Acta Geodyn. Geomater., Vol. 12, No. 2 (178), 169–171, 2015
DOI: 10.13168/AGG.2015.0012
journal homepage: http://www.irsm.cas.cz/acta

ORIGINAL PAPER

INTEGRATED TECTONIC STUDIES: A NEW CONCEPT EXPLORED IN THE GEODYNAMIC LABORATORY OF THE SPACE RESEARCH CENTER IN KSIĄŻ

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ARTICLE INFO

Article history:
Received 19 January 2015
Accepted 31 March 2015
Available online 30 March 2015

Keywords:
Geodynamics
Tectonic activity of the Earth
Tectonics of the Sudetes region
Geodetic and geophysical measuring instruments

ABSTRACT

The instruments of geodynamic laboratory of the Space Research Center (SRC) in Książ record vertical movements and tilt of the bed rock. They do not provide information about the main component of the tectonic signal, i.e. horizontal movements of the bed rock. Simultaneously recorded observations of the effects of tectonic activity are purely local, limited to the laboratory passages. Studies of mechanisms of contemporary tectonic activity of the Sudetes region based on current observations of phenomena (in real time), which is unique in the Polish conditions. These studies can be conducted due to exceptionally favorable natural conditions in the laboratory such as an underground system of passages excavated in solid and non-absorbent rocks, stable temperature and humidity, and space perfectly suited for installation of very sensitive geodynamic instruments that enable to perform precise measurements. A new idea of integrated tectonic studies includes a plan of supplementing the geodynamic information by extending the measurement area by including the laboratory surroundings which comprises the castle hill and the so-called "main southern fault "and installation of instruments (gap gauges and extensometers) in the underground, which will provide the missing information about the horizontal movements of the bed rock.

Research survey network will be established in the laboratory surroundings. Observations will be made in this network using modern measuring techniques: short-range laser scanning, precise electronic tachometric and interferometric measurements, precise geometric levelling and gap gauges.

The established spatial geodetic control and survey network in connection with measuring instruments which have already existed in the laboratory and which were designed by the authors will provide a holistic and comprehensive information of the processes that occur in the Książ Massif: tectonic deformation, the bed rock tilts, vertical movements and displacements on faults. Geodynamic information obtained from the research survey network will be integrated with the observations recorded with instruments that are located in the underground of the laboratory and the two GNSS stations located on the opposite flanks of the "main southern fault". An integrated measuring-interpretative system will allow the creation of a multi-component model of the Książ Massif mechanics and finding the direction, time and amplitude characteristics of tectonic events. The multi-component model enables to estimate the compensation effect of tectonic deformation and the main direction of stresses. It will also provide information about the multi-phase nature of the tectonic event.

1. INTRODUCTION

The purpose of the planned research is to investigate the mechanics of contemporary tectonic deformations in the Książ Massif and in the Świebodzice Depression. As shown by previous studies tectonic deformations in the Książ Massif occur as displacements of individual rock blocks along the faults surfaces, tilts of the bed rock and deformations of the object.

Determination of tectonic deformation enables to model them and to assess the direction and quantitative changes of deformation in the investigated area.

The evolution of stress and deformation fields depends on their compensation coefficient, and has a significant impact on the behaviour of the Książ Massif. For the Świebodzice Depression, the compensation coefficient of tectonic deformation does not equal one, which is indicated by tectonic deformations of the meander of the Pełcznica river gorge. As a result of the tectonic extension the shape of the Pełcznica river valley was transformed in the gorge region from a cycloid into a rectangular curve (Fig. 1).

A large value of the residue of stresses and deformations (small compensation) increases the probability of the local seismic earthquake occurrence. The investigated mechanism of tectonic deformations describes the tectonics of the local structure - Świebodzice Depression. Nevertheless, the developed research methodology will have universal components, which can be applied in other areas.

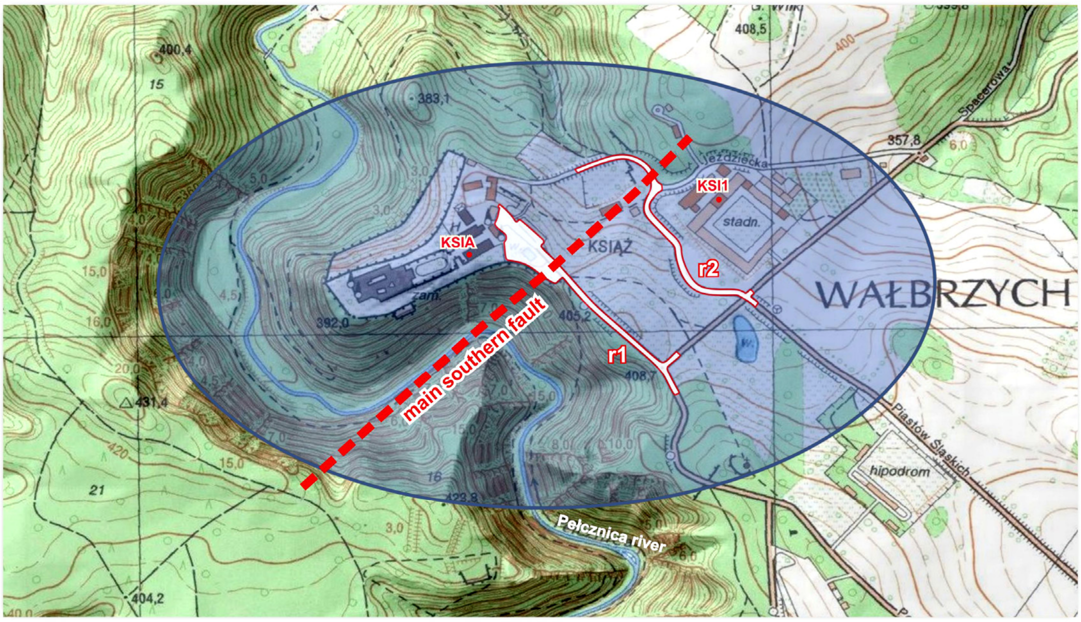


Fig. 1 The area in which the spatial control network with the marked main southern fault will be established.

