauges were setup in the Bear Cave near Stronie Sląskie (3 instruments) on local faults in the Snieżnik Massif. The newest application of the crack gauges is in the Sudetic Marginal Fault zone: in the old adits of Złoty Stok gold mine (2 instruments), in the area of the Dobromierz Dam (2 instruments) and in an old adit near Janowice Stare - located in the Intra-Sudetic Fault zone (1 instrument). Location of the TM-71 gauges in the Polish part of the Sudeten close to the Czech frontiers is shown schematically in Fig. 1.

The oldest crack gauges were observed for 30 years with one-month measurement frequency, the newest ones provided only dozen or so observation epochs. Data series obtained from selected instruments, observed for at least two years, were analysed regarding linear trends and periodicity changes, temperature correlation of the observation results and analysis of episodic interference events into the observed data. Results of the analysis were interpreted regarding the character of movement on the observed tectonic structures.

2. DESCRIPTION OF THE TM-71 MEASUREMENT DATA

Construction of the TM-71 gauge and its operation has been described by Košťák (Košťák, 1971). The gauge is equipped with two pairs of glass plates, one in horizontal and the other one in vertical positions that bear etched diffraction grids. The grids are in superposition attached to the opposite rock blocks via solid holders. Thus the holders mounted into boreholes bridge over the fissure and transfer displacements of the opposite blocks into the gauge (Fig. 2a). Relative movements are then observable in

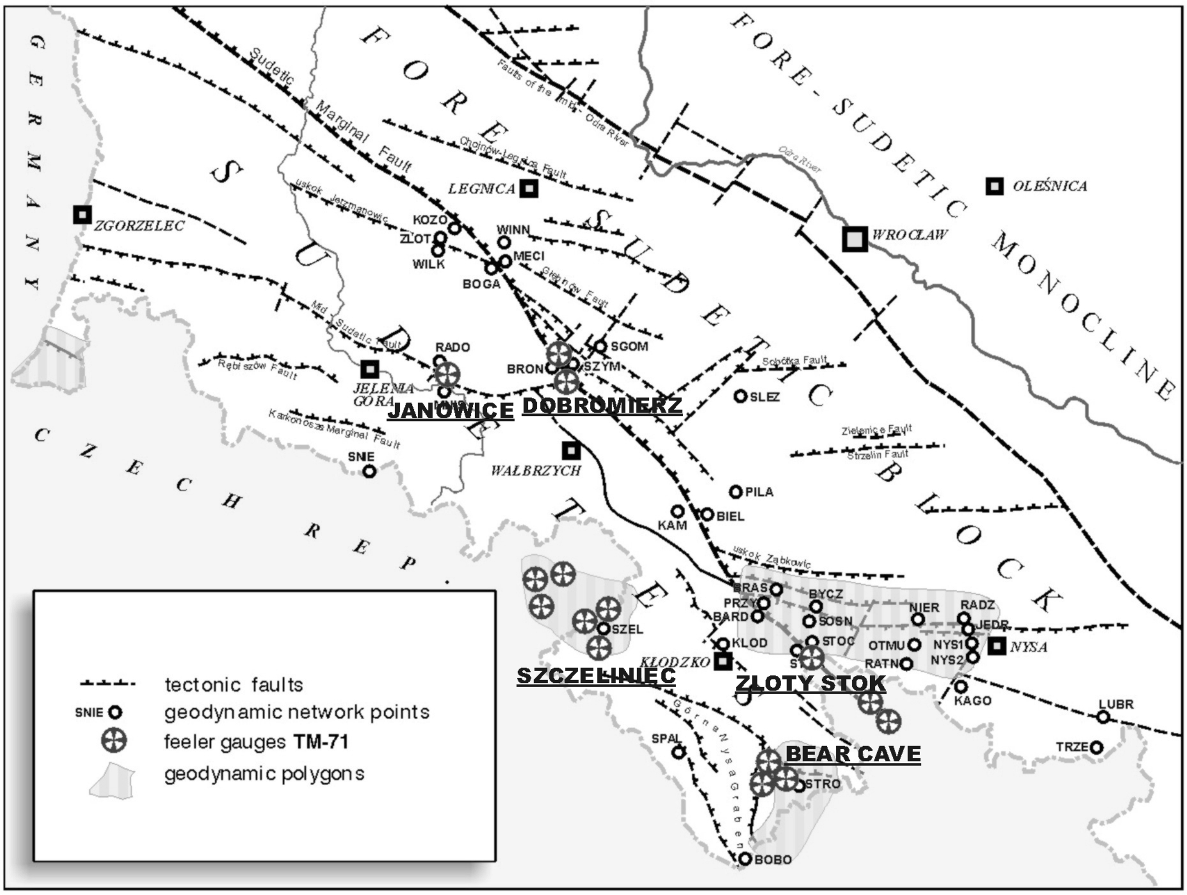
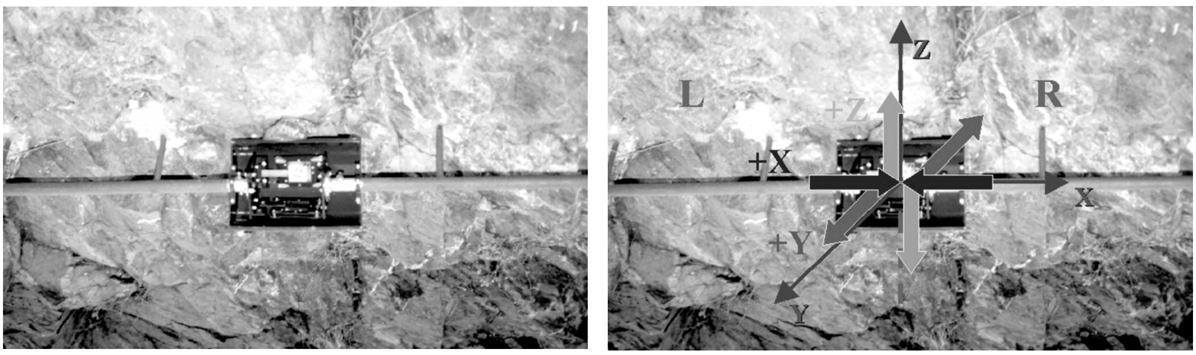


