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ORIGINAL PAPER

MONITORING OF TECTONICALLY ACTIVE AREA OF BOCHNIA

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ABSTRACT

Geodynamic studies on tectonic activity in the region of the Polish Carpathians have been carried out by many years with insufficient results. They were usually evaluated from geological data and particular approaches led to ambiguous, different or contradictory conclusions.
The authors discuss displacements in the area of Bochnia evaluated from underground measurements as well. The deformations observed are linked to old mining. However the characteristics of the deformations can not be explained by mining effects alone. The horizontal displacements and deformation of shafts in Bochnia correspond to similar effects observed in the Wieliczka salt mine; there is a northward tendency despite the differences between its geological and mining environments. The direction of this tendency corresponds to the orientation of tectonic stress and the orientation of tectonic structures.
The authors draw conclusions about the modern geophysical methods to be applied in the research into the tectonic activity of the area. According to the authors reliable investigations should be carried out both on the surface (GNSS) and underground with the use of a combination of geophysical and geodetic methods: strainmeter measurements, clinometers etc. These methods provide reliable permanent observations of stress-strain variations – essential for filtering data to allow a separation of the non tectonic components and for determining the linearity or non-linearity of tectonic processes in real time. New type of data will be investigated by using the results of deformations permanently monitored by geophysical and geodetic methods.

1. INTRODUCTION

According to many authors the vertical movement rate of the Carpathian Foothills based on geological data is about 0.3 mm/year. Despite this, the results of the leveling measurements, which have been carried out for 70 years, provide ambiguous results which range from -1 mm/year to +1 mm/year (Zuchiewicz, 2010). From the above one can conclude that a long-term analysis is necessary, which goes beyond the time of any individual research project. The GNSS technique is promising as a tool in marking the field of horizontal dislocations of the Carpathians. But there are still not enough reliable data describing the mobility of the Carpathians in detail and from a sufficient time perspective. This is connected with the inadequate number of geodynamic traverses or the failure to fully use the existing measurement points. On the other hand GNSS permanent working stations provide displacement results which are affected by many factors, such as weather conditions or seasonal changes of groundwater level.

According to Szczerbowski and Jóźwik (2002) the non-typical rock mass in Wieliczka reveals spectacular deformations when observed by geodetic methods. The characteristics of horizontal displacements there led them to the conclusion that the shafts in the Wieliczka Salt Mine had deformations corresponding to the directions of geodynamic movements occurring in the Wieliczka rock mass. The present analysis – the underground monitoring of geodynamic movements - can be defined as an innovative approach in geodynamics. The investigations presented in this paper by an augmented team of authors are a continuation of the above mentioned research work. Dealing with the same problem in another but tectonically and geomechanically comparable salt deposit in Bochnia, another case study is presented, the Bochnia salt mine, where deformation rates are much higher than in Wieliczka.

2. GEOLOGICAL SETTING AND MINING CONDITIONS

The geology of the salt deposit in Bochnia is well recognized thanks to long-time mining exploration works and has been widely discussed in numerous papers (Poborski, 1952; Poborski and Skoczylas-Ciszewska, 1963; Garlicki, 1968; Garlicki, 1979; Tarka, 1992; Wiewiórka et al., 2006; Wiewiórka et al., 2008; Wiewiórka et al., 2009).

The area of Bochnia is at the boundary of the Outer Carpathians and the Carpathian Foredeep (Fig. 1). This zone can be described as having

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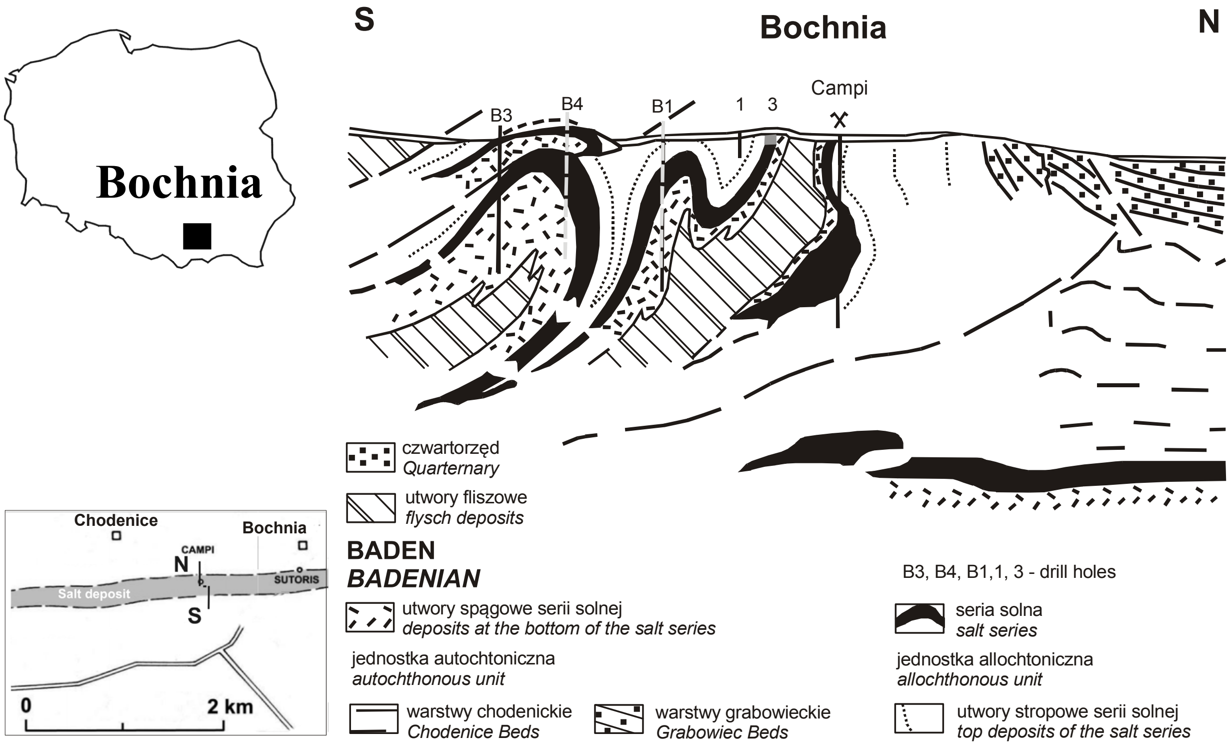