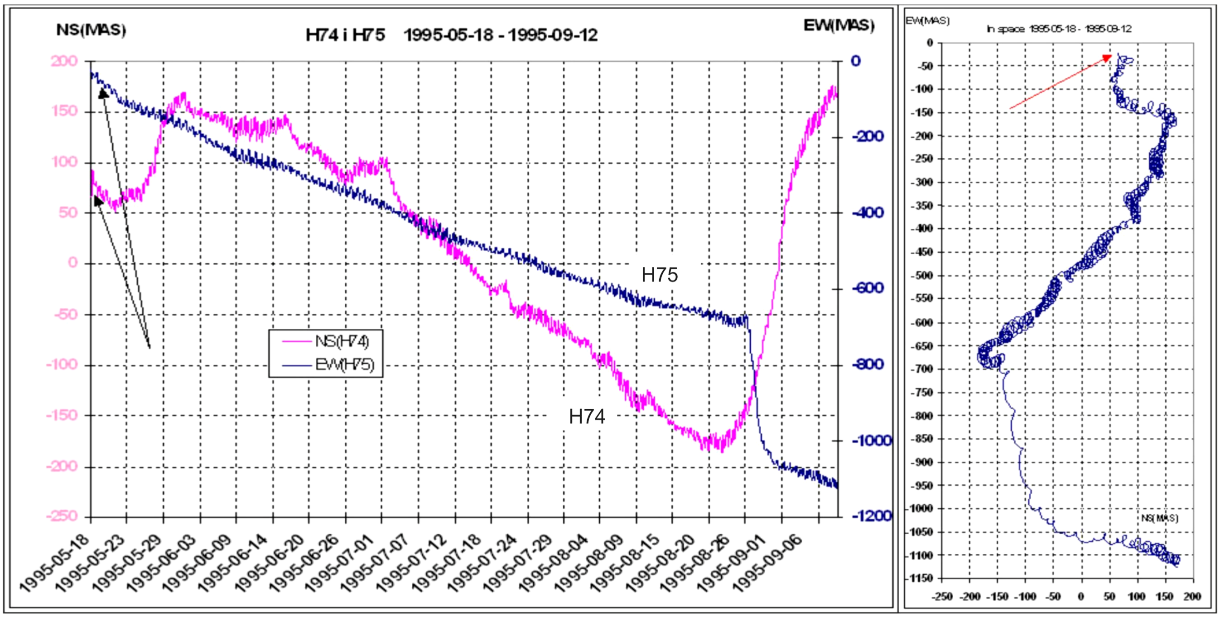


Fig. 2 The effect of rapid changes of the equilibrium azimuth of the quartz horizontal pendulums and the chart of balancing changes of the verticals in the space registered at the end of August 1995.

Long-term clinometric observations carried out with quartz horizontal pendulums provided numerous examples of rapid events of pendulums' equilibrium changes which lasted several days (Fig. 2) (Chojnicki and Blum, 1996). These effects occurred irregularly at various times of the year. These were the first observations of the bed rock inclination that confirm the contemporary tectonic activity in the Sudetes region (Żelaźniewicz and Aleksandrowski, 2008).

Before 2000 it was not possible to verify the indications of pendulums by other instruments because the research in this field has not been undertaken. Only the water-tube tiltmeters (WT tiltmeters) built in 2003, within a short period of time after installation confirmed the existence of irregular signals which indicate inclinations and vertical movements of the bed rock (Kaczorowski, 2006, 2007, 2008, 2009a, 2009b; Bower, 1973).

The tectonic originations of the observed effects is argued for such factors as irregularity of occurrence, lack of seasonality, similarity of courses of events and a very large amplitude (tidal amplitude is 10 times the original value). The discussion considers the geological structure of the Książ Massif and the results of the absolute measurements of gravity which indicate the high stability of the gravitational field in the laboratory region, and thus a stable local water level in the Geodynamic Laboratory (GL)

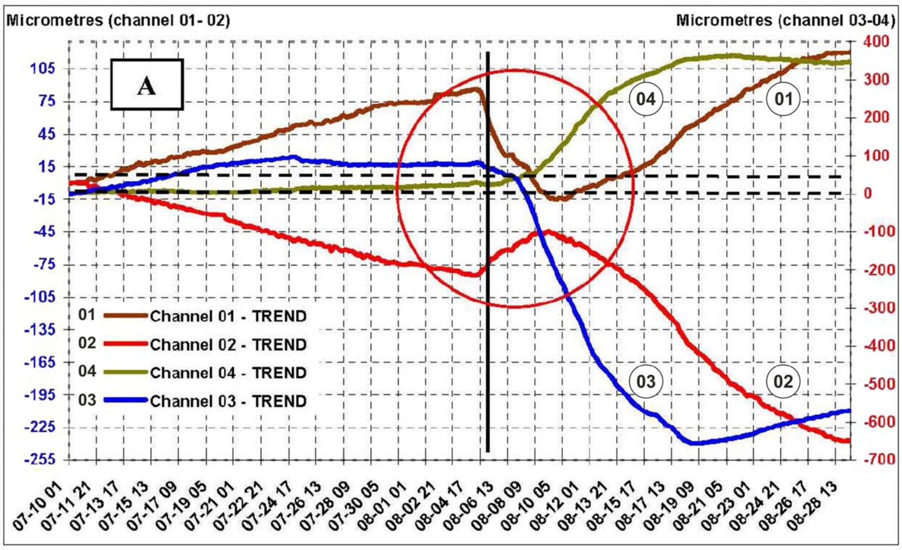


Fig. 3 Image depicting complexity and a multi-stage process of water level changes in WT 01-02 and 03-04 caused by the tectonic event that took place in July-August 2006 after removing tidal signals and water evaporation effects (Kaczorowski and Wojewoda, 2011).

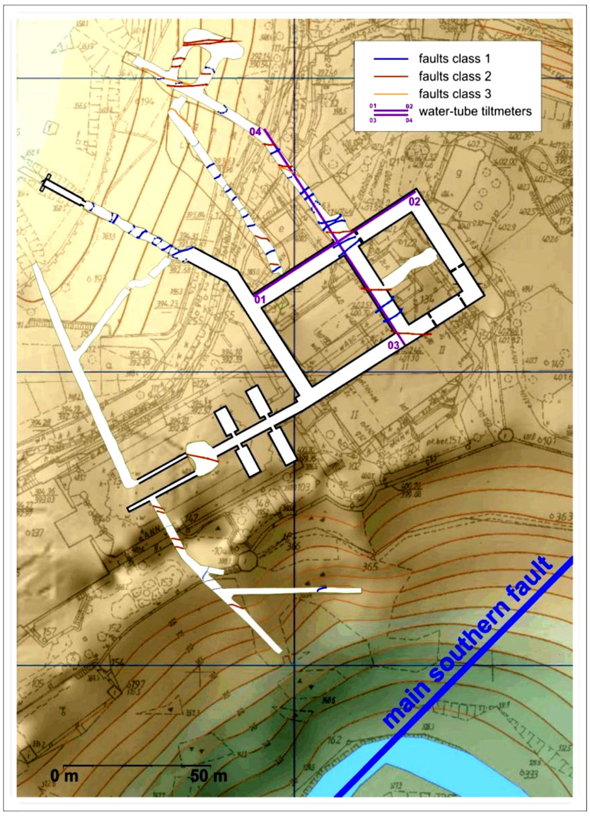


Fig. 4 The underground map depicting the location of secondary faults with a division into classes and the location of the WT tiltmeters.

surroundings (Kaczorowski et al., 2012), which enabled to ignore a non-tectonic cause of the observed signals, such as water level changes in the Książ Massif.

