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High energy events as a combined effect of human impact and geoenvironmental factors - the case study based on GNSS data

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Abstract

In the Upper Silesian Coal Basin (USCB) mining region in Poland, coal production has been gradually reduced for many years. Nevertheless, the number of high-energy tremors remains at a similar level or decreases much slower than production. We analyze this problem in the aspect of geological setting and on the base of geodetic data. We explain the paradox by specific interaction between man-induced and natural tectonic stress as seasonal hydrological effects. Anomalous energies released during large seismic events exceeded the predetermined threshold, typical for mining tremors in the area. Further, the authors point out the seasonal occurrence of these events.

Temporal variations of distances between continuously operating GNSS (Global Navigation Satellite Systems) reference stations were analyzed, and linear strain, inferred from these geodetic observations, corresponded to high-energy tremors in the area. Consequently, the seismic events usually occurred when the analyzed baseline performance demonstrated significant seasonal increases or decreases of evaluated temporal distribution of strain. The aim of the analysis was to evaluate the relationships between the characteristics of the time series of deformations and the occurrence of seismic tremors of energy $E \geq 3 \times 10^7$J occur.

Seasonal occurrences of high-energy seismic events as the energy they released suggest the influence of environmental factors.

Keywords
monitoring; seismic; tectonic stress; mining; GNSS observations

Introduction

The initial state of stress in the rock mass depends on many factors, including the weight of the overburden, tectonics, rock properties, etc. (Gibowicz and Kijko, 1994). When disturbed by mining operations, that state leads to local disturbances in the form of an increase or decrease in the value of stresses. The initial state, however, fundamentally influences the nature of deformation and the value of secondary stresses. High concentrations of primary or secondary stresses in the rock mass may result in earthquakes (tremors) of natural or artificial origin. In the active fault zone where the stress level is critical, variations of small external stresses may become a trigger to the occurrence of earthquakes. Various kinds of phenomena are reported to be able to act as triggers. In particular, seasonal variations of some meteorological phenomena may also trigger earthquake occurrence (Matsumura, 1986).

Seismicity modulated with annual or semi-annual periodicities was a subject of many studies. This problem has been examined in tectonically active regions of the world, in particular: Japan (Matsumura, 1986; Heki, 2001), the Alps (Roth et al., 1992; Panza et al., 2011), the western USA (Gao et al., 2000; Christiansen et al., 2005; Dutilleul et al., 2015), the southern and midwestern United States (Craig et al., 2017), and the Himalayas (Bollinger et al., 2007; Christiansen et al., 2007; Adler and Avouac, 2013). Moreover, relations between seismic events and the hydrological cycle were discussed in various contexts and related to factors such as snow loading in Japan and in the western USA (Christiansen et al., 2005; Heki, 2003), variations of the water table (for example, Roth et al., 1992; Christiansen et al., 2005; Heki, 2003; Costain et al., 1987; Saar and Manga, 2003), precipitation in the Himalayas (Bollinger et al., 2007), in Ethiopia (Birhanu et al., 2018) or atmospheric pressure changes in California (Gao et al., 2000).

Mining operations are the most commonly reported human activities proposed to have caused tremors on the surface. The triggering nature of engineering activities in the release of preexisting stresses of tectonic origin induces is strongly affected by local geology and tectonics, that is, by medium inhomogeneities and discontinuities and interaction between mining, lithostatic and residual tectonic stresses on a local and regional scale (for example, Gibowicz and Kijko, 1994; Cook, 1976).

Seismicity caused by mining and natural earthquakes has the same mechanism of formation (Gibowicz and Kijko, 1994). However, natural earthquakes and mining tremors occur at different scales, and they are characterized by different amplitudes and depths of occurrence as well as surface effects (differences in intensity, time duration of the shocks, etc.). As Gibowicz's statement "so far no systematic differences have been found between mine tremors and natural earthquakes" (Gibowicz and Kijko, 1997) is still actual, then the question arises: to what extent this experience in the field of relationships between earthquakes and rock mass movements (activity of faults), conditioned by seasonal hydrological changes, can be transferred to the mining exploitation area? However, such relationships have been observed in areas with different tectonic settings and activity as California and the Himalayas (Matsumura, 1986; Gao et al., 2000, Craig et al., 2017; Christiansen et al., 2007).