Fig. 1 Geological cross-section through Bochnia vicinity (after Garlicki, 1968).

complicated tectonics, whose recent tectonic activity was already discussed by Liszkowski (1982).

The Bochnia salt deposit is situated in a narrow belt of folded Miocene strata, called the allochthonous unit, which spreads along the northern border of the Carpathians. Uplift of the deposit was related to overthrust movements of the Flysch Carpathians over the strata of the Carpathian Foredeep. Due to these movements, the salt series were thickened and uplifted towards to the surface (see: Poborski, 1952; Poborski and Skoczylas-Ciszewska, 1963; Garlicki 1968; Garlicki, 1979).

Investigations on recent tectonic movements of the Outer Carpathians have been ongoing for several decades, involving of successive generations of researchers.

According to Zuchiewicz there are several uplifted tectonic zones, with similar uplift intensities, rates and durations in different parts of the orogen (Zuchiewicz, 2001). These zones are aligned subparallel to the Carpathian belt, and the Bochnia area is one of them.

The problem of determining neotectonic movements in the Bochnia salt mine lies in separating tectonic from human-induced movements. Rock mass changes were analyzed geodynamically underground by Szczerbowski Z. and Jóźwik M. (2002) in the Wieliczka salt deposit about 30 km west of Bochnia. The northward direction of displacements of the Kinga and the Danilowicz shafts in the Wieliczka Salt Mine were interpreted by the authors as involving the impact of the tectonic stress field.

Long experience in the protection of old excavations and long time observations of convergence in the Bochnia mine provided data showing a diversity in the distribution of stress within the mine, which is an effect of the tension of the Carpathian overthrust. This diversity in stress distribution is reflected in the different convergence rates of the mine galleries, which are both parallel and perpendicular to the strike of the deposit, thus showing extremely different orientations to the Carpathian massif and the direction of overthrusting (Toboła and Bezkorowajny, 2006).

The Bochnia mining excavations, which are N-S oriented i.e. in a direction perpendicular to the strike of the salt deposit and parallel both to the general movement of the Carpathians and to the orientation of the stress field, as estimated by Jarosiński (1998). The historical chambers oriented in that way are usually well preserved and they are considered to be stable in the long term. In contrast, W-E oriented excavations demonstrate deformations and convergence rates which are much higher reaching values of over 6 mm/year (Toboła and Bezkorowajny, 2006). These rates were calculated on the basis of geological and mining indicators, such as the shortening of mine timbering elements and remnants after the complete closure of galleries due to the convergence of mine workings (Toboła and Bezkorowajny, 2006). This existing stress and its northward orientation may be evidence of recent movements of the Carpathians. Recent estimations of convergence are based on high accuracy measurements. The observed linear velocities of the compression in the Bochnia mine is 1-2 ‰ per year and the accuracy of the measurements is 0.1 mm for the convergence bases with the length 6 m (Bieniasz and Wojnar, 2007).

Some more geological manifestations of recent rock mass movements within the deposit after its final formation are discussed in (Toboła and Bezkorowajny, 2006).

Observations in the Bochnia mine show differences in the convergences of mining excavations in some areas of the rock mass according to their orientations to the deposit's strike and to the margin of the Carpathians (Toboła and Bezkorowajny, 2006). The rate of several per mille of the convergence of the excavations of the Bochnia mine and the problem of their maintenance is well-known from historical times (Wodyński, 1991). Preceding geological investigations in the mine and geodetic measurements (carried out for usual every day purposes of the mine) on ground level and underground made available an outline of the deformation state or the overall characteristics of geometric changes. The results of these surveys do not single out unambiguously the tectonic component in the general outline of the deformations.