The tectonic origination of the phenomenon is indicated by the structure of the system of faults in the Książ Massif, whose inventory was compiled in 2013; deformation of the tertiary valley of the Pełcznica river (Teisseyre and Gawroński, 1965) and linear damages of the Książ castle architecture.

The presence of compensatory phase, high repeatability of subsequent events and similarities in the course of these events as well as constant gravitational field exclude the effect of gravitational dissolution of the rock mass (irreversible process) (Kaczorowski, 2009a and 2009b). Moreover, observed signals of water level changes in WT tiltmeters cannot be accounted for the atmospheric effects (pressure changes) due to the amplitude and the duration period lasting several days.

2. TECTONIC PHENOMENA IN KSIĄŻ

The oldest observations of tectonic signals come from quartz horizontal pendulums installed in Książ between 1974 and 1975 (Chojnicki and Blum, 1996).

After 2009, there had been a change in the occurrence of tectonic events. The deformation proportion was reversed and their temporal characteristics had changed which enabled us to assume that the tectonic event in Książ has two phases: strike-slip phase and compensation phase.

By 2008 the effects recorded in the azimuth 328.60^0 (03-04 WT tiltmeter) were stronger than the results recorded in the azimuth 58.60^0 (01-02 WT tiltmeter) (Fig. 3). The effect of the bed rock inclination (inclination of the whole Massif) in the

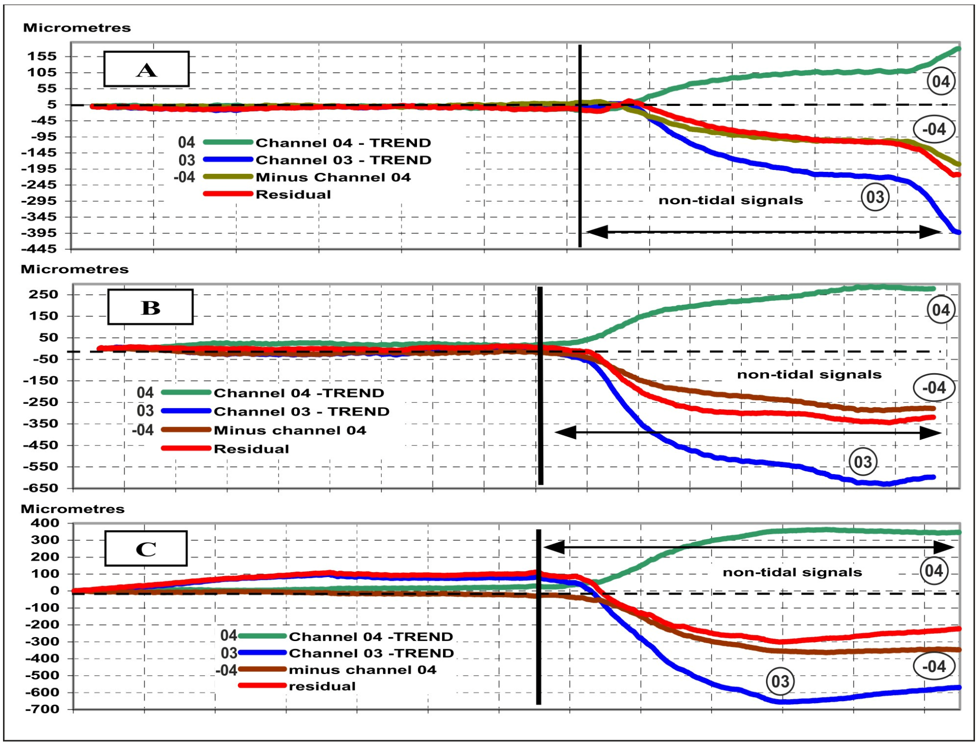


Fig. 5 Image of the mechanical repeatability of water level changes caused by tilts and vertical movements of the bed rock. Charts present tectonic events from the period 2004-2006 registered with 03-04 WT tiltmeter (about 2 weeks from the registration) (Kaczorowski and Wojewoda, 2011).

azimuth of 0102 tiltmeter usually preceded vertical movements. It often occurred several hours or even several days before the effect of vertical movements of the bed rock registered on tiltmeter 03-04 (Fig. 3). Multi-stage character of the tectonic event which was detected by the WT tiltmeter results from the location of instrument tubes on the local faults which are activated in similar way by repetitive changes of the stress field.

In 2013, the inventory of faults crossing underground passages of the GL and tubes of the WT tiltmeters was made. Geodetic methods were used to determine their strikes and dips. It turned out that faults are divided into classes of parallel faults (Fig. 4). Faults from both classes intersect at angles of approx. 40 and 90 degrees. First class of faults is almost parallel to the main southern fault, and the second class is inclined by about 35 degrees to the West (Fig. 4), while the third class of faults is perpendicular to the southern fault. The faults determined inside the massif, where the tiltmeter tubes are located, are secondary faults located obliquely to the main southern fault (Fig. 4). Thus, the WT tiltmeters record the results of the transformation of the horizontal movements into vertical movements and rotations (inclinations) performed on secondary faults.

The tectonic activity of secondary faults (Fig. 4) results, inter alia, from the strike-slip speed differences of the southern and northern flanks of the main southern fault (Fig. 1). Measuring methods and devices used in the GL, apart from GNSS, do not provide any data regarding this fact. Therefore, it was necessary to introduce new measurement methods in the laboratory surroundings to provide for lacking information.

Over a period of 35 years, dozens of events (on average one to two per year) have occurred, when the quartz horizontal pendulums rapidly changed their equilibrium, pointing to the inclination of the bed rock. Recorded amplitudes of pendulum movements had shown that the bed rock inclination is ten times higher than the tidal amplitude, i.e. approx. 30 msec of arc.

Observations of tectonic events collected up to 2008 show high repeatability of tectonic events registered with the hydrostatic and pendulum tiltmeters (Fig. 5), indicating the activity of the same faults in similar stress states (Kaczorowski, 2007, 2008, 2009a and 2009b; Kaczorowski and Wojewoda, 2011).

There had been a change in the occurrence of tectonic events after 2009. The deformation proportion was reversed and their temporal characteristics had changed which enabled us to assume that the tectonic event has two phases: strike-slip phase and compensation phase.