Fig. 1 Location of the TM-71 gauges in the Polish Sudeten



a) **b)**

Fig. 2 The TM-71 crack gauge: a) general view, b) orientation of measurement axes

Table 1 TM-71 „Dobromierz 1" measurement data (displacements in components X,Y,Z, and total vector length U in mm, inclination R in π /200)

DAY	MONTH	YEAR	DATE	T [°C]	X	Y	Z	U	RXZ	RXY
30	11	2001	2001.915525	8	-0.385	0.202	-0.321	0.54	-0.022	0.01
12	12	2001	2001.949543	5	-0.283	1.325	-0.695	1.523	-0.022	0.01
26	1	2002	2002.071233	7	-0.352	1.584	-0.665	1.754	-0.029	0.023
18	2	2002	2002.132648	4	-0.389	1.566	-0.687	1.753	-0.017	0.054
5	3	2002	2002.180365	6	-0.329	1.568	-0.658	1.732	-0.026	0.05
22	3	2002	2002.226941	4	-0.435	1.566	-0.655	1.752	0.013	0.01
6	4	2002	2002.266438	-1	-0.465	1.641	-0.705	1.845	-0.008	0.049
23	4	2002	2002.313014	12	-0.21	1.988	-0.848	2.171	0.008	-0.039
13	5	2002	2002.368950	18	-0.257	1.938	-0.801	2.113	-0.004	0.023
2	7	2002	2002.505479	24	-0.285	2.116	-0.915	2.323	-0.017	0.02
26	7	2002	2002.571233	24	-0.225	2.22	-0.934	2.419	0.008	0.05
17	8	2002	2002.629909	27	-0.214	2.173	-0.838	2.339	0.009	0.08
12	9	2002	2002.699543	18	-0.237	2.191	-0.834	2.356	0.013	0.037
23	9	2002	2002.729680	14	-0.608	2.82	-1.138	3.101	0.036	-0.011
9	10	2002	2002.774658	9	-0.516	2.99	-1.17	3.252	0.009	-0.028
23	10	2002	2002.813014	13	-0.562	2.685	-1.16	2.978	0.026	0.023
18	11	2002	2002.882648	7	-0.743	3.086	-1.302	3.431	0.039	0.023
20	12	2002	2002.971461	-2	-0.82	3.27	-1.446	3.669	0.056	0.018
24	2	2003	2003.149087	5	-0.834	3.812	-1.763	4.282	0.027	0.071
11	3	2003	2003.196804	14	-0.69	3.677	-1.581	4.062	0.027	0.084
21	3	2003	2003.224201	2	-0.636	4.021	-1.638	4.388	0.055	0.101
22	5	2003	2003.393607	16	-0.528	4.48	-1.731	4.832	0.055	0.06
26	6	2003	2003.487900	24	-0.61	4.363	-1.719	4.729	0.055	0.08
28	7	2003	2003.576712	27	-0.594	4.498	-1.731	4.856	0.055	0.117
25	8	2003	2003.651826	24	-0.582	4.462	-1.708	4.814	0.055	0.107
17	9	2003	2003.713242	15	-0.755	4.572	-1.786	4.967	0.055	0.112
3	10	2003	2003.758219	15	-0.678	4.614	-1.769	4.988	0.055	0.121
11	12	2003	2003.946804	5	-1.255	5.53	-2.285	6.113	0.055	0.085
16	1	2004	2004.043836	2	-1.145	5.709	-2.302	6.261	0.055	0.15

the transformation of the moiré pattern on the plates and can be registered on photosensitive paper or photography - analogue or digital. The accuracy of measured displacement of the plates in relation to each other is estimated to be approximately 0.01 mm.

The arrangement of the plates in the instrument enables measurements in three perpendicular directions: X, Y, Z (Fig. 2b). The X-axis is oriented along the holders, usually horizontally and perpendicularly to the plane of the fissure. Positive value of distance change (measurement value) indicates shortening of the distance (fissure or crack closing). The Y-axis is oriented perpendicularly to the X-axis in the horizontal plane indicating lateral movement. The Z-axis is oriented vertically and the measured value represents vertical displacement between the left and right holders. Generally, the gauge can be mounted arbitralily in space and positive meaning of the resulting displacements recalculated regarding the fissure and gauge orientation. Most usual arrangement of the gauge is represented with Fig. 2b.

Readings or photographs are taken at regular time intervals, usually once a month. The date and hour of the measurements as well as temperature of its surroundings are recorded with the interference pattern. The spatial components of changes between holder ends are calculated from changes found between interference patterns during successive readings. Correction to temperature is calculated to compensate expansion of the steel holders. The newest type of TM-71 crack gauge enables also registration of the changing inclination between holders in two perpendicular planes (XY and XZ). An example of data obtained from the instrument placed in Dobromierz is given in Table 1.

The analysis which is going to be given and discussed is based on data from measurement sites of the following crack gauges:

(a) "Schronisko" („Shelter House") and "Piekielko" ("Hell") installed in the Szczeliniec Wielki Massif in the Table Hills Mts.;

(b) "Korytarz Wodny" ("Water Corridor") and "Kaskad" ("Cascade Alley") in the Bear Cave;

(c) "Dobromierz 1", "Zloty Stok" in the Sudetic Marginal Fault Zone;

(d) "Janowice" in the Intra-Sudetic Fault Zone.