Although vertical displacements caused by tectonic stress are possible if not significant, the horizontal component is probably the dominant effect of the total displacement effect. As mentioned above, indications of this in Wieliczka were given by geodetic methods, and horizontal displacements had characteristics that cannot be explained by mining (Szczerbowski and Jóźwik, 2002). Maximum magnitude of displacements observed in the Wieliczka shafts is located at the depth 160-180 m and it amounts to about 140 mm, where the accuracy of the measurements is 3-4 mm. It means that a speed of the process in this case is 3-4 mm/y. No such geodynamic observations for a determination of a tectonic stress have been carried out in the Bochnia mine, as yet.

So, given the similarity of the Wieliczka and Bochnia salt deposits, the same effect can be expected in the Bochnia mine.

3. MEASUREMENTS OF UNDERGROUND AND TERRESTRIAL DISPLACEMENTS

Although there are many studies dealing with geodetic underground measurements, they are usually devoted to practical problems in mining, such as tunneling. The displacements currently evaluated also used measurements carried out in the Bochnia mine for engineering purposes. A detailed examination of the data was performed by the authors to detect effects of tectonic impact.

Geodetic monitoring of underground excavations was involved in efforts to preserve the Bochnia mine as a historical object. Geodetic surveying in the mine has a long history, addressing geological, mining, networking (cartographic) matters. Not only have documents devoted to mine surveying survived through the ages, but the geodetic infrastructure itself (control points, benchmarks) as well, so they are still of use today. It is essential to monitor still existing deformations caused by the compression of old excavations as a response of surrounding rocks to loads. The plasticity of the rock salt is the main "damper" in the cave-in process (Jeremic, 1994).

So, in the context of maintenance works geodetic measurements are carried out as follows:

- leveling for the estimation of vertical displacements. There are particular terrain and underground networks, and highly accurate observations of benchmarks reveal displacements important for the estimation of potential hazards. The average time period between campaigns is 3-5 years, maximal rate is about 15 mm/year;
- horizontal observations. Distance and angle measurements are carried out on observational lines comprised of control points. Evaluated changes in their coordinates are used in the estimation of orientations and rates of displacements. There are two main lines: the BB – located on the terrain surface, passing the Bochnia town nearly longitudinally. Another line is divided into sections and it is located at various levels of the mine. The accuracy of the measurements is lower than that of leveling.
- observations of mine shaft deformations. Previously, measurements were devoted to deformation of a shaft's axis and the verticality of shaft guides. Currently the measurements are based on control points mounted in the Bochnia shafts, so they reveal vertical and horizontal displacements of the points. The points form an extraordinary spatial network that can be used for the monitoring of a large portion of rock mass deformations in a particular cross-section with decent accuracy (1-2 mm). There are three still existing historical shafts in the mine: Campi, Sutoris, Trinitatis.
- convergence surveying of underground excavations. The surveys are carried out for the design of the protection of underground excavations. There is a specialized engineering service involved in measurements (Bieniasz and Wojnar, 2007):

1. stationary tubular, rod, tape or wire convergometers – for deformation measurements of bases in caverns, headings, pillars,
2. portable, spring tool for reading the measurements made using typical measuring tape (wire) or the even more popular laser rangefinders.

All these methods have a stationarity in nature: they yield changes in positions, the latter methods giving only the relative change in measured distances.

Assuming that the orientation of the main component of tectonic stress is longitudinal, in