In accordance with the thesis during the strike-slip phase, the peninsula where the Książ castle is located, lies ahead of the southern flank of the main fault (Fig. 1 and Fig. 9). During the compensation phase, the flank of the main southern fault catches up

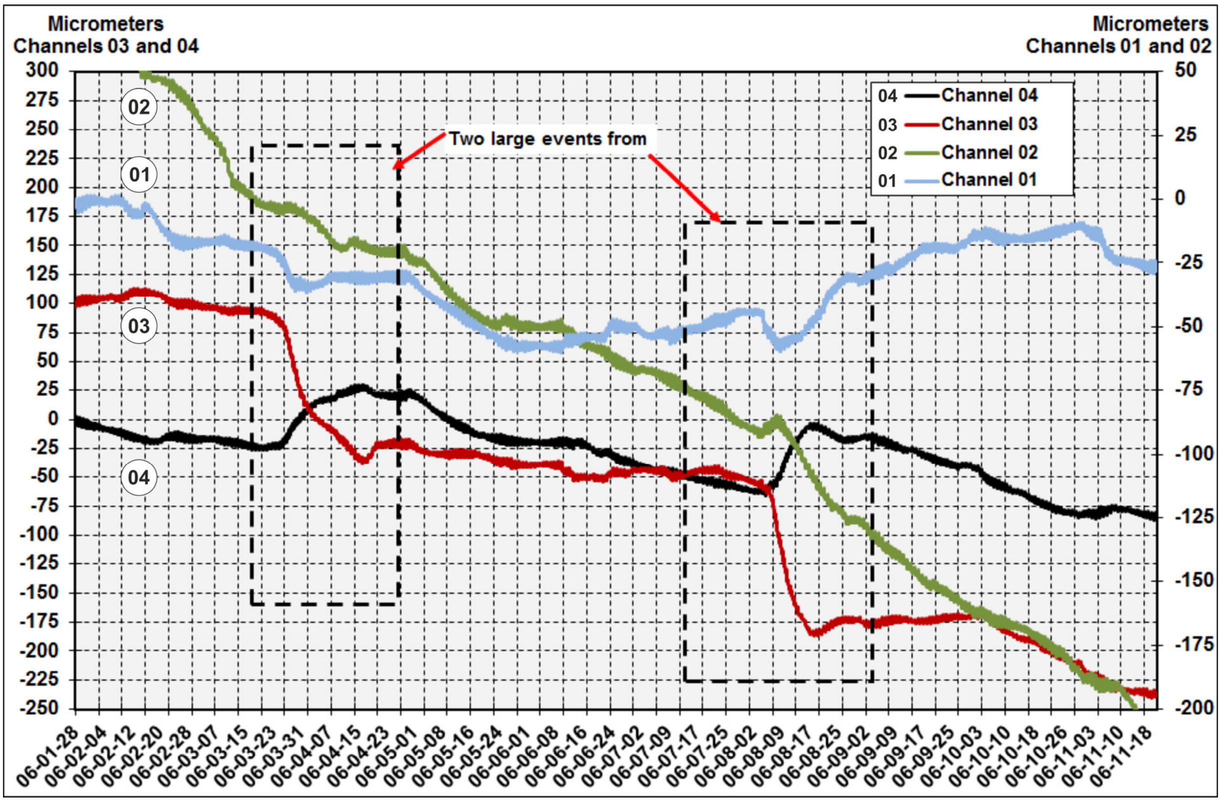


Fig. 6 Tectonic signals of vertical movements and inclinations of the bed rock registered with the WT tiltmeters 01-02 and 03-04 in 2006.

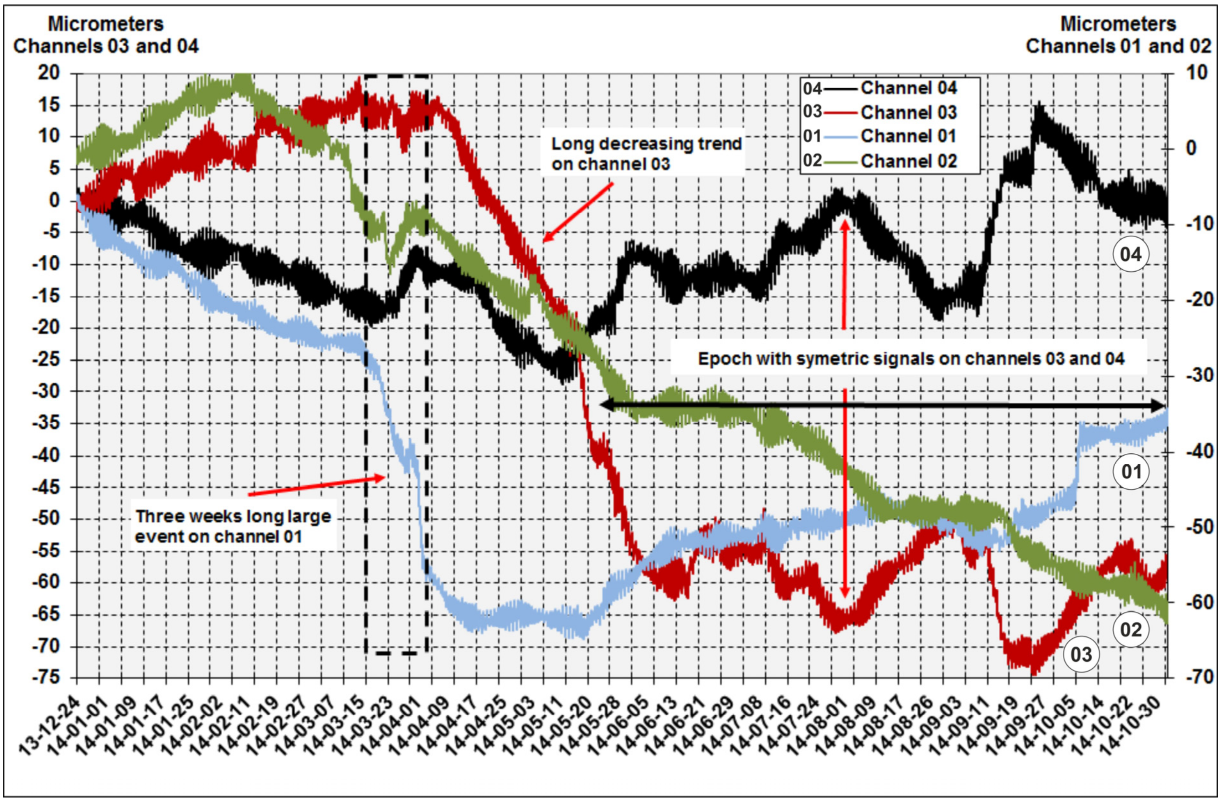


Fig. 7 Tectonic signals of vertical movements and inclinations of the bed rock registered with the WT tiltmeters 01-02 and 03-04 in 2014.

with the Książ peninsula, reducing the Pełcznica river valley deformation. Such a scenario is suggested by the existence of three systems of secondary faults in the rock mass (Fig. 4), which are alternating in the individual phases of the phenomenon. Probably each class of faults relates to a different form of the rock mass deformation, e.g. the class of faults perpendicular to the main fault indicates extension of the Książ Massif.