Observation period of the remaining crack gauges has been too short (the third gauge in the Bear Cave and the second one in the Zloty Stok gold mine) or data affected by additional anthropogenic factors (the third instrument on the Szczeliniec Wielki and that of Dobromierz Dam gallery).

Table 2 Velocity components of the selected TM-71 crack gauges

	LS estimation			Robust M-estimation		
Gauge	VX (mm/y)	VY (mm/y)	VZ (mm/y)	VX (mm/y)	VY (mm/y)	VZ (mm/y)
SCHRONISKO	+0.01	+0.00	-0.01	+0.01	+0.00	-0.01
PIEKIEŁKO	+0.15	+0.03	-0.35	+0.14	+0.03	-0.36
KORYTARZ WODNY	+0.01	-0.00	+0.00	+0.01	-0.00	+0.00
KASKAD	+0.00	+0.01	-0.00	+0.00	+0.01	-0.00
DOBROMIERZ 1	-0.34	+2.23	-0.85	-0.32	+2.20	-0.84
ZLOTY STOK	-0.02	+0.03	+0.06	-0.02	+0.05	+0.06
JANOWICE	+0.01	-0.09	+0.01	+0.01	-0.08	+0.01

Table 3 Periodicity parameters of the selected TM-71 gauges

	Length of main period			Magnitude		
Instrument	LX (year)	LY (year)	LZ (year)	AX (mm)	AY (mm)	AZ (mm)
SCHRONISKO	1.0	29 (and 0.5)	1.0	1.0	0.2 (0.06)	0.4
PIEKIEŁKO	12 (and 6)	1.0	12	0.3 (0.2)	0.6	0.5
KORYTARZ WODNY	-	-	-	-	-	-
KASKAD	-	-	-	-	-	-
DOBROMIERZ 1	1.1	1.1	1.1	0.3	0.5	0.2
ZLOTY STOK	-	-	-	-	-	-
JANOWICE	1.2	1.2	1.2	0.06	0.08	0.06

3. METHODS USED FOR TM-71 DATA TIME SERIES ANALYSIS

Time series of data of selected TM-71 crack gauges have been studied by

- linear trend analysis of relative displacements,
- periodicity analysis,
- temperature dependency analysis,
- detection of and analysis of episodic data disturbances.

Linear trend analysis was performed with estimation of linear formulae coefficients approximating data time series. Two independent estimation methods were used: Least Squares (LS) and robust M-estimation method with logistic dumping function (Matlab, 1999). The robust estimation eliminates influence of outliers on the calculated coefficient values. The values of linear formulae coefficients describe the linear velocity of relative motion in the given direction of the instrument measuring axis as well as the initial displacement.

The periodicity analysis was performed using discrete Fast Fourier Transform (FFT). The missing data in time series were calculated using cubic spline interpolation. The calculated frequency and magnitude of periodic changes characterise periodicity of the observed rock block relative motion (eg. on a fault).

The relationship between instrument readings and temperature is given by a correlation coefficient calculated for these data. The correlation coefficient approaching the value of 1.0 indicates very high dependence, coefficient of less than 0.5 signifies lack of such a relationship. Negative value of the coefficient points to an inverse relationship.

In the TM-71 measurement data time series sudden leaps or interruptions in the form of several observations significantly differing from the rest of data (i.e. “data peaks”) may occur.

These disruptions, predominantly short-lived and chaotically spaced in the time scale indicate an influence of episodic factors such as earthquakes. Timing of episodic interferences in observation data of analysed crack gauges were compared with seismic shocks registered by the International Seismological Centre (ISC On-line Bulletin, 2004). Local events of magnitude above 3.0 and distant events (of the Mediterranean Sea Basin origin) of magnitude higher than 6.0 have been analysed.

4. RESULTS OF ANALYSES

Components of the rock block relative motion provided linear velocities. Velocities calculated on the basis of monitored data obtained form TM-71 in the Sudeten and the Fore-Sudetic Block area are given in Table 2. Both estimation methods used produced similar results (max. differences did not exceed the value of 0.03 mm/year). Representative graphs of the linear trend for two selected crack gauges representing the lowest and the highest (“Schronisko”, Table Hills Mts. and “Dobromierz 1”, respectively) movement velocities are shown in Figs. 3 and 4.