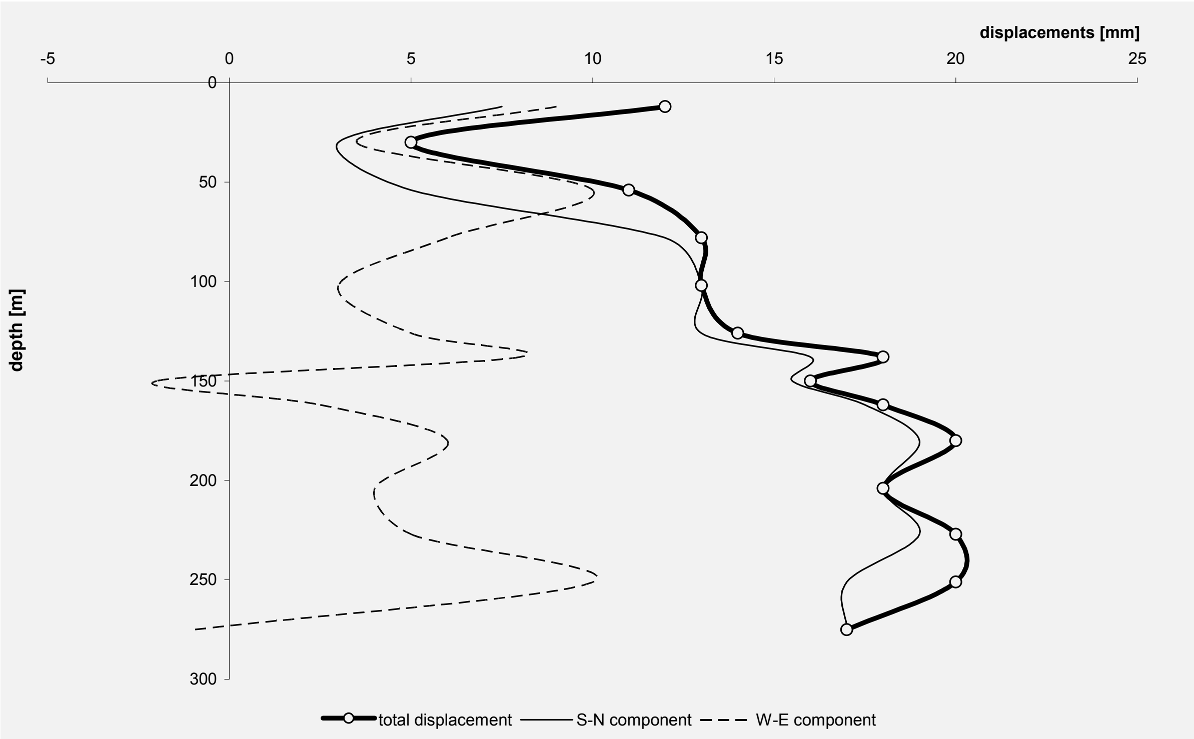

Fig. 2 The Campi shaft. Displacements of benchmarks (the Rp.1 series) on particular mine's levels between 2009-2011 [mm]. Accuracy for the S-N and W-E components is 3 mm and total displacement is determined with the error 9 mm. Data interpolated by fitting curve using third degree polynomial.

accordance with the deposit's strike and with the margin of the Carpathians, horizontal displacements were studied, displacements of Bochnia mine shafts and displacements of the control points of the observational line mentioned before. Although influence of mining excavations is the main factor of the observed displacement process, there are some deviations that may be a manifestation of tectonic stress.

3.1. DEFORMATIONS OF THE CAMPI SHAFT

According to mining regulations all working shafts in the Bochnia mine are under the control of geometry. This involves periodical measurements of the verticality of shaft guides, deformation of the shaft vertical axis etc. As a result of control measurements, deformation parameters are determined as follows: vertical and horizontal displacements of a shaft's housing with its fitment, horizontal and vertical tensions of a shaft's housing with its fitment and torsions of a shaft's housing with its fitment.

The control measurements in the Bochnia were carried out over years and as in many other mines the evaluated values of rates were only relative. They were related to the theoretical verticality of the shaft's axis and tensions were based on differences in measured distances. In 2009 a new type of measurement was started. Control points were mounted in the shaft tube, with four around the tube at particular levels, and the distance between the levels was 12-24 m. The deepest level was 275 m below the surface. Over 2 years of observations horizontal displacements amounted to 20 mm (Fig. 2). The mean error of the measurements was 3.0 mm for each component of the displacement vector. The dominant component of the displacements – X is longitudinal (S-N). This means that the Campi inclined northward. This is a direction of deformations quite other than expected i.e. as evaluated from the subsidence basin with the center developing in the south east of the shaft and implying centripetal displacements. The calculated azimuths of the horizontal displacement vector vary from 353° to 64° with the average value amounting to 23° (Fig. 3). The estimated average error of the azimuth was 12.5°. This is almost exactly the azimuth of the displacements of the Kinga shaft in Wieliczka (Szczerbowski and Jóźwik, 2002). There is a distribution of the vectors on the particular mine's levels presented as well. The calculated displacement rates estimated by absolute measurement (in reference to stabile points of the geodetic network on the surface) amounted to 15 mm/year. This value is 2-3 times higher than estimated from earlier relative measurements in the Campi, and in the Kinga (Szczerbowski and Jóźwik, 2002). Unfortunately this new approach forecloses a direct comparison between the results of previous measurements (different reference points and coordinate system). Although the