Further part of this paper includes the comparison of the flow of tectonic signals registered in 2006 and 2014. In 2006 (Fig. 6) the two tiltmeters at the same time registered two powerful events lasting for about a month between which the long periods of the steady trend occur. After a year, deformations were partly offset. Signals on channels 03 and 04 were a few times higher than on channels 01 and 02. On channel 03 the signals were very weak.

After tectonic effects calmed down between 2007 and 2009 the phase changed due to a radical variation in the flow of tectonic signals, reversing the tendency and proportion of deformation. In 2014 (Fig. 7) on channel 01 a strong effect was registered, while it could hardly be detected on channel 02. After it, long and steady trends were recorded. At the time of the strong effect on channel 01, a two-month strong downward trend started on channel 03 began, after which three minor effects were recorded. A similar downward trend, but a shorter one, was registered on channel 04. After it, three minor effects with the opposite phase to the one in channel 03, were noticed. The effect on channel 01 was particularly rapid, which did not happen before the phenomenon phase change. In observations from 2014, only in the second part of the year, on channels 03 and 04 the symmetric effects occurred (a mirror image on the opposite channels), which indicates that the recorded signals were generated mainly by vertical movements of the bed rock, and not by inclination.

Since 2009, after the change of the event phase, the model explaining water level changes in the WT tiltmeters by the rock mass deformation in the system of faults class 2 (Fig. 4) started to provide non-physical solutions (Kaczorowski and Wojewoda, 2011). The loss of functionality of the existing model indicates the phenomenon phase change and the beginning of the compensation period. This is the thesis of the planned research. This change involves activation of a different system of faults – probably faults of class 1 (Fig. 4). The thesis will be subject to verification using the existing measuring systems and geodetic spatial survey and control network.

In the absence of compensatory phase we observed the effect of accumulation of stresses and deformation which increases the extension of Pełcznica river valley along the main fault between the southern and the northern flank. This condition sooner or later would lead to violent relaxation of rock mass stresses which are probably caused by the earthquake.

Nevertheless, compensation is not complete, which is indicated by the extension of the Pełcznica valley meander by several metres in the southern part of the valley. An attempt to estimate deformation residuum (the lack of compensation), is the basis data for evaluating the effect of stress accumulation and predicting seismic activity in the Sudetes region.

If the alternate movements of the main fault flanks are confirmed, we will need to search for answers to new questions. Where does the gradient element of the blocks movement velocity that is normal to the surface of the main southern fault come from and what is the mechanism of differentiating the blocks speed?

3. RESEARCH METHOD

Previous studies of the Książ Massif mechanics lack information about the horizontal components of displacements on the secondary faults and on the main fault, which is located several metres from the laboratory. Missing information will be complemented by the GNSS KSIA station and the KSI1 station (Fig. 1) located on opposite flanks of the main fault and by gap gauges deployed on secondary faults inside the laboratory (Fig. 8 and Fig. 11). We also plan surveying measurements of the surface inside the GL and in the laboratory surroundings (Ayson and Lang, 1996), i.e. linear interferometric measurements, geometric precise levelling, short-range laser scanning and precise tachometric measurements (Fig. 9 and Fig. 13). The existing passageways and land configuration in the GL surroundings make it possible to establish the survey network (stabilization of geodetic points in the bed rock, convenient pointing lines), in which precise topographic surveys will be performed. Figure 1 shows two routes (*r1* and *r2*) which are located

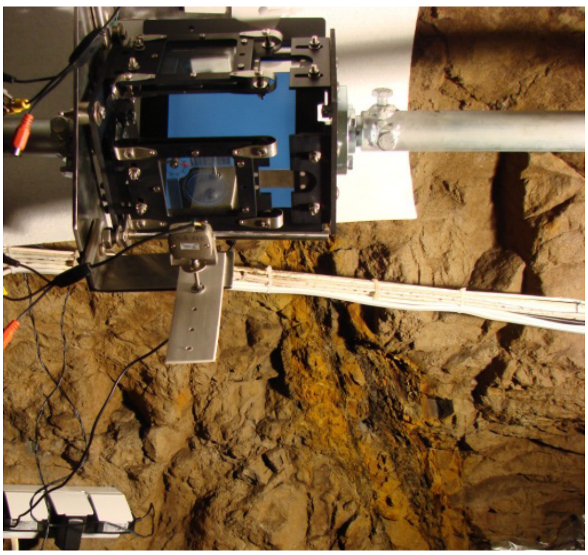


Fig. 8 The TM-71 crack gauge with electronic registration system on the secondary fault inside the GL.