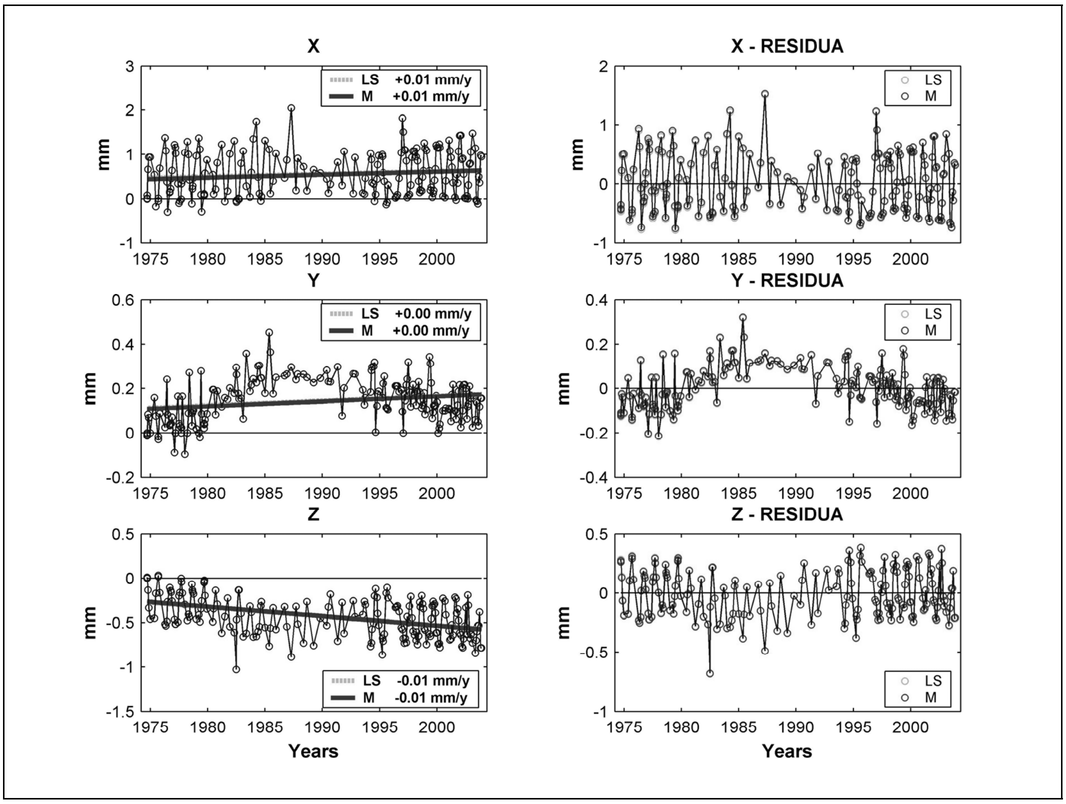


Fig. 3 Graph of the linear trend of "Schronisko" data

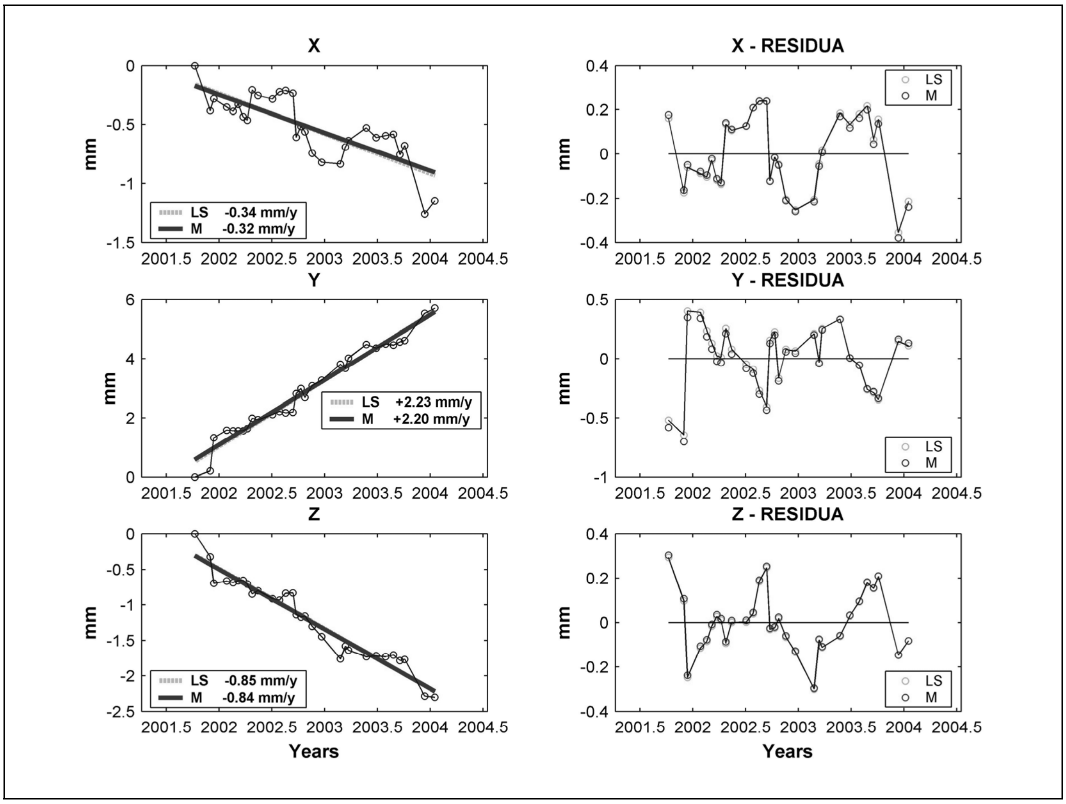


Fig. 4 Graph of the linear trend of "Dobromierz 1" data

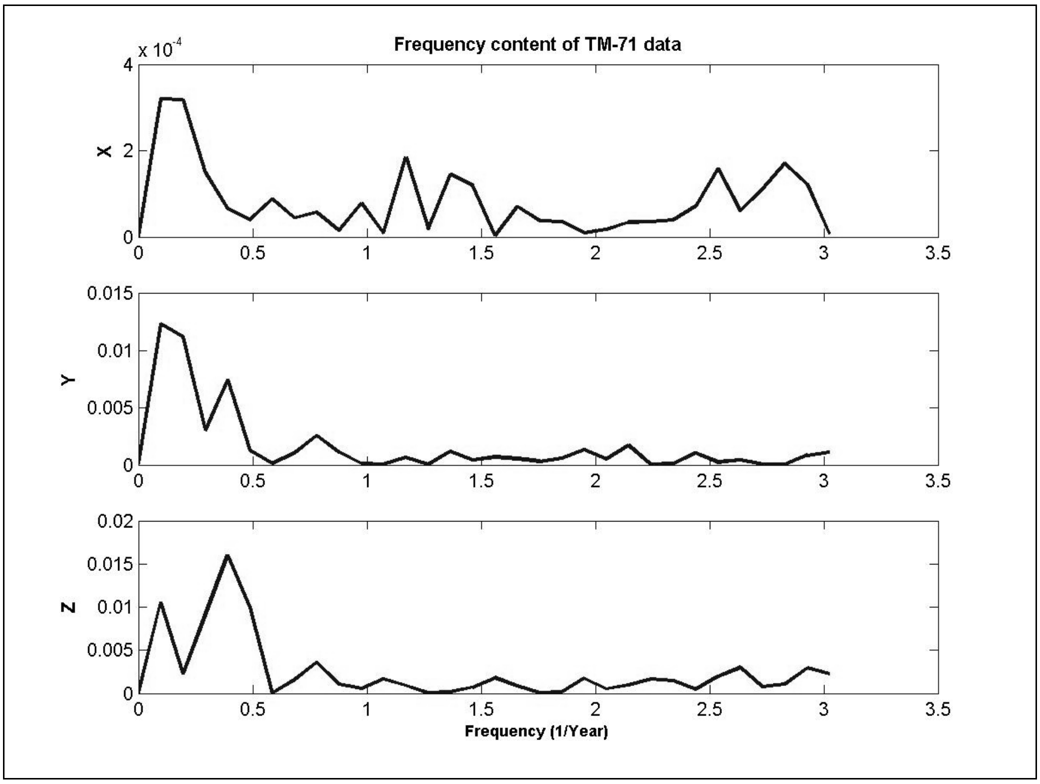


Fig. 5 Frequency spectrum power for “Schronisko”

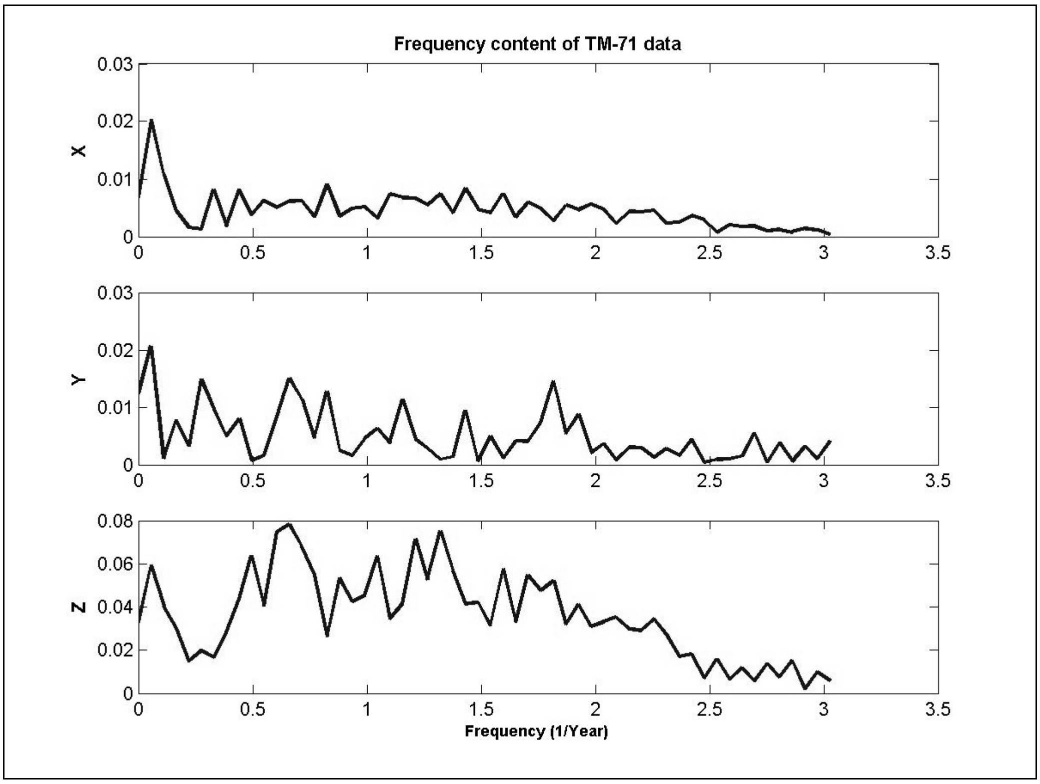


Fig. 6 Frequency spectrum power for “Kaskad”

Table 4 Displacement-temperature correlation coefficients for the selected TM-71 gauges

	Correlation coefficients		
Instrument	X	Y	Z
SCHRONISKO	+0.79	-0.03	-0.58
PIEKIEŁKO	-0.17	+0.70	+0.43
KORYTARZ WODNY	+0.18	-0.02	+0.06
KASKAD	-0.36	-0.08	+0.14
DOBROMIERZ 1	+0.82	-0.43	+0.60
ZLOTY STOK	+0.67	-0.37	+0.07
JANOWICE	-	-	-