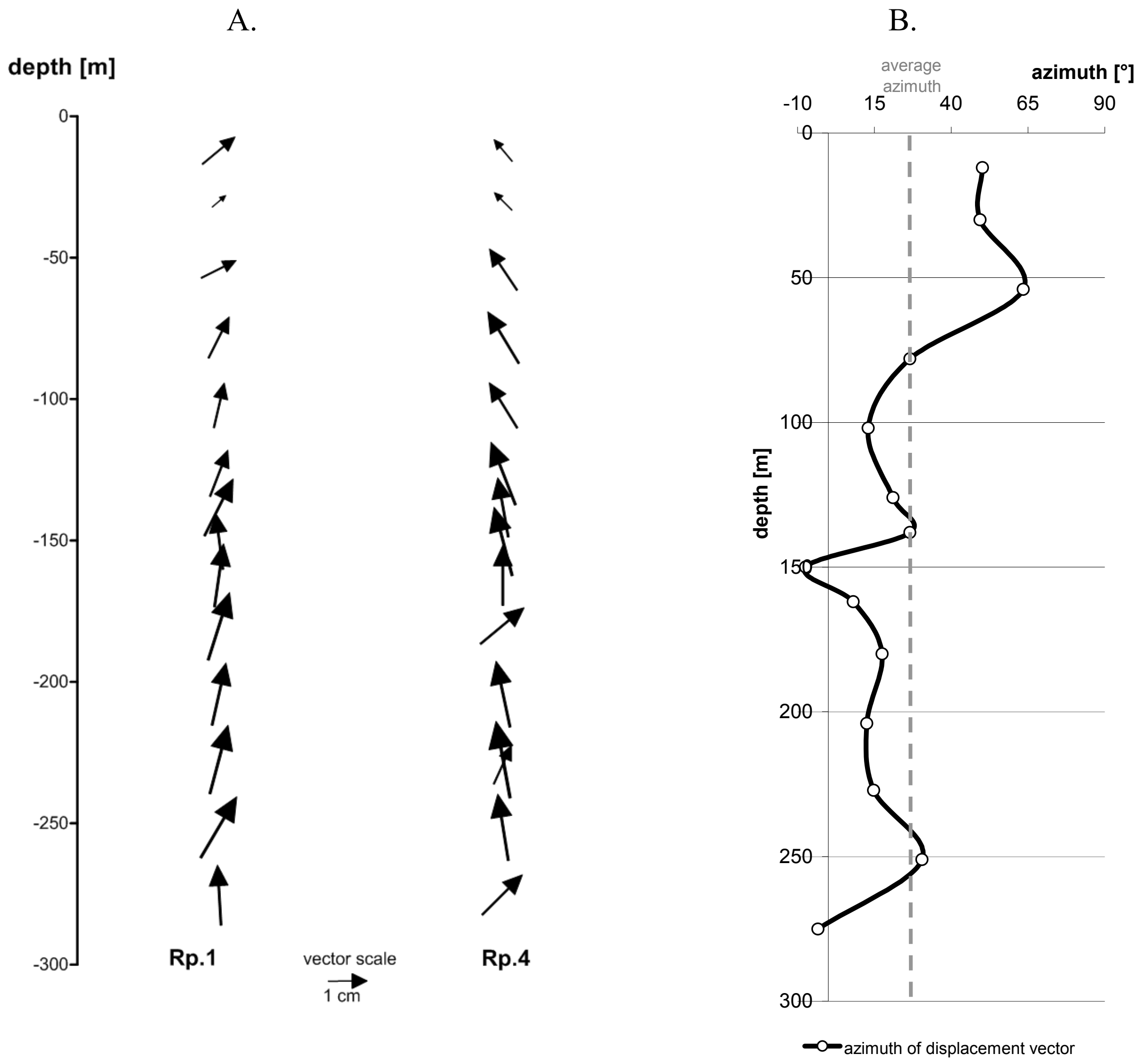

Fig. 3 The Campi shaft. Displacement vectors s of benchmarks (the Rp.1 and the Rp.4 series) on particular mine's levels between 2009-2011 (A) and azimuths of the vectors in that period (B). Average value of error of measured displacement vector is 9 mm and for average error of derived azimuths – 12.5°.

process of the deformation of the shaft's axis is steady, it is impossible to combine old and recent observations as a recalculation of displacement rates.

There are disturbances, as in the Kinga, probably resulting from the influence of mining workings located near the shaft. The best illustration of that similarity is the diagram of azimuths (Fig. 4), which is nearly the same as the diagrams of the Kinga in Wieliczka (see: Szczerbowski and Jóźwik, 2002), where there is completely different situational plan of mining excavations the source of stress induced by compression process.

3.2. HORIZONTAL DISPLACEMENTS OF CONTROL POINTS

The angle and distance measurements carried out in the area of the Bochnia mine yielded the results of horizontal displacements and the azimuth of the displacement vector of control points mounted both on the surface and underground in the mining excavations. The surveys carried out by Jóźwik in 2004 are highly accurate for engineering purposes (especially given the conditions in the underground measurement environment). Unfortunately, a 2-4 mm error is not satisfying for a detailed analysis, but in the context of total displacements amounting to 10-160 mm (within 6 years) the general outline of the movements is reliable. So, according to the measurement error, the azimuths may be distorted by about 10-30°. Even so, any qualitative estimation of the displacement process is valuable. The authors just concentrate on the mine's shafts. So, these results may be evaluated independently of those presented in section 3.1 and they concern control points located in the shafts. Regular spirit leveling measurements of benchmarks on the surface provide information about vertical displacements in the city of Bochnia. All benchmarks revealed linear subsidence trend as an effect of old mining activity, and the geometry of the subsidence contour lines is steady. So, the geometry