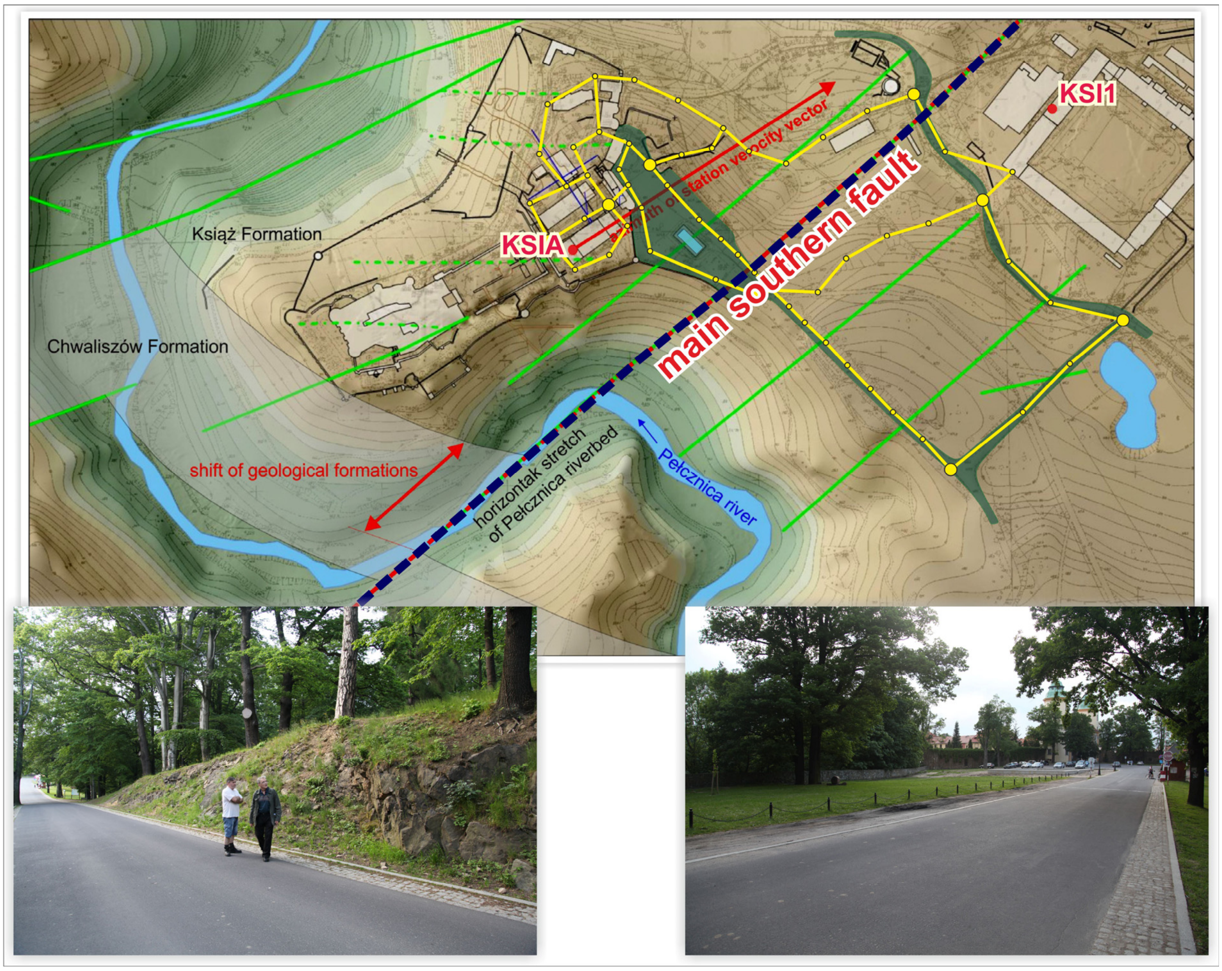


Fig. 9 Site plan depicting location of the spatial control and survey points and GNSS (KSIA and KSI1) stations with respect to the main southern fault.

laterally to the main southern fault. In addition Figure 9 depicts two pictures of the road *r1*.

These measurements will enable to determine functional relations between horizontal components of displacements on the secondary faults and the main fault and vertical movements and inclinations of the bed rock, which are observed inside the rock mass in the GL. On this basis, it will be possible to build the rock mechanics model and determine directional characteristics and the amplitude of tectonic events and their changeability resulting from the variation of the stress field.

Observations obtained from the external geodetic research network, established in the area of the main fault, provide us with information about the main fault activity (Fig. 1 and Fig. 9) and the current phase of the phenomenon (strike-slip / compensation) as well as relations between activity of the secondary fault and activity of the main fault. Calculation of the proportion between the activity of secondary faults and activity of the main fault will be used to determine the main direction changes of the stress fields. After the phenomenon phase switch (strike-slip/ compensation) changes in deformation directions and directions of the Książ Massif stress field will occur.

It is also likely that the stress field mode will change in the Książ Massif from tensional to compressive, or vice versa. These changes can be detected by means of the system consisting of large-scale interferential extensometers, vacuum and mobile quartz ones, gap gauges, a precise geometric levelling network, linear and angular measurements preformed with total station and satellite observations from GNSS KSIA and KSI1 stations (Fig. 9).

The proposed geodetic research networks will have two functions. Observations made in this network will provide a quantitative description of various geometric parameters changes and it will integrate observations made on the surface with observations performed inside the Massif (i.e. in the passages of the laboratory). Presentation of all observations in a uniform reference system will provide for their correct geodynamic interpretation.

So far, STAGE I of the survey network extension has been completed. Points of the levelling network (Fig. 10) were established inside the GL in November 2013, while the baseline measurements

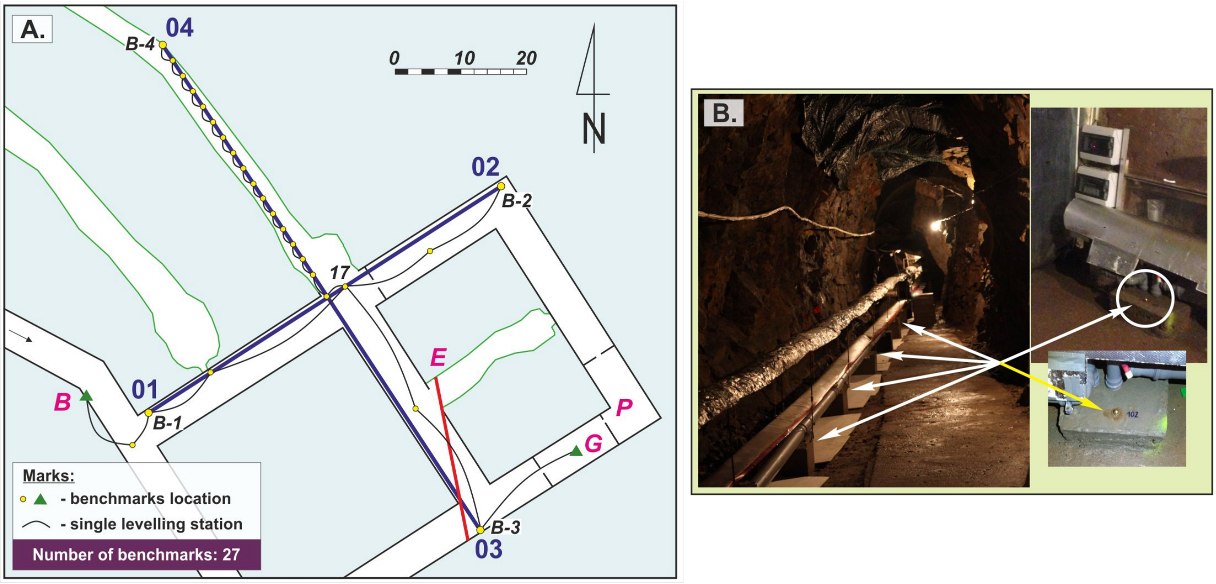


Fig. 10 Vertical control and survey network established in the GL (STAGE I)
A. Location of measuring points (STAGE I);
B. Location of stabilized bench marks.
Symbols: ***01-02*** and ***03-04*** - WT tiltmeters, ***E*** - extensometer, ***G*** - gravimeter, ***P*** - horizontal pendulums, ***B***, ***B-1***, ***B-2***, ***B-3***, ***B-4*** and ***17*** - benchmarks.