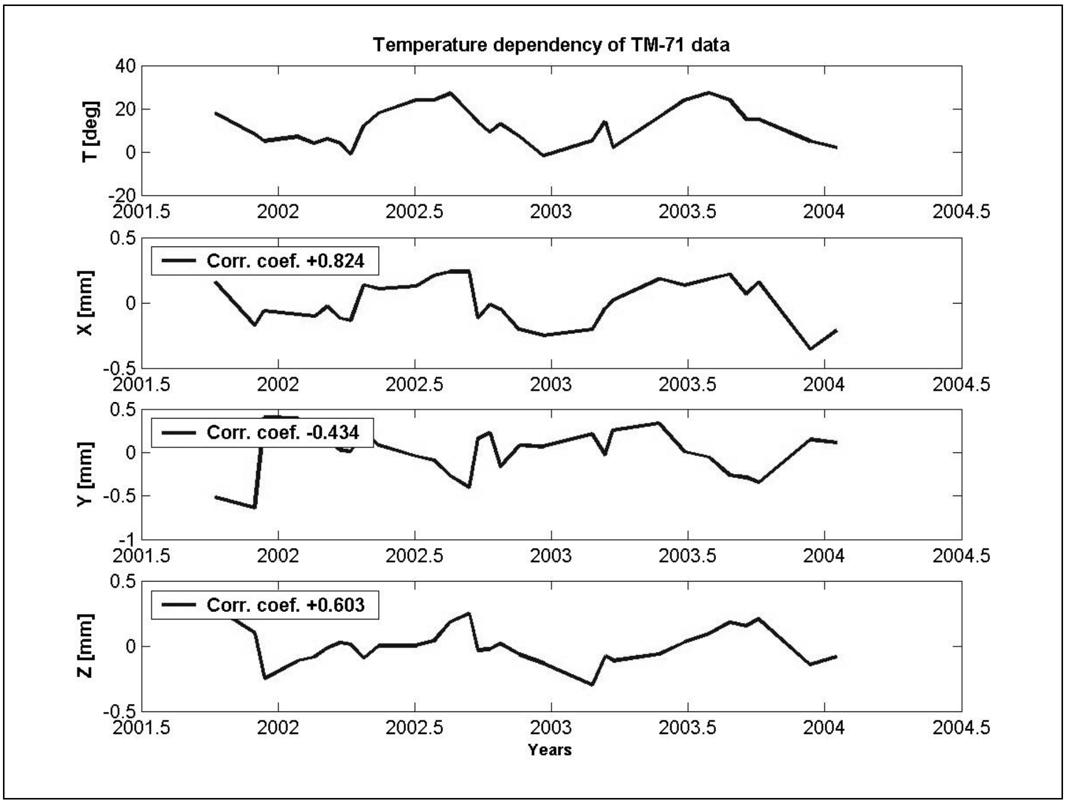


Fig. 7 Graph of the temperature and displacement time series for the "Dobromierz" TM-71 gauge

Frequency spectrum strength calculated with Fast Fourier Transform (FFT) tested data from crack gauges selected for the analysis of graphs and values of magnitude changes for the recorded periodic movements. The values of calculated parameters of changing periodicity are given in Table 3. As an example the "Schronisko" graph obtained for the instrument where observations covered the longest time period is shown in Fig. 5. The graph of spectrum strength for the "Kaskad" gauge located in the Bear Cave can be given for comparison (Fig. 6). No periodicity of relative motion has been found for this instrument.

In case of the crack gauges located under stable environment conditions (cave, adit) no periodicity of relative changes has been found. However, gauges situated outside showed yearly periodicity with dominating seasonal temperature variation. High dependence of data from instruments placed outside on temperature is confirmed by the calculated correlation coefficients (Table 4). To illustrate the relationship between the results and surrounding temperature appropriate graphs for the "Dobromierz 1" crack gauge are shown in Fig. 7. Correlation coefficients for data from "Janowice" could not be calculated as no temperature measurements were taken for this instrument.

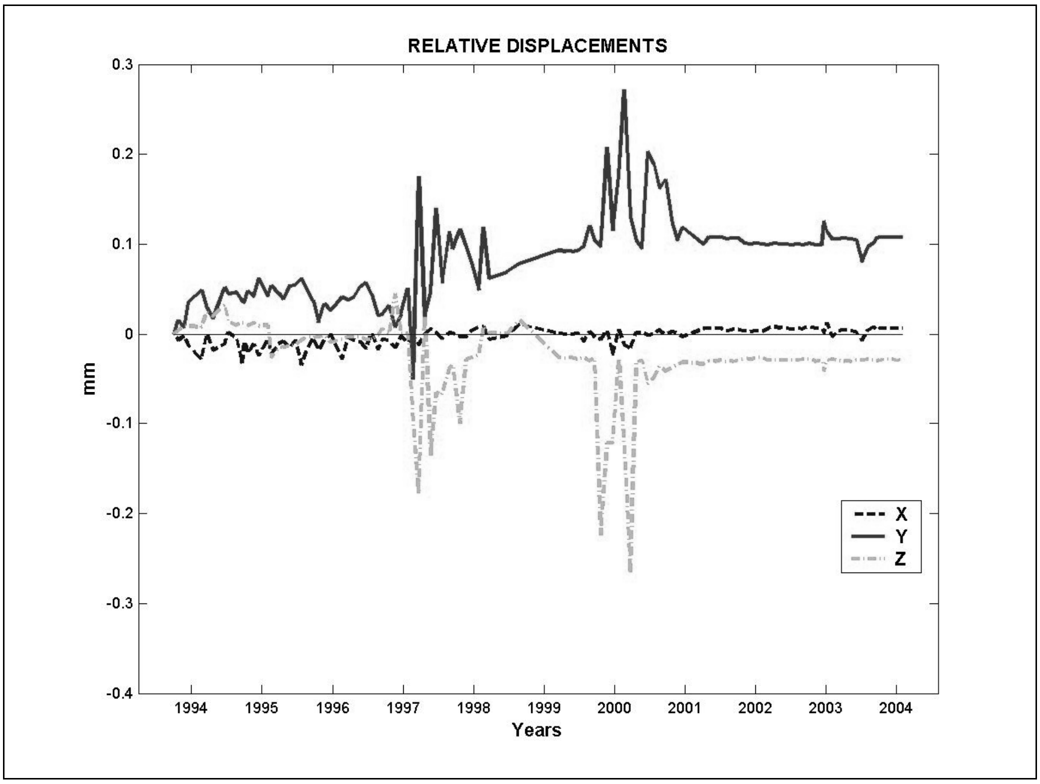


Fig. 8 Kaskad" TM-71 data time series

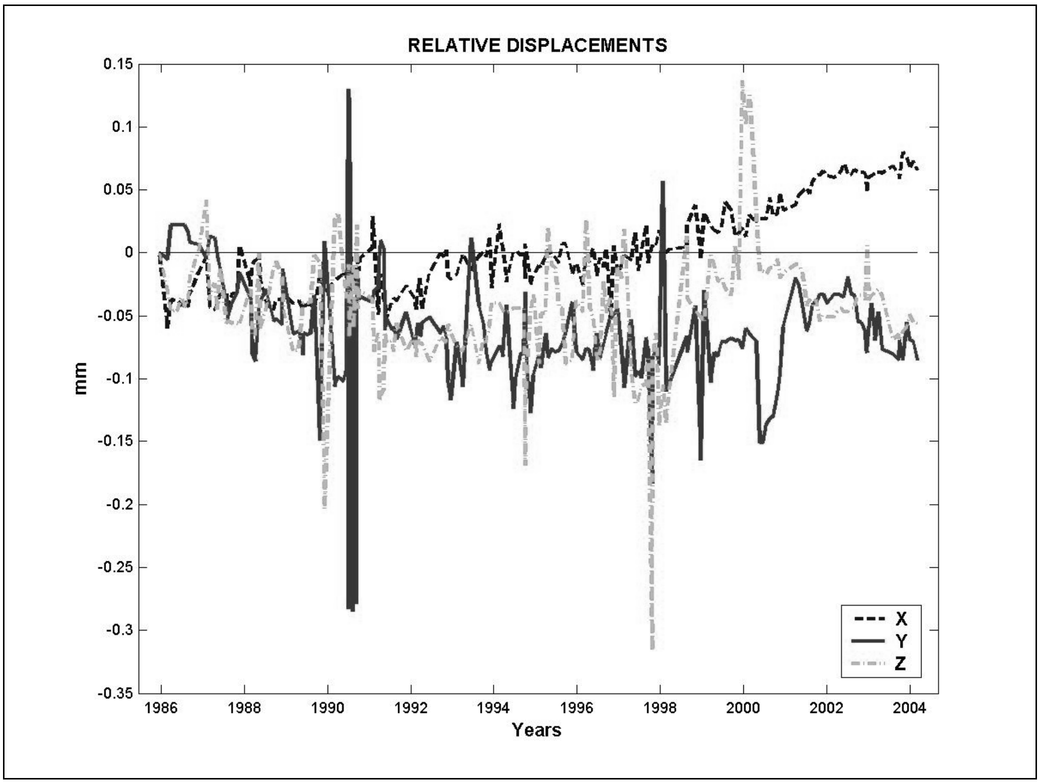


Fig. 9 "Korytarz Wodny" TM-71 data time series

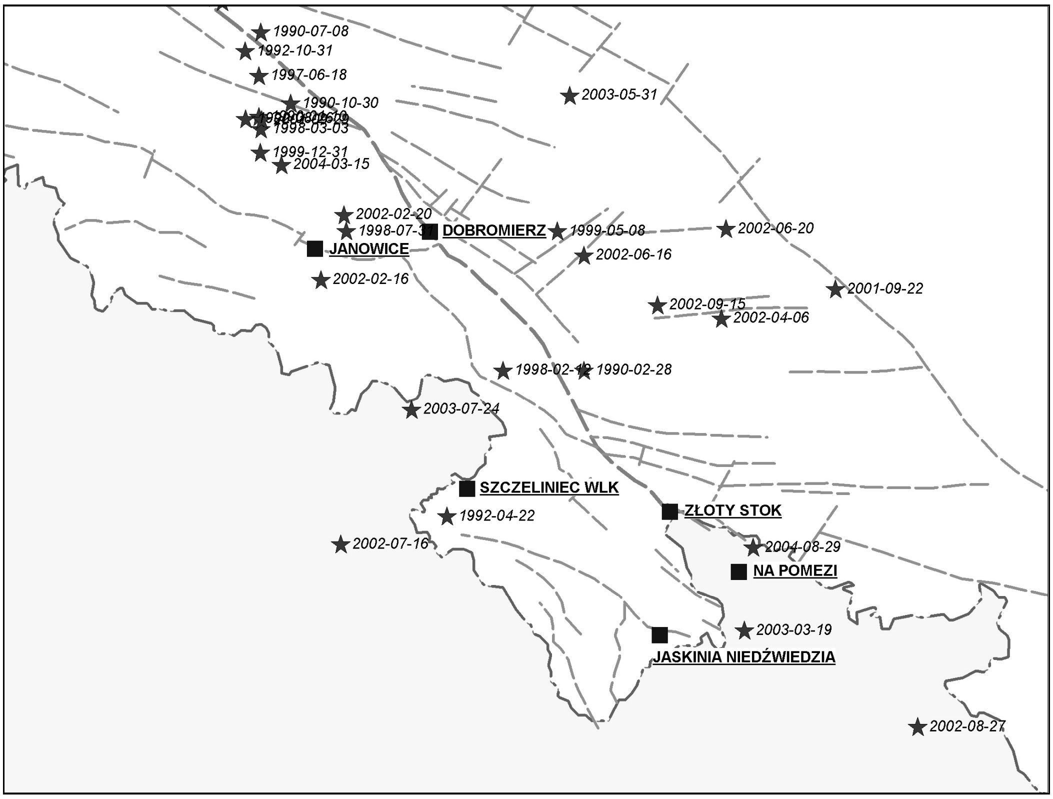


Fig. 10 Probable tectonic local seismic events M>3.0 in the 1989-2004 period

Episodic displacements and data disturbances are clearly visible in data series of crack gauges placed below the Earth's surface, i.e. in the Bear Cave ("Kaskad" and "Korytarz Wodny") as well as in the former gold mine ("Zloty Stok"). Characteristic time series graphs for the instrument data obtained underground are shown in Fig. 8 and 9.

Episodic disturbances in registered graphs are most likely to be connected with seismic shocks. Locations and dates of local earthquakes of magnitude 3.0 or higher, having tectonic character registered in the International Seismological Centre data base (ISC On-line Bulletin, 2004) are presented in Fig. 10.

There is no obvious time correlation between local events and the disturbances in data from TM-71 gauges. On the other hand it is correlation with strong shocks (M>6.0) occurring in the Mediterranean Sea Basin that is much better expressed. Following events are particularly well reflected: Algeria 1989/10/29 (M=6.4), Greece 1997/03/10 (M=6.3), Turkey 1999/11/12 (M=7.4), Turkey 2003/01/27 (M=6.0), Algeria 2003/05/21 (M=7.0). However, disturbances after these shocks are not evident for all the instruments. According to the Kostak's hypothesis a strong earthquake would respond to and produce temporary changes in the Earth' crust stress field detectable in the readings of sensitive extensometric instruments (Košťák 1998, 2002).

5. FIRST INTERPRETATIONS

Apart from the crack gauges located in the Szczeliniec Wielki Massif, Table Hills Mts., and serving for the purpose of observation of mass movements of rock blocks, another network of TM71 instruments have been set on tectonic faults to check displacements due to active tectonics. Due to technical problems main fault zones cannot be investigated with crack gauges in full. It is rather minor structures accompanying the zones and parallel to them that can be instrumented. However, if we assume that the character of movement of such structures reflects the character of the movement of the whole fault zone, an attempt to interpret the results of relative measurements with the TM-71 crack gauges in the context of kinematics of main tectonic structures in the Sudeten, particularly the Sudetic Marginal Fault and the Intra-Sudetic Fault, may be made. The result of such an interpretation expressed by arrows in marked directions of relative motion is shown schematically in Fig. 11. It should be added that the arrows in this figure do not represent the magnitude of movement but direction only.

The area of the Sudetic Marginal Fault Zone is under geodetic GPS investigation. Preliminary results of the two measurement systems, GPS and crack gauging, can be therefore compared.

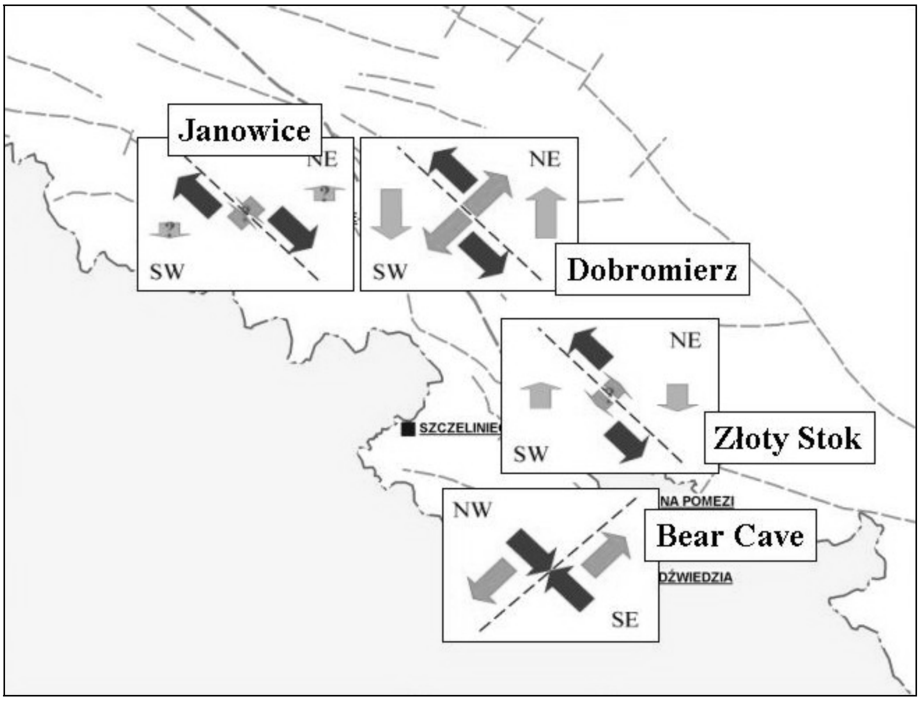


Fig. 11 The character of relative movements from the TM-71 data results

In Dobromierz on both the gauges installed within the Sudetic Marginal Fault Zone left-lateral and tensile character of movement was observed. This does not fully correspond with the results of geodetic GPS measurement in this area. Although GPS measurements indicate to some extent left-lateral movement also, GPS results are different and compressive character of movement is rather indicated in the direction perpendicular to the fault plane (Kontny, 2004). Relative lateral movements measured by the "Janowice" gauge, on the Intra-Sudetic Fault are right-lateral and the gauges placed in the Bear Cave on the Klesnica Fault indicate very small left-lateral and compressive movements.

6. CONCLUSIONS

Several years long time series of observations using crack gauging with TM-71 makes estimation of linear trends possible. Very slow relative movements (below 0.1 mm/year) are detectable at most sites in the Sudeten. Only results from Dobromierz site show horizontal movements above 2 mm/year, which is probably a movement of a particular rock-block in the given situation.

Estimation of periodicity requires longer (more than 10 years) data series without many gaps. As for the instruments located on the surface one-year periodicity has been found dominant, and follows seasonal temperature variations. Longer periodicity was also detectable (e.g. approx. 12 years solar cycle). No such a periodicity was detected for gauges located underground, in more stable environment (cave, mine adit etc.).

The „echoes" of strong, far away earthquakes are probably observable in the TM-71 data time series in episodic displacements. The effects of local seismic events are not clearly noticeable. As for the magnitude of relative movements detected by the TM-71 gauges in the Sudeten area it is very small, but such micro-movements are evident and confirm contemporary mobility of the tectonic structures.

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