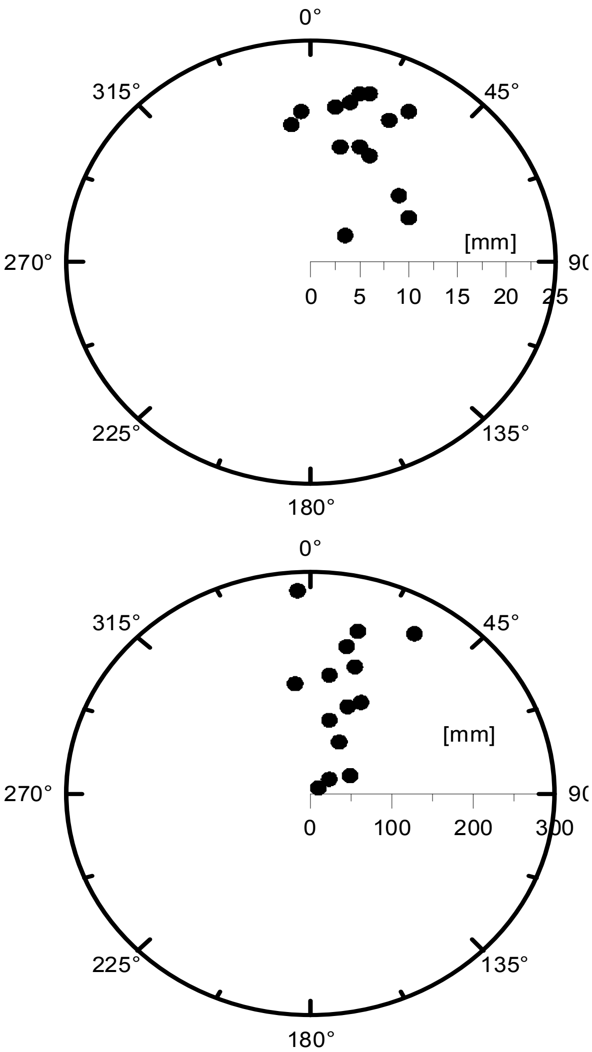

Fig. 4 Diagram of azimuths as a function of vector's magnitude (A) and as a function of depth (B).

of the contour line distribution for any period is nearly the same. As an example, vertical displacements in the area of Bochnia from 1997 to 2011 are presented in Figure 5. The evaluated values of the vertical displacements are characterized by very high accuracy, the average error of a benchmark vertical displacement being about 1 mm. The data of vertical displacements were evaluated from the results of measurements carried out by personnel of the Bochnia mine surveying department (Józefko, 2002). The contour lines were evaluated by the kriging algorithm. The central part of the subsidence basin (maximal vertical displacements) is located southward of a line passing the Campi and Sutoris shafts. The distribution of the displacement should be a superimposed on the underground effect (subsidence at lower elevations should correspond to the surface subsidence basin) but there is no adequate underground network, by which to evaluate a map of vertical displacements. Expected horizontal displacements should be oriented to the center of the basin but they are not. The values of horizontal displacement vectors are the averaged results of the displacements of underground control points located near a particular shaft (Fig. 5). The maximal value of horizontal displacements was found in the Campi shaft – 11 mm/year and the error of total displacement for the points is 8-9 mm. This value corresponds to the horizontal rates of benchmarks mounted in the shaft tube and discussed in the previous section. The average azimuth of control points located just at the shaft was 6°. This northward direction is close to that estimated for of the Campi on the basis of the above mentioned benchmarks (23°). The rates of horizontal displacements determined for the Sutoris are similar – 9 mm/year but the azimuth is 324°. It is nearly northward in direction but slightly distorted, probably by the influence of mining – the

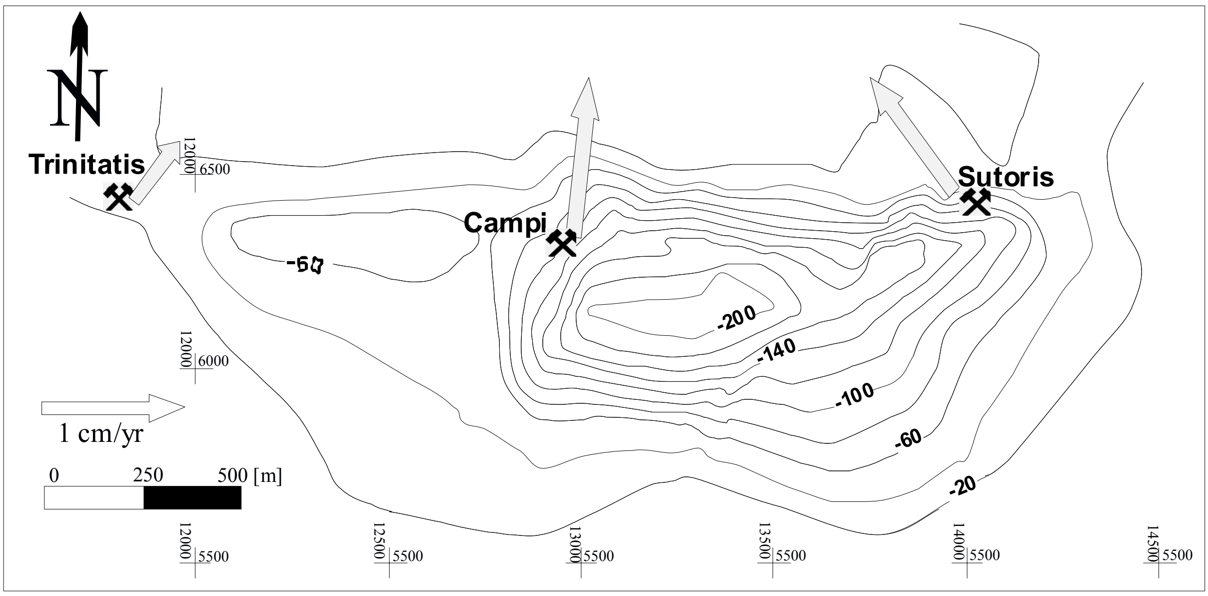

Fig. 5 Directions of horizontal displacements determined from observations of control points located at the Bochnia shafts and vertical displacements in the area of Bochnia from 1997 to 2011 [mm].