Table 1 Summary of adjusted heights and their errors for selected bench marks.

Benchmark number	Adjusted height *H* [m]	The average error of adjusted height m_H [mm]
G	352.161794	0.013
B	352.024998	0.008
B-1	352.100541	0.007
B-2	352.081049	0.008
B-3	351.956894	0.008
B-4	351.969193	0.007
17	352.085948	0.006

were performed in spring 2014. Currently, the network consists of 27 points (including two existing ones), stabilized along 01-02 WT tiltmeter and 03-04 tiltmeter, in their concrete supports. The location of points facilitates monitoring of vertical movements along individual tiltmeters. Measurements were performed using a precise electronic level DNA03 by Leica.

The levelling network measurements (geometric levelling from the centre) and precise adjustment of results (least squares method) enabled to determine the elevation of all bench marks along with height differences between them. On the basis of these calculations it was possible to determine the average errors of benchmarks and average height differences between them, which are respectively: m_H = ±0.01 mm and m_{dh} = ±0.01 mm (with m_0 = ±1.0028). Table 1 presents results for selected 5 bench marks.

As part of levelling control surveys were made. Their aim was to check the influence of environmental conditions in the GL on the measurement results. Concurrently to reading the levelling staff we recorded the basic parameter that characterises the measuring environment, i.e. the temperature. Figure 11 is a chart presenting results of the continuous measurement of the temperature by the sensor 01WT installed in the GL and changes of the line of sight of the level that is set on two stations in the time function. The first station of the level is situated at the crossing of the two WT tiltmeters (benchmark *17*), and the second station near the end of the tiltmeter tube (benchmark ***B-1***) (Fig. 10). On the basis of the measurement results we can notice interdependence between the change of the levelling staff readings and the temperature registered in the GL. The change of readings on the staff was +0.04 mm while the temperature changed by +0.3 °C. In connection with this fact, the research also revealed that during the stay of people in the GL environmental conditions are distorted. Due to this fact, while analysing precise levelling observations in the GL, the change of environmental parameters caused by the presence of people in the GL needs to be considered. Levelling measurements demonstrated the validity of this method of measurement (it is possible to achieve the measuring accuracy at the level of hundredths of a millimetre) when environmental conditions are stable in the GL.

During STAGE I four “photogrammetric 3D gap gauges” (Fig. 12) were stabilized on the selected faults of the GL passage (along 03-04 WT tiltmeter). Figures 12B and 12C present two selected tectonic faults with the installed passive targets of the

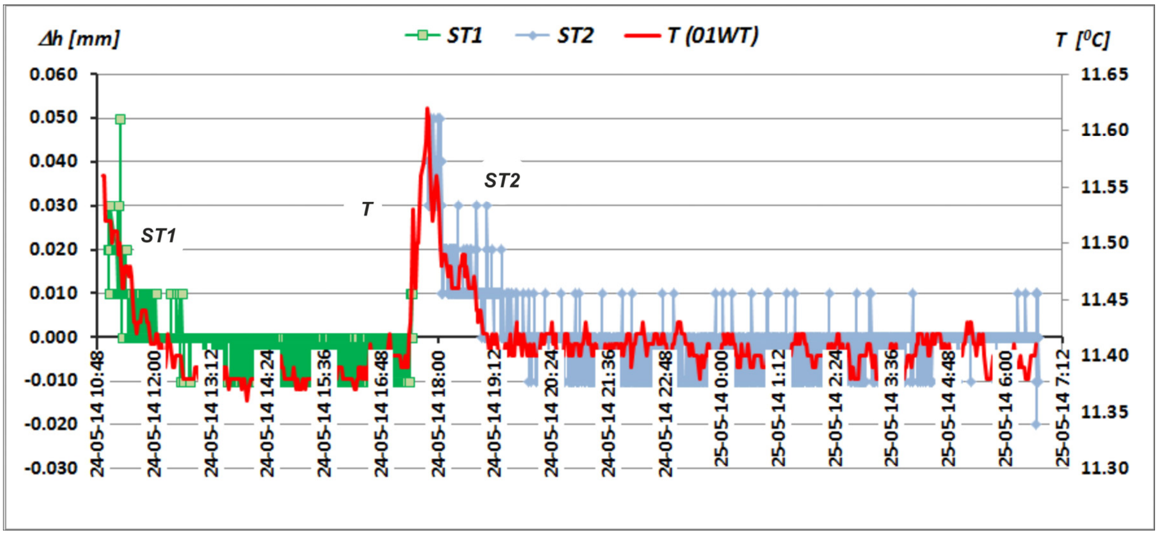


Fig. 11 Results of temperature measurement in the GL and height changes of the level line of sight (on two stations) in the time function.
Where: ***T*** - temperature measurement inside the GL - sensor 01WT;
ST1 - height changes of the level line of sight (Δh_1) on station 1;
ST2 - height changes of the level line of sight (Δh_2) on station 2.

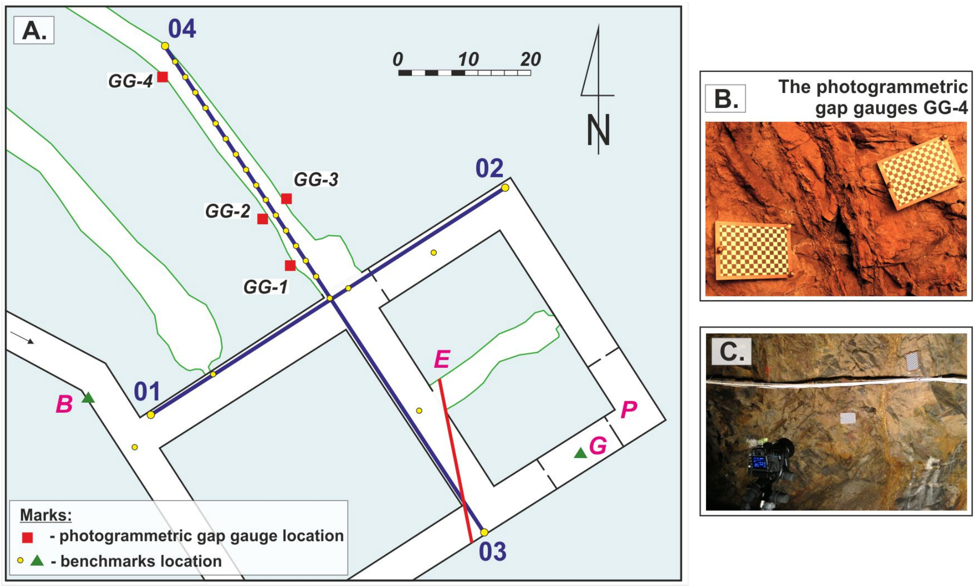
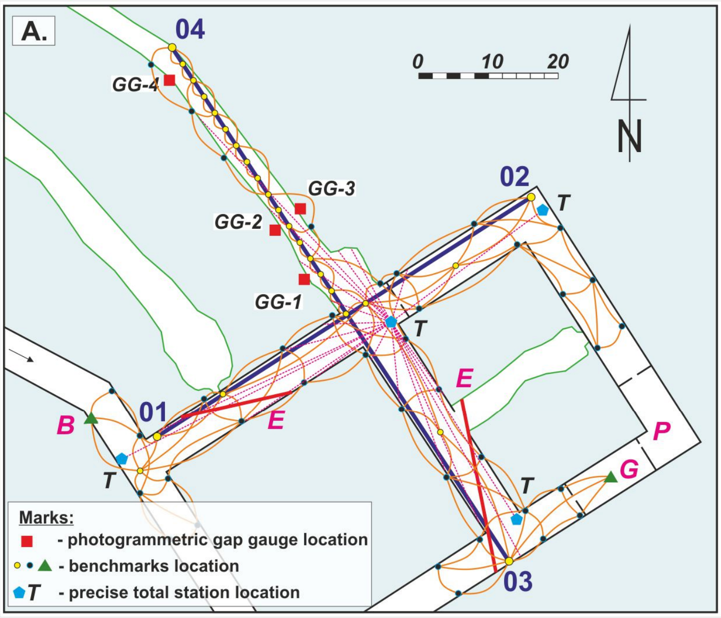


Fig. 12 Position of the measuring equipment in the GL (STAGE 1).
A. Location of photogrammetric 3D gap gauges on selected faults in the GL passage and of stabilized bench marks (STAGE I);
B. Stabilized targets of the ***GG-4*** photogrammetric gap gauge on the fault;
C. Location of measuring equipment on the fault ***GG-1***.
Symbols: ***01-02*** and ***03-04*** - WT tiltmeters, ***E*** - extensometer, ***G*** - gravimeter, ***B*** - benchmark, ***P*** - horizontal pendulums, ***GG-1, GG-2, GG-3*** and ***GG-4*** - 3D photogrammetric gap gauges.

photogrammetric 3D gap gauges. Measurements of target displacements are based on principles of mono photogrammetry. Recorded images of ***GG-4*** photogrammetric gap gauge targets during 4 observation cycles will enable us to assess the activity of the investigated tectonic fault. To determine translations and rotations of the fault flanks we will use our own software. The obtained results are currently being processed and analysed. Analyses we conducted so far indicated that measurement accuracy is at the level of hundredths of millimetre.

Figure 13 illustrates the idea of extending the research network inside the GL. Figure 13A depicts the planned hypothetical location of survey points, instrument stations and measuring equipment in the GL compared to the original situation (Fig. 13B).



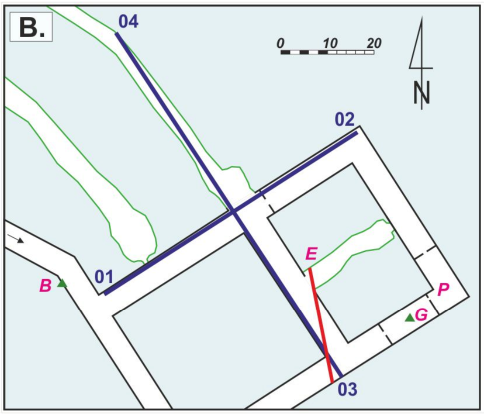


Fig. 13 The idea of extending the research network in the area of the GL

A. The planned location of the survey points, instrument stations and measuring equipment in the GL area;

B. The original location of measuring equipment in the GL area.

Symbols: ***01-02*** and ***03-04*** - WT tiltmeters, ***E*** - extensometer, ***G*** - gravimeter, ***P*** - horizontal pendulums, ***B*** - benchmark, ***T*** - precise total station ***GG-1***, ***GG-2***, ***HH-3***, and ***GG-4*** - 3D photogrammetric gap gauges.

Figure 13A also shows the planned stations of a precise electronic tachometer, whose angular and linear observations enable spatial linking of points that constitute the control and survey network. It can be seen that the distribution of survey points along the WT tiltmeter is "superficial", which will enable to identify the active intermediate faults in the GL. Such a design of the control and survey network will help to obtain information necessary to interpret indications of the WT tiltmeter.

4. CONCLUSIONS

We expect that the proposed research will enrich our knowledge about the changeability, the course and direction characteristics and amplitude of tectonic events. This knowledge will enable to build a model of tectonic deformations of the Książ Massif, with a qualitative and quantitative description of this phenomenon. Tectonic deformation modelling will help to indicate directions of the main tectonic pulses causing movements on faults, displacements and inclinations of rock blocks and to estimate the deformation compensation coefficient. Evaluation of deformation compensation coefficient is an important element in the assessment of seismicity in the region. Estimation of the deformation cumulative component gives rise to the discussion on the possibility of predicting future tectonic events and on the tectonic activity in the Sudetes.

The location of very sensitive instruments of the GL that have a nanometre and microsecond resolution and precise geodetic control and survey network will provide a holistic and comprehensive overview of processes that occur in the Książ Massif. These data after processing will be used to study changeability of the main direction of deformation and stresses and to build a realistic, multi-component rock mechanics model of the Książ massif. The rock mechanics model will be the basis for evaluation of the tectonic deformation compensation effect.

The specific location of the GL of the SRC in the tectonically active area and its unique measuring instruments, which register in real time tectonic pulses with the nanometre resolution, create favourable conditions for investigating how tectonic events occur (Bower, 1973; Kaczorowski, 2009a, 2009b; Kaczorowski and Wojewoda, 2011).

Tectonic activity of the Earth crust is accompanied by the large-scale (global) displacements of tectonic plates. Large-scale movements of plates activate smaller tectonic units (regional units) such as the Bohemia Massif or the Sudetes massif, which, in turn, necessitate the activity of local tectonic units, for example of the Świebodzice Depression. Thus, the mechanical behaviour of the Świebodzice Depression blocks, including the Książ block, is determined by the stress fields that are propagated from significant distances through contact surfaces of adjacent blocks. Contact surfaces transmit the stresses to the interior of the Książ Massif causing local deformation fields observed by the GL instruments such as displacements and tilts of the rock bed, movements on faults and the object deformations. High complexity of tectonic signals recognised so far that were registered by the GL instruments is caused by numerous faults in the area of the Książ Massif and likely changes of the stress field main directions.

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