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ORIGINAL PAPER

RECENT RELATIVE VERTICAL MOVEMENTS IN THE TECTONIC ZONE OF THE SUDETY MTS.

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ABSTRACT

Recent geodynamic activity of the Sudeten in the area of Poland and the Czech Republic has been confirmed by the results of geodynamic, seismic, geodetic and other tests. This is especially the case for the periodical (the last 25 years) satellite GPS/GNSS and gravimetric measurements in the regional research network GEOSUD, SILESIA, SUDETY and the local geodynamic polygons ("Snieznik", "Stolowe Mts."), as well as observation of crack-gauges on several tectonic faults. Vertical movements are indicated in the maps of recent movements of the Earth's crust. Two adjacent countries in the area of the Sudeten achieved results from +0.5 mm/year to -2 mm/year with reference to the tide gauge on the coast of the Baltic Sea. They present absolute value received on the basis of a comparison of the results of repeated (in intervals of 20–30 years) measurements of 1st order levelling lines. The characteristics of this data do not allow for an assessment of recent tectonic activity in the Sudety Mts. because the isolines of absolute velocities of vertical movements of the Earth's crust surface on the maps (Wyrzykowski, 1985; Kowalczyk, 2006; Vyskočil, 2002) present "smoothed" large-area changes without a proof of dynamic changes in the Sudeten tectonic zones.
This paper presents results of analysis archival data on repeated measurement precise levelling networks. The results of analysis were used to produce maps of vertical movements of the Earth's crust surface. Analysis is focused on the part of levelling lines which intersect Sudeten main tectonic faults. This paper included methodology of data processing. In research period relative vertical movements of tectonic zones are referencing to the relative stable benchmark. The values of these velocities between -0.8 ÷ +0.8 mm/year confirm recent geodynamic mobility in this Central European area.

INTRODUCTION

The geological structure of the Sudety Mts. having the nature of a block is defined as a mosaic because of the large variety of rocks and numerous dislocations separating tectonic units of different ages and structure (Stupnicka, 2007). Recent seismic activity in this area is confirmed by the size of the earthquakes as 5.5° MSK, observed in the area of Jilovice Fault (Procházková, 1989), in the tectonic zone Poříčí-Hronov (Zedník et al., 2001) and the active tectonic region Hrubý - Jeseník (Jechumtálová and Šílený, 2014).

The geodetic and geological research in the Sudety Mts. based on the periodical GPS measurement in the last quarter of the 20th century showed horizontal movement slip of the main tectonic zone of the Sudety Mts. and Fore-Sudetic block (Cacoń et al., 2004, 2010; Kapłon and Cacoń, 2009; Kapłon et al., 2014; Kontny, 2003; Schenk et al., 2003). These same GPS measurements showed no significant changes of vertical movements of these tectonic zones because results of GPS measurement (vertical component - absolute height) are not determined with high precision. The vertical movements of the Earth's crust surface in the Sudety Mts. area are confirmed by repeated measurements of basic levelling lines, 1st and 2nd order, which include the period of the last 50 years of the 20th century (Wyrzykowski, 1985; Kowalczyk, 2006; Vanko and Vyskočil, 1987; Vyskočil, 2002). Figures 1, 2 and 3 show the isolines of velocities of vertical movements of the Earth's crust surface in the Sudety Mts. as maps encompassing the area of Poland and the Czech Republic. Wyrzykowski (1985) showed on the map (Fig.1) the results based on measurement on Polish levelling networks in the years 1952–1956 and 1975–1977. Kowalczyk's (2006) results are showed in Figure 2, including measurements of the same networks in 1975–1977 and 1997–2003. In Figure 3 Vyskočil (2002) showed isolines of velocities of vertical movements of the Earth's crust surface in the area of Karkonosze-Jeseniky based on measurements on Czech levelling networks in the years 1960–1973 and after 1990 for selected levelling lines. Measurements of these levelling networks performed after 1990 for selected levelling lines have not yet been included in this study. It should be noted that graphic image changes of the Earth's crust surface presented in three figures, although they are not complementary on both sides of the Polish-Czech