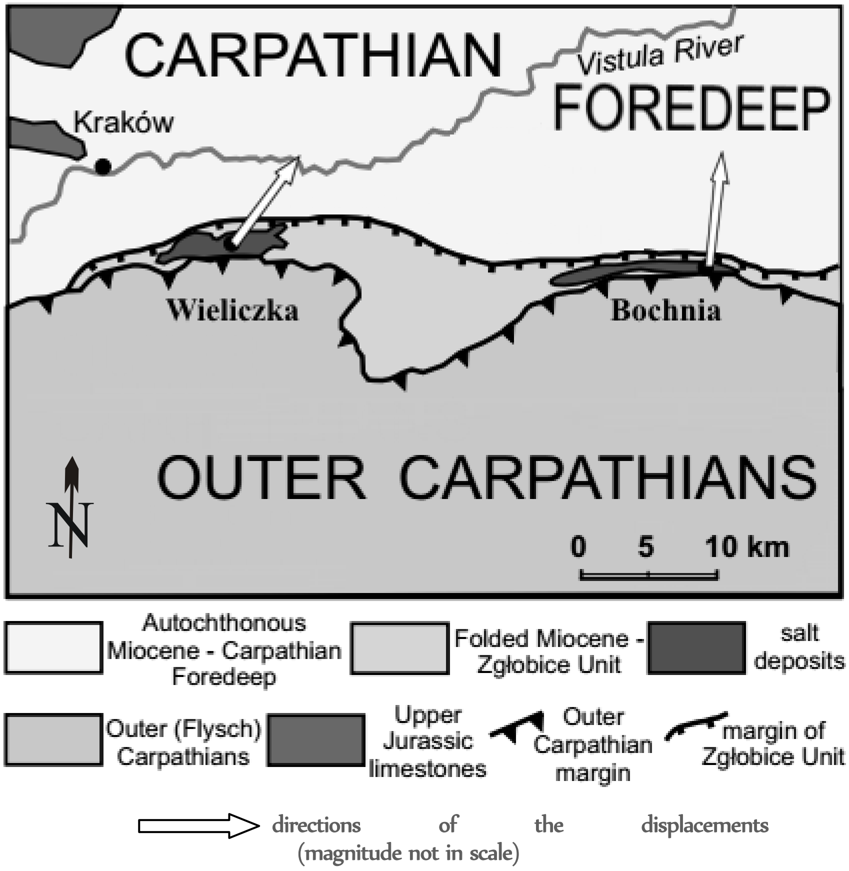

Fig. 6 Directions of horizontal displacements determined from measurements in shafts in Wieliczka and Bochnia salt mines on geological background (geological situation according to Wiewiórka et al, 2008).

excavations at the centre of the subsidence basin are located in the west of the Sutoris, so a westerly distortion is observed. The third shaft, the Trinitatis, is located west of the center of the subsidence basin and behind the mine workings, so should be practically free of rock mass deformations caused by mining. However, long time observations proved that these are, in fact, shaft displacements unrelated to mining. According to the results of measurements carried out in 1996-2002 by the mine's surveyors the average displacement rate was 5 mm/year – much higher than the error of measurements. The azimuth of the control points located near the shaft was 45°.

All azimuths of the displacements of the control points in the Bochnia shafts show a visible trend in displacements that cannot be related to mining factors. The impact of mining chambers may be seen as a distortion of the trend.

The displacements of the shafts considered proceed differently. The vectors are generally northwards. The same results were obtained in Wieliczka. Three shafts of the Wieliczka mine displace northward, although there are some distortions caused by mining as well (Szczerbowski and Jóźwik, 2002).

The general direction of rock mass dislocations observed in the shafts in Wieliczka is parallel to the orientation of neotectonic movements determined by geological methods used in some articles (Tarka, 1992; Zuchiewicz, 1995).

The average value of displacement vector azimuths observed in the Campi shaft (considering benchmarks and the control points) is 15°. The azimuth of the resultant displacement vectors of all the shafts in the Bochnia mine is 8° and in the Wieliczka it amounts to 38° (Szczerbowski and Jóźwik, 2002). Figure 6 illustrates the average values of the displacements determined from observations in the shafts of both mines. Relationship between the tectonic orientation of the salt deposit formations in Wieliczka and Bochnia and the vectors of the displacement process is clear.

4. UNDERGROUND MONITORING IN THE BOCHNIA MINE –CONCEPT AND ITS APPLICATIONS

Bearing in mind some geologists' conceptions of the recent tectonic activity of the Carpathians (Zuchiewicz, 2010) and the results of the geological analysis of strain tensions by borehole breakout analyses (Jarosiński, 1998), the question arises of how this stress manifests itself in time in terms of its values or directions and which deformations of rock mass it induces. A number of fundamental research problems are raised. These involve the distribution of stress over time; the possibility of identifying the tectonic component in the process of the rock mass deformations effected by old mining; the delineation of permanent deformations of plastic salt rocks or outer barren rocks as the outcome of tectonic stress; the possibility of describing deformations caused by various factors (tidal stress, loadings, for example atmospheric pressure); the identification of seasonal effects related to changes of weather. Any estimation of regional tectonic mobility is often difficult due to interactions between the mobility of local and regional geological structures. An additional difficulty in investigations of this area arises from the interpolation of a non-tectonic component which interferes with the values of the kinematic parameters of geological structures.