The article presents an analysis of the relationship between the GNSS data and the time distribution of high-energy tremors within the area of the Upper Silesian Coal Basin (USCB). For this purpose, the characteristics of displacements recorded in the period between 2008 and 2014 in the ASG-EUPOS stations (Active Geodetic Network EUPOS): KATO (located in Katowice city), KRAW (located in Krakow city), WOD1 (located in Wodzislaw town) and ZYWI (located in Zywiec town) were analyzed. We analyze the position of VSBO station (Ostrava, Czech Republic), which operates in the Czech Reference Station Network – CZEPOS.

Next, linear deformations of the baselines, which were determined by changes in the position of these stations, were analyzed, and the obtained characteristics were compared with the moments of occurrence of high-energy seismic events. The aim of the analysis was to evaluate the relationships between the characteristics of the time series of deformations and the moments when seismic tremors of energy $E \geq 3 \times 10^7$J occur. To our knowledge, it is the first application of geodynamics theory to analyze the cause of high-energy tremors in USCB.

This paper aims to consider seasonality in so-called "mining-tectonic" seismic events that are generated by the interaction between mining and tectonic stresses in the example of the Upper Silesian metropolitan area (Poland, Czech Republic).

Since seasonal periodicity of seismicity in response to annual stress variation inferred from GNSS observations is still under debate in many journals, we found the relationship between the occurrence of mining-tectonic seismic events and seasonal deformations determined from geodetic data.

The paper's novelty is in expanding the problem of seasonal stress and seismicity in urban areas affected by mining operations; however, the movement of GNSS stations was free of direct mining effects. The submitted paper raises the important issue of geodetic strain variations in studies on seismic hazards in the area where seismic events are the result of interaction between mining and tectonic stresses. This multidisciplinary problem is focused on a regional tectonic, encompassing both natural and social features. Human impact on existing natural stress fields in rock mass was not considered in this context in any publications.

Scientific research across disciplines has a significant role in understanding the seismic mechanism and developing hazard and risk assessment approaches. Contemporary research in seismicity encompasses investigations in the geophysical, engineering, geodetic and environmental sciences. The presented paper is an example of such research.

The research comprised the following steps:

1. data collection: GNSS data (ASG EUPOS database) and seismic data (European-Mediterranean Seismological Centre – EMSC database),
2. GNSS data transformation to the local coordinate system (N, E, Up) – daily coordinates for the period June 1, 2008 - February 1, 2014 (the period of GNSS data obtained from ASG-EUPOS service). The data concern stations located in the USCB area as in adjacent areas (ZYWI, KRAW),
3. calculation of baselines' daily horizontal lengths (dimensions),
4. calculation of changes of the lengths and strain rates - a strain which was expressed as the ratio of total horizontal displacements to the initial dimension of a baseline and the changes,
5. comparison of seismic data (especially tremors of energy $E \geq 3 \times 10^7$J) and the strain for some baselines presumed as representative.

Geological overview of the study area

Mine seismicity in the USCB area is strongly affected by local geology, especially tectonics, and tectonic stress plays a more and more important role in seismicity of the USCB area due to the increase of the depth of mining operations and fault zones, which can be considered as tremor-prone-areas (Gibowicz, 1996; Patynska and Stec, 2017; Dubinski et al., 2019).

However, the lithological model of the area is simple; its tectonic setting is quite complicated due to a dense system of faults. The USCB is a triangle-shaped synclinal form with an area size of 6,100 km². It is located at the Variscan front of the Moravosilesian Fold Zone and belongs to the western frame margin of the inner-Variscan Upper Silesian depression (Jura and Kuzak, 2002). The basin was partly overthrusted along its southern boundary by the folded Carpathian massif of the Alpine orogeny partly, and the main structural pattern is formed by the two brachysynclines and overturned anticlines with thrusts oriented NNE–SSW (Jura, 2002). The coal-bearing formations of the USCB include several Upper Carboniferous lithostratigraphic series with a total thickness of 8,500 m. This mudstone and sandstone complex with numerous coal seams series is featured a moderate thickness reduction in E and SW directions. The lower part includes sediments characterized by numerous periodic marine transgressions (paralic sediments) separated by a sedimentary gap from the overlying "limnic" part of the sequence, consisting of continental sediments (Perski and Jura, 2003). The most favourable conditions for coal exploitation occur in the north and southwest of the basin, where tectonic uplifting took place, exposing a part of the Upper Carboniferous coal-bearing formation (Cabala et al., 2004).

Numerous fold, flexure and thrust structures were investigated mainly in the underground mines and many detailed tectonic studies on mesostructural scale during the subsurface mapping of the USCB area (Jura and Kuzak, 2002; Perski and Jura, 2003). Good geological recognition gave a base for the interpretation of fold-and-thrust shortening. The fundamental tectonic structure of the USCB was formed during Variscan orogenesis when the main fault and fold systems were created. In general, the basic pattern of the rock motion of the USCB was the shortening by Carboniferous coal-bearing molasse displaced horizontally in two directions: first from the north and dominant second from the west (Jura and Kuzak, 2002). Arrangement and the size of thrusts among the fault network registered in Carboniferous formations were continued in Triassic and Miocene, but the influence of the Alpine tectonic movements on the basin structure is not well identified (Pilecka et al., 2005). Possible tectonic movements during the Alpine orogenesis, new fault zones or renewal of older fault zones did not change the principal tectonic configuration of the USCB created during the Variscan orogenesis (Pilecka et al., 2005).

The local geology is presented in Figure 1a. The next Figure 1b shows the location of seismic tremors within the area of USCB of energy $E \geq 3 \times 10^7$J during the period from June 1 2008, to February 1 2014.

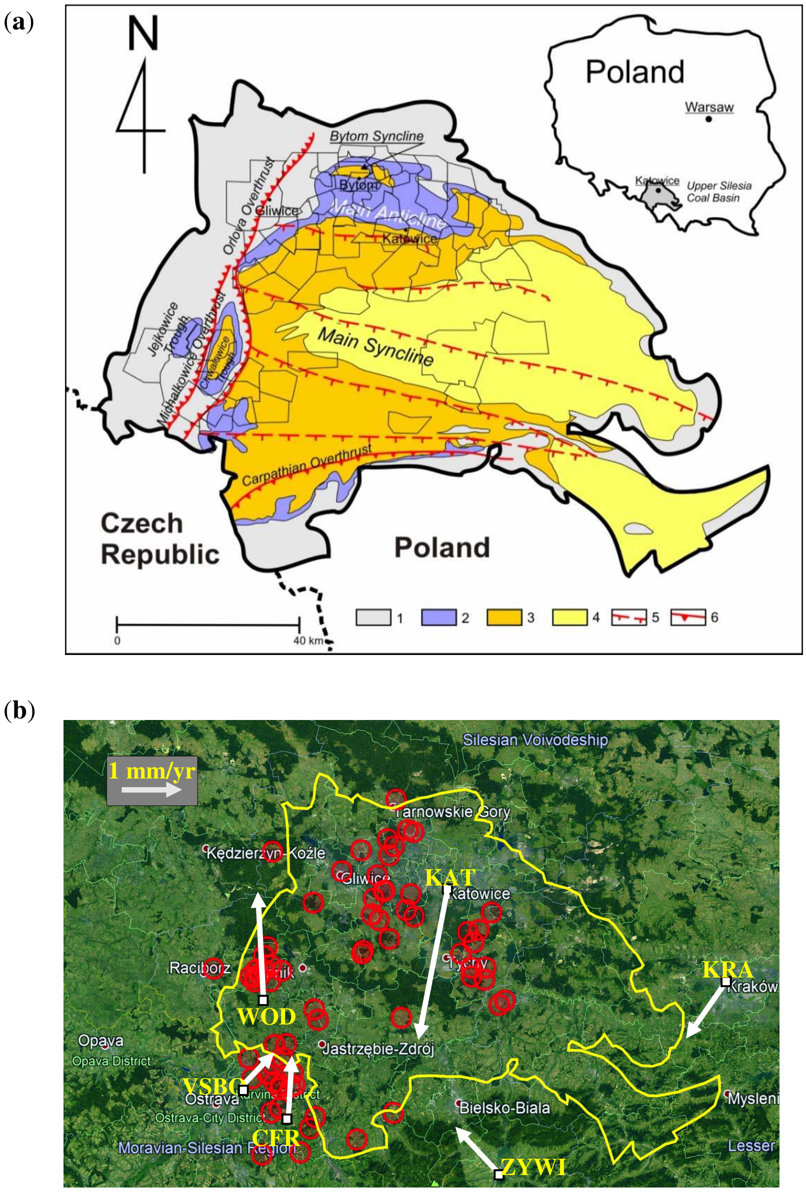

*Figure 1. The Upper Silesian Coal Basin (Poland, Czech Republic): (**a**) Lithostratigraphy and tectonics of the USCB: 1 - Paralic Series (upper Mississippian-lower Pennsylvanian), 2 - Upper Silesian Sandstone Series (lower Pennsylvanian), 3 - Mudstone Series (lower-middle Pennsylvanian), 4 - Krakow Sandstone Series (middle Pennsylvanian), 5 - important faults, 6 - overthrusts. After (Kedzior, 2015) and (Mendecki et al., 2018), modified; (**b**) Location of tremors of high energy in the period from June 2008 to February 2014 (red circles) and location of analyzed permanent GNSS station in the USCB area with vectors of annual rates of their horizontal displacements mentioned in the text – table 1 (image: Google Maps).*

Due to the occurrence of mining tectonic tremors mentioned above, the tectonic pattern is important to appreciate present-day seismic activity in the area. So, considering tremors of this type, some authors suggest several factors influencing the relationship between tectonics and mining-induced seismicity (Zuberek et al., 1997; Goszcz, 1997):

1. tectonic stress resulted from the Alpine orogeny. Such stress was recognized on the basis of geomorphological studies, and it is the result of possible strike-dip and displacements of the deep basement below the sedimentary cover of the USCB and from the overthrusts which are formed by folding of the Carpathian napes;
2. residual stress resulting from tectonic forces acting in the past;
3. stress concentrations in some tectonic structures, such as compressive stress concentration in the syncline core or the reverse fault's downthrown side. Such effects are observed in the USCB;
4. activation of stable so far regional faults due to disturbance in existing balance in stress regime by mining operations. The strongest tremors in the area are not related to underground operations, and their

localization does not correspond current position of mining operation faces – they are far away and close to larger faults;

5. changes of physical properties of rocks as a result of the state of stress influencing rock mass in the past. Some studies show relations between locations of tremors and zones of compression of the rocks that occurred for a long time in the past during orogenic phases (Zuberek et al., 1997; Goszcz, 1997).

The seismic data

The Upper Silesian Coal Basin is one of the world's most seismically active mining areas, where high energy tremors of energy $E \geq 10^5$J can be compared with some earthquakes in tectonically active areas (Gibowicz and Kijko, 1994; Zembaty, 2004). More than 59,200 mining-induced tremors of energy $E \geq 10^5$J (local magnitude $M_L \geq 1.5$) occurred over the period 1974–2017, and 25% of them were tremors of energy $E \geq 10^6$J (Patynska and Stec, 2017; Dubinski et al., 2019). Tectonics plays an important role in the seismic activity of the USCB, and the bimodality of induced seismic energy distribution is a specific feature of this area. It is generally assumed that tremors of energy $E \geq 10^5$J, considered to be high-energy, are the result of the interaction of mining-induced and tectonic stresses (tectonic-mining tremors). This issue has been discussed in many works on mining seismology (Gibowicz and Kijko, 1994; Patynska and Stec, 2017; Dubinski et al., 2019; Zembaty, 2