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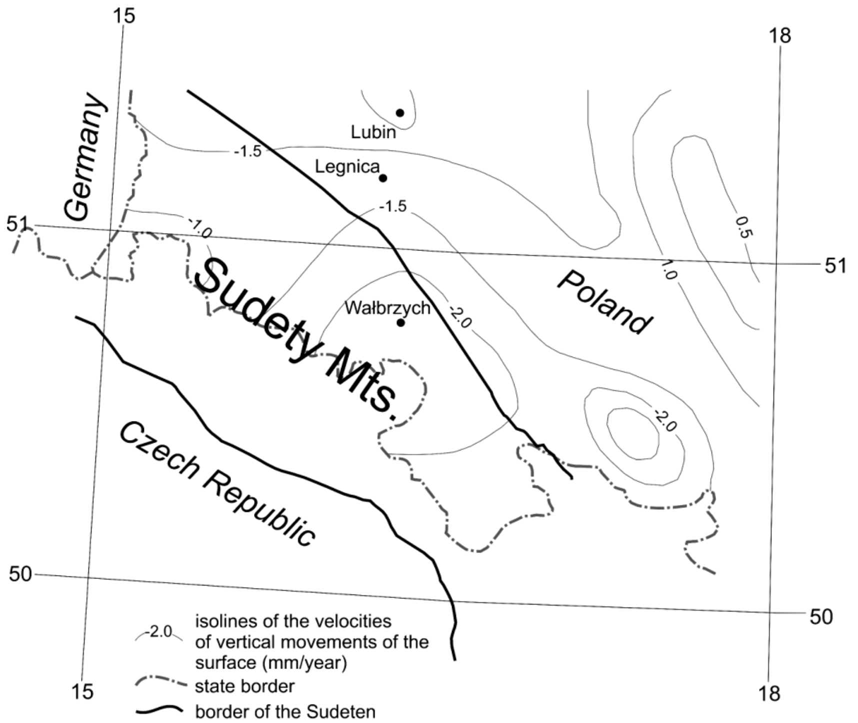

Fig. 1 The part of map velocities of vertical movements of the Earth's crust surface in the area of Poland (study based on (Wyrzykowski, 1985)).

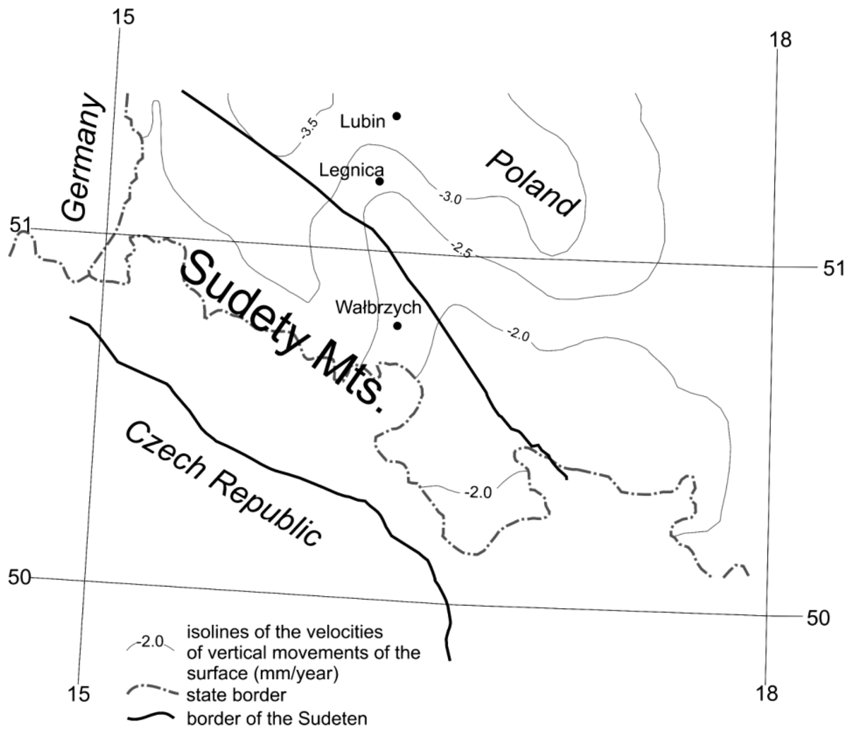

Fig. 2 The part of map velocities of vertical movements of the Earth's crust surface in the area of Poland (study based on (Kowalczyk, 2006)).

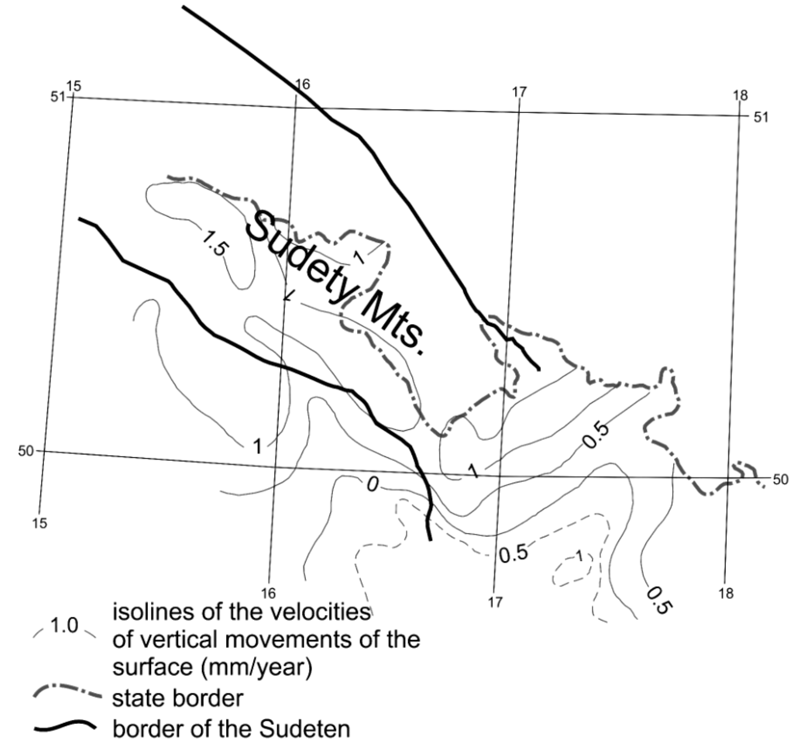

Fig. 3 The part of map velocities of vertical movements of the Earth's crust surface in the area of the Czech Republic (study based on (Vyskočil, 2002)).

border in the Sudety Mts., confirm the theory of recent mobile geological structure of this area. The results of this research intend to describe relative changes in movements of blocks of rocks on their borders in coincidence with the main tectonic faults. Due to the limited number of levelling lines (possible to use) and intersecting these tectonic faults, it is impossible to investigate all blocks of rock extracted in the geological research.

METHODOLOGY

The calculations contained only these levelling lines, which were measured in at least two measurement epochs (Fig. 4). The archival data contained sets of height differences between benchmarks in research period. They were the basis for determining the relative stable reference benchmark in each line. The calculations were carried out according to the formulae in (Wyrzykowski, 1993).

The first step involved calculating the root mean square error (RMSE) of height differences of the analysed levelling section ($m_{\Delta h_i}$):

$$m_{\Delta h_i} = \pm m_0 \cdot \sqrt{R_i} \tag{1}$$

where:

m_0 – RMSE of 1km [mm], (1st order lines 1 mm, 2nd order lines 2 mm)

R_i – length of section between two benchmarks [km].

Then the height difference change between measurement epochs (r_i) was calculated for each section:

$$r_i = \Delta h_i^{II} - \Delta h_i^{I} \tag{2}$$

where:

$\Delta h_i^{II}; \Delta h_i^{I}$ – height differences respectively for the two measurement epochs.

The next step was determination of RMSE of height difference change r_i :

$$m_{r_i} = \pm m_{\Delta h_i} \cdot \sqrt{2} \tag{3}$$

In the next step the stability of benchmarks was determined separately for each part of the levelling line. The relative stable benchmark must satisfy the condition that the height difference change (r_i) between measurement epochs could not exceed (at the significance level α=0.05) the "double error" = two times (m_{r_i})

$$r_i \leq 2 \cdot m_{r_i} \tag{4}$$

The specified relative stable reference point is the basis for calculating the height benchmarks ($H_I; H_{II}$) for which the RMSE ($m_{\Delta H_i}$) are calculated on the basis of:

$$m_{\Delta H_i} = \pm m_0 \cdot \sqrt{2L_i} \tag{5}$$

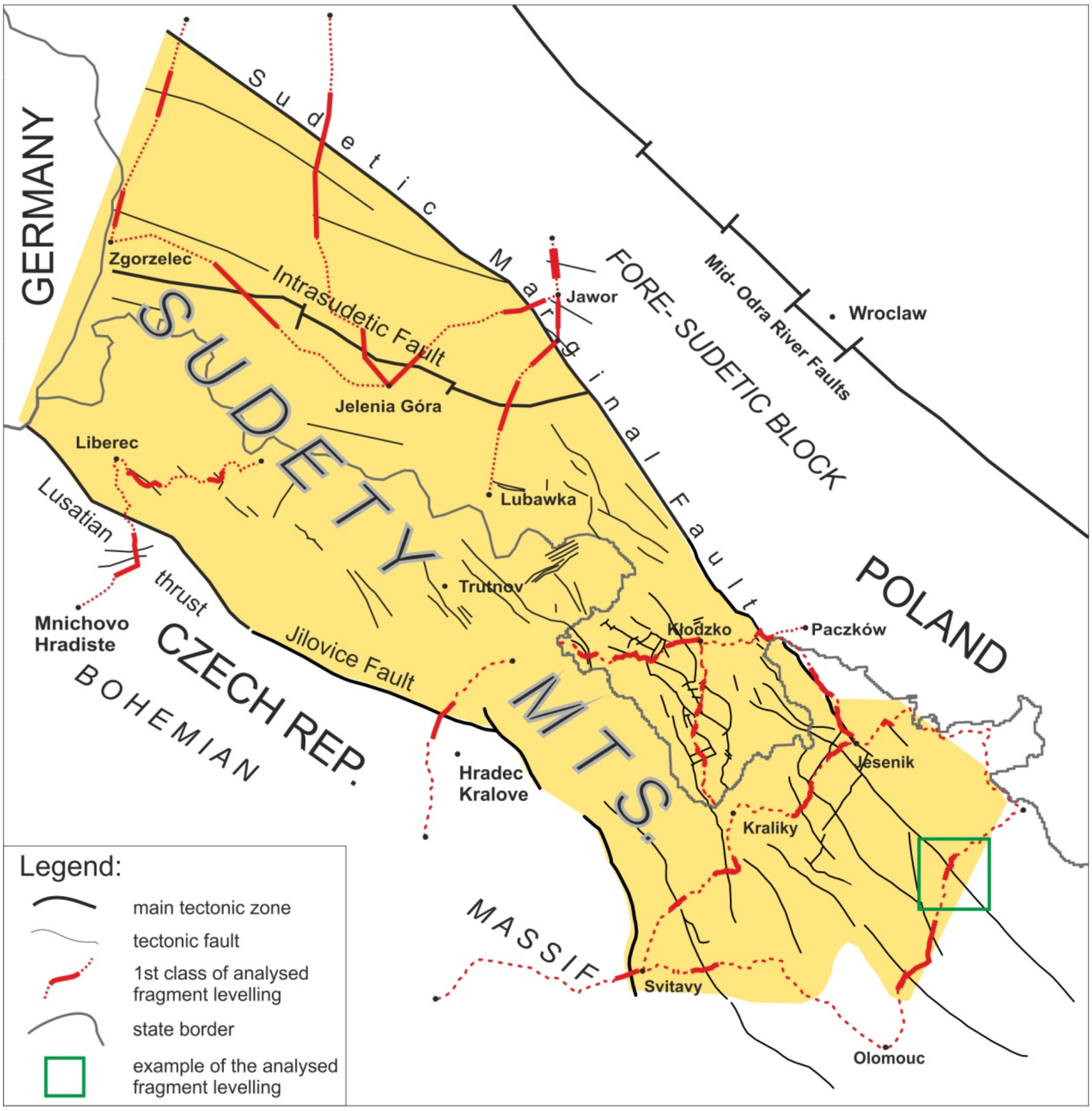

Fig. 4 Levelling lines in the part of Poland and the Czech Republic.

where:

$2L_i$ – double length between the benchmark set and relative stable benchmark [km].

To standardize the results of this analysis velocities of height change ($V_{\Delta H_i}$) of analysed benchmarks were calculated according to the formula:

$$V_{\Delta H_i} = \frac{H_{II} - H_I}{t_{II} - t_I} \quad (6)$$

where:

$t_{II};t_I$ – year of measurement respectively for the two epoch of measurements

The root-mean-square error of height change velocities for individual benchmarks are calculated using the formula:

$$m_{V_{\Delta H_i}} = \pm\sqrt{\frac{2 \cdot m_0^2 \cdot L_i}{(t_{II} - t_I)^2}} \quad (7)$$

Significant displacement was detected using criterion given by the formulae (4) and (5).

Course of action with the use of the above formulae the relative changes of height benchmarks were calculated. Selected parts of levelling lines used in this paper are shown in Figure 4.

EXAMPLE OF THE ANALYSES

Figure 4 presents the state levelling networks that are located in the area of Poland and the Czech Republic. These fragments are marked on the analysed levelling lines.

The repeated precision levelling data of the Polish territory were measured in campaigns: II (1952-1956), III (1975-1977) and IV (1997-2003). The levelling data for the Czech Republic were measured in years 1940-48 and 1975. The archival data in this analysis include results of field measurements based on repeated 1st order precise

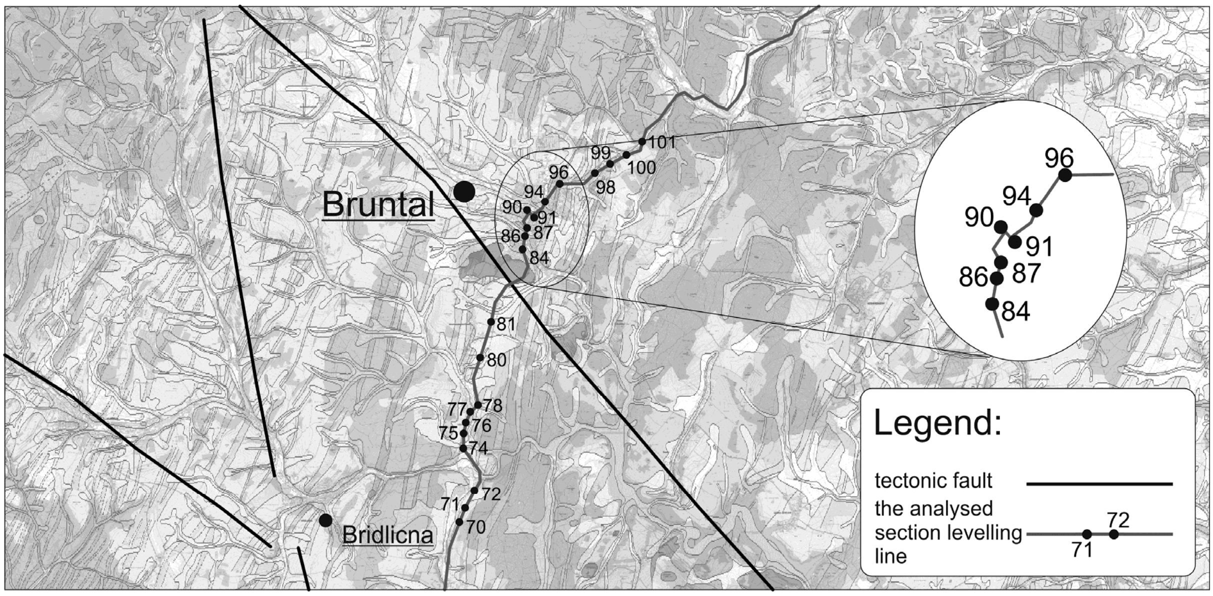

Fig. 5 Example of analysed fragment of the levelling line (Czech Republic).

levelling, which accuracy was determined on level m_0=1mm/km in order to unify heterogeneous data in the area of the Sudety Mts. (Polish and the Czech Republic). The data structure for the vertical movement calculation includes height differences between the benchmarks taking into account comparation and temperature corrections for rods. These analyses were performed for fragments of levelling line (Fig. 4) based on principles, which were presented in section "Methodology". Results of these analyses are shown on example of the Czech levelling line part (Fig. 5). This line has been measured in 1948 and 1975. Quantitative data are shown in Tables 1 and 2.

The analysed part of the levelling line consists of 21 benchmarks that intersect the tectonic fault.

Table 1 Determination of relative constant reference benchmark for the analysed part of the levelling line.

Benchmarks		Length of section [km]	Height difference *Δh* [m] Epoch of measurement		Height difference change *r* [mm]	RMSE height difference change [mm]	Double error of difference change [mm]	Condition $r \le \lvert m_r \rvert$ (stable point "+")
from	to		1948	1975				
70	71	0.47	-2.92554	-2.91799	7.55	0.69	1.94	
71	72	0.61	-22.23039	-22.22924	1.15	0.78	2.21	+
72	74	1.80	-5.56178	-5.56337	-1.59	1.34	3.79	+
74	75	0.56	2.39008	2.38889	-1.19	0.75	2.11	+
75	76	0.34	-0.94446	-0.94762	-3.16	0.58	1.65	
76	77	0.48	-1.16046	-1.16158	-1.12	0.69	1.96	+
77	78	0.33	-2.61260	-2.60582	6.78	0.58	1.63	
78	80	1.61	20.99866	21.00151	2.85	1.27	3.59	+
80	81	1.14	13.15458	13.15994	5.36	1.07	3.02	
81	84	2.70	-19.52932	-19.53064	-1.32	1.64	4.65	+
84	86	0.46	-5.24099	-5.23985	1.14	0.68	1.92	+
86	87	0.26	5.85923	5.85784	-1.39	0.51	1.44	+
87	90	0.56	8.96982	8.97348	3.66	0.75	2.12	+
90	91	0.16	1.34450	1.34440	-0.10	0.40	1.12	+
91	94	0.66	-2.87139	-2.87010	1.29	0.81	2.29	+
94	96	0.73	21.28022	21.27661	-3.61	0.85	2.42	
96	98	1.34	-69.78730	-69.79333	-6.03	1.16	3.27	
98	99	0.56	-23.92936	-23.91814	11.22	0.75	2.12	
99	100	0.65	-18.64652	-18.64736	-0.84	0.80	2.27	+
100	101	0.71	-14.73366	-14.73020	3.46	0.84	2.39	

Table 2 Height changes of benchmarks on part of the levelling line.

Number of benchmark	Height referenced to relative stable benchmark *H* [m]		Height difference change between epochs *ΔH* [mm]	RMSE of height difference change [mm]	Double error of difference change [mm]	Velocity of change of height V [mm/year]	RMSE of velocity of height change [mm/year]
	1948	1975	1948-1975				
70	553.44430	553.42568	**-18.62**	4.79	9.59	-0.69	0.18
71	550.51876	550.50769	**-11.07**	4.69	9.39	-0.41	0.17
72	528.28837	528.27845	**-9.92**	4.56	9.12	-0.37	0.17
74	522.72659	522.71508	**-11.51**	4.15	8.30	-0.43	0.15
75	525.11667	525.10397	**-12.70**	4.01	8.02	-0.47	0.15
76	524.17221	524.15635	**-15.86**	3.93	7.85	-0.59	0.15
77	523.01175	522.99477	**-16.98**	3.80	7.60	-0.63	0.14
78	520.39915	520.38895	**-10.20**	3.71	7.43	-0.38	0.14
80	541.39781	541.39046	**-7.35**	3.25	6.50	-0.27	0.12
81	554.55239	554.55040	-1.99	2.88	5.76	-0.07	0.11
84	535.02307	535.01976	-3.31	1.70	3.39	-0.12	0.06
86	529.78208	529.77991	-2.17	1.40	2.80	-0.08	0.05
87	535.64131	535.63775	**-3.56**	1.20	2.40	-0.13	0.04
90	544.61113	544.61123	0.10	0.56	1.12	0.00	0.02
91	545.95563	545.95563	0.00	0.00	0.00	0.00	0.00
94	543.08424	543.08553	1.29	1.15	2.29	0.05	0.04
96	564.36446	564.36214	-2.32	1.67	3.33	-0.09	0.06
98	494.57716	494.56881	**-8.35**	2.34	4.67	-0.31	0.09
99	470.64780	470.65067	2.87	2.57	5.13	0.11	0.10
100	452.00128	452.00331	2.03	2.81	5.61	0.08	0.10
101	437.26762	437.27311	5.49	3.05	6.10	0.20	0.11

Table 1 shows the height differences between benchmarks in two measurement epochs, which formed the basis for the calculation of height difference change between epochs (2). Additionally the associated statistics are calculated: RMSE of height differences (1), double error of height difference - the maximum acceptable error of height differences change (3), and indication of benchmark stability (4). It also indicated stable and unstable height differences in both measurement epochs. Among the analysed values the unchanged height differences were recorded between benchmarks 90–91 and 91–94. For further analysis the stable point number 91 was adopted. Table 1 presents stability of height differences between benchmarks in research period (data obtained from the Land Survey Office of the Czech Republic).

In the next step the height of the benchmarks in two measurement epochs was determined in terms of the reference point number 91. These data are presented in Table 2, which presents the height differences (2), RMSE for determined height (5), double error of determined height, velocities of height change (6) and RMSE of velocities of height change (7). New benchmark heights were calculated as referenced to relative stable point in research epochs. Significant displacement of benchmarks is marked in bold.

The graphic illustration of the changes of height benchmarks along the levelling lines is shown in Figure 6. Generally it can be stated that the south-west tectonic fault part is subsidence while the north-east tectonic fault part is uplift.

Significant velocities of change of height benchmarks are marked with a dot (Fig. 6). The mean value of these changes is shown in Figure 6 (-0.3 mm/year and -0.1 mm/year) which concerns the tectonic zone to 3 km from the tectonic fault.

ACTIVITY OF TECTONIC ZONES IN THE SUDETY MTS.

Results of these analyses covering the area of the Sudety Mts. are presented in Figure 7. Different directions and values of velocities of benchmarks vertical changes in each tectonic zone in the area under study confirmed the geological block structure of the Sudety Mts. The maximal changes concern the Intrasudetic zone, as well as the area of the Poříčí-Hronov tectonic zone. The most active tectonic zones should include also the area between the towns Králiky and Svitavy along the levelling line EF. Main tectonic faults (Sudetic Marginal fault, Jilovice fault

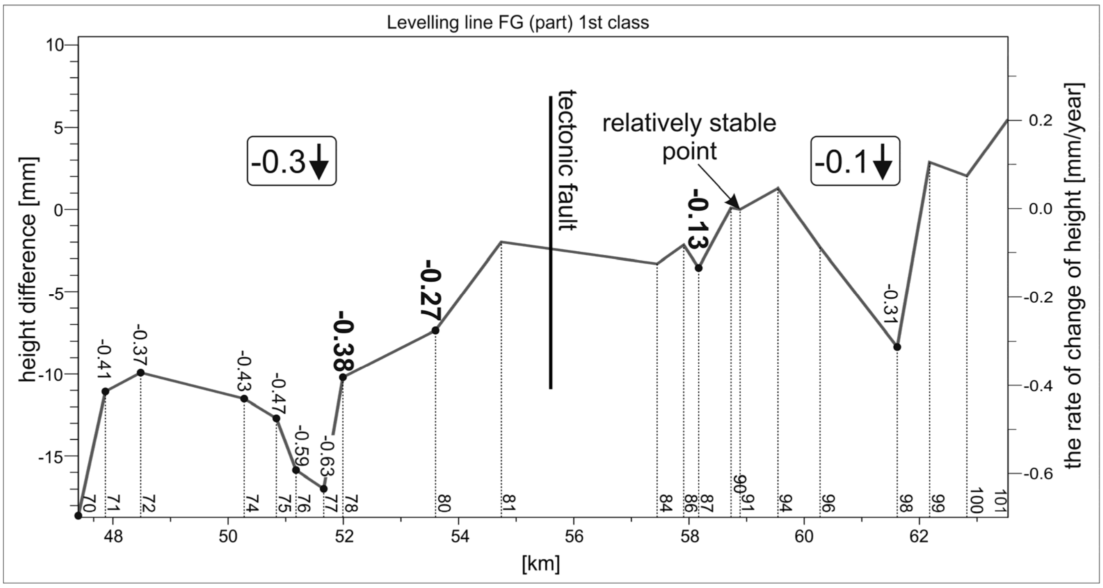

Fig. 6 Height changes of benchmarks and their velocities of height changes.

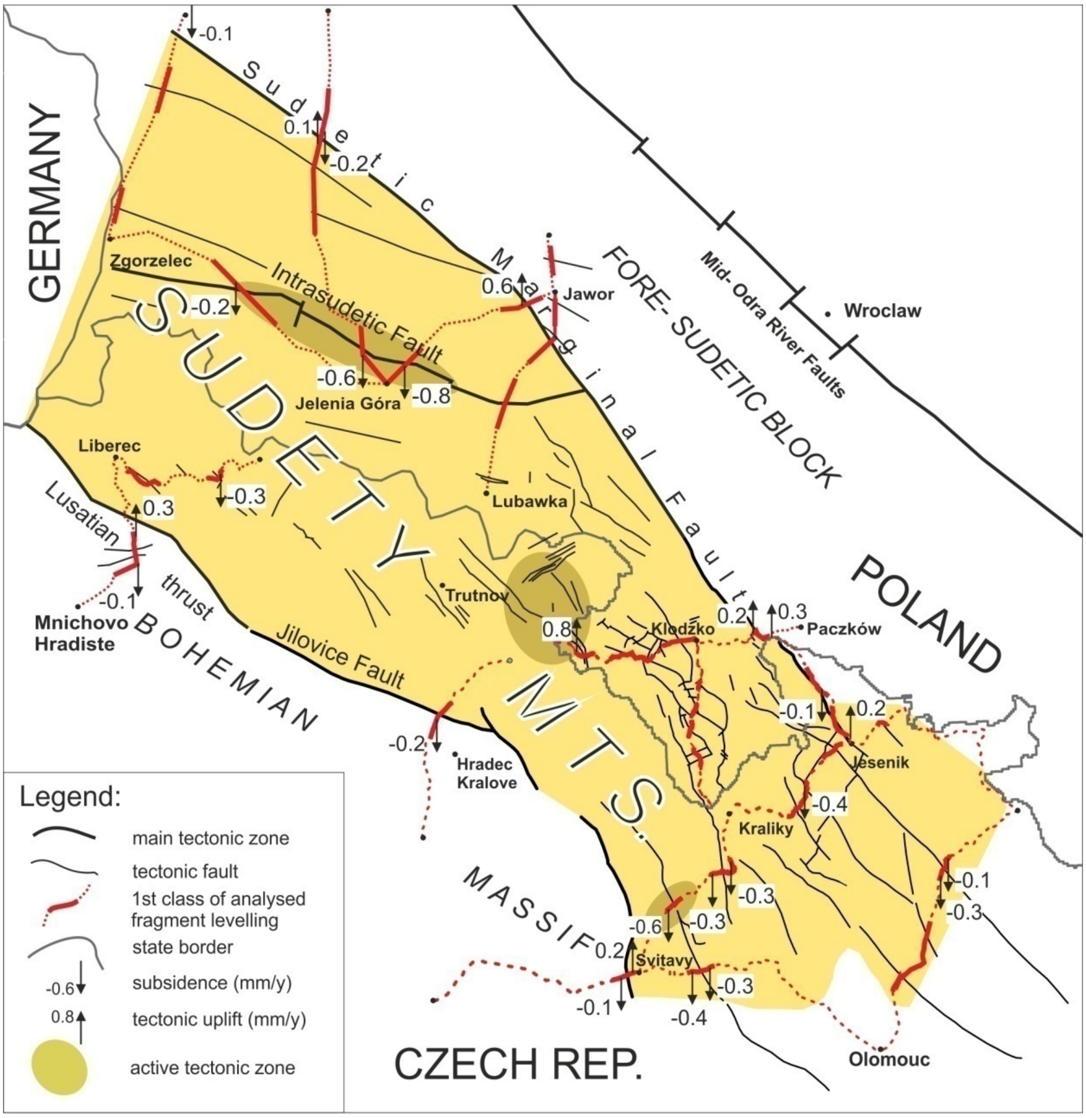

Fig. 7 Vectors directions and values of average velocities of benchmarks vertical movements.

and Lusatian thrust) which form borders of the Sudety Mts. have low tectonic activity.

CONCLUSION

The result of research shows the relative vertical movements of the tectonic zones in the Sudety Mts. in the last half-century of the 20th century. This is another verification of the geodynamic mobility of this area. The movements are characterized by values between +0.8 and -0.8 mm/year. The largest of them are located in the Intrasudetic zone (Western Sudetes), where the changes indicate subsidence (from -0.2 to -0.8 mm/year). In the Eastern Sudetes the largest, positive values of these movements (+0.8 mm/year) are located in area of the Poříčí-Hronov tectonic zone. In external geological structures of the Sudety Mts. to the north-east from the Sudetic Marginal fault there are subsidences in its west part up to -0.2 mm/year, while the east part tends to uplift +0.3 mm/year. On the south-west zone from the border of the Jilovice fault and Lusatian thrust there are movements of subsidence to -0.2 mm/year. The presented quantitative values of this research have a cognitive character consistent with the qualitative results of geological research concerned with the geological block structure of the Sudety Mts. The utilitarian research aspect is related to adequate protection of the proposed road infrastructure and modernized transit routes intersections of the mobile Sudetic fault. This involves the possibility of activating tectonic movements and vibration induced by heavy car transport. This also applies to large new engineering investments on the active tectonic faults.

The discussion of the tectonic activity of the Sudety Mts. focused on the analysis of changes of height of each benchmark in the tectonic zones is a further step in the research of recent geological activity of this area. It is reasonable also to extend the analysis for repeated measurements of the levelling lines of 2^{nd} order. Results of previous research and their extent may be the basis for detailed interpretation of the geological block structure of the Sudety Mts.

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