These displacements can be for the following three reasons (Poborski, 1982): the influence of mining excavations (a mining factor), neotectonic stress related to Carpathian movements (a tectonic factor), uplift movements of salt deposits (a halo-tectonic factor). Each factor generates a different component of the displacement vector. Moreover, the dislocation process proceeds in mechanically diverse rocks. The results presented provide a general outline of the deformation process in the area of Bochnia. The positions of control points have differed with time, so the process of displacements is not completely clear and sources of the observed effects cannot be recognized. To produce a detailed outline embracing particular sources of deformation and their particular contribution to an end result is challenging but this area seems to be a good place to accumulate and analyze the necessary data.

From their analysis of the conditions in this environment the team of authors drew the same conclusions and they suggest a new approach in neotectonic studies. New research should engage with a wide range of geodynamical phenomena i.e. non-periodic tectonic phenomena, post-mining deformations of salt rock mass and periodic phenomena i.e. tides and free oscillations of the Earth (Kaczorowski and Wojewoda, 2011). In both cases (periodic and non-periodic) there are some effects to be observed related to changes in the stress field involving vertical and horizontal deformations, inclinations of the basement and volumetric deformations of the rock mass. According to results evaluated in the only geodynamic Polish observatory, in Książ (LG Książ), tectonic deformations of the rock mass have an episodic (event) character caused by changes in the tectonic stress field, whose source is not clearly established (Kaczorowski and Wojewoda, 2011; Kaczorowski, 2013). For engineering purposes there have been analogous systems based mainly on geodetic methods and working in tectonically active mining areas, widely discussed in (Blachowski et al., 2099; Blachowski et al., 2010).

Permanent geophysical monitoring carried out underground (free of atmospheric effects etc.) is essential. The investigations of strains and deformations in rock mass with the application of specialized apparatus will elicit precise information on their temporal and directional distributions.

The implied aim of the project is to obtain temporal and directional outlines of strain changes of the Bochnia rock mass, which will allow the identification of the tectonic component of Carpathian activity. Since the projected surveys will be carried out in the Bochnia mine in a salt rock massive, it may be expected that recorded signals will be those caused by mining (anthropogenic – a compensation movements of mining excavations) and signals resulting from tectonic effects of Carpathian orogeny. Appropriate analysis of observations carried out permanently and appropriately designed measurement stations will enable the separation of these signals and acquire data about recent tectonic activity of the Carpathians and their temporal and directional characteristics. This was of interest to generations of geologists but ambiguous results did not allow the formulation of a theory about the recent mobility of the Carpathians. In this sense this research has fundamental scientific significance. The instruments which are to be installed in the corridors of the Bochnia mine for the determination of deformations of the salt orogen with micrometric accuracy (10^{-3} mm) by the method of crack gauge measurements and with nanometric accuracy (10^{-6} mm) in the case of an interference extensometer with a 50 meter long measure base. The authors expect that observed deformation signals will reflect local scale effects produced by the post-mine activity of the orogen, as well as global scale geodynamic effects.

The separation of non-periodic signals or long periodic signals of tectonic origin (tectonic activity of Carpathians) from the signals of local deformations of the salt orogen caused by gravity compensation processes is an indirect goal of this project. To solve this problem, methods to minimize mining origin signals and to properly magnify geodynamic signals will be adopted. Such analysis for the elaboration and separation of signals registered by instruments is already successfully applied in the Geodynamic Laboratory in Książ.

5. CONCLUSIONS

The geodetic investigations carried in the Bochnia salt mine have revealed the rock mass movements of the salt deposit. The displacements of shafts in the Bochnia mine demonstrated in general a northward direction, completely incomprehensible in terms of the influence of mining. The authors did also consider the impact of mining factors on deformations but its role is not significant in the process. In addition the directions determined from control points mounted in the Campi shaft or in the vicinity of this and other shafts in Bochnia show displacement directions almost identical to those of Wieliczka shafts. Although the relative displacement rates correspond to those in the Wieliczka mine (Szczerbowski and Jóźwik, 2002) but new surveys in the Bochnia mine will be connected to the national network. Horizontal displacement rates in absolute terms amounted to 15 mm/year, i.e. three times higher than displacements related to the theoretical verticality of the shaft's axis. All such facts suggest the impact of tectonic tension and that these displacements result from geodynamic movements or that they illustrate the action of geological stress related to the development of salt structure.

The general conclusion of the paper is to urge the application of a measurement system for a detailed estimation of deformations. The suggestion of the authors for deep underground permanent monitoring which combines geodetic and geophysical instruments in the rock salt mass for an estimation of tectonic activity is a novel approach in geodynamics. The adoption of these measurement systems will provide a reliable and satisfying description of the tectonic activity of the Carpathian orogen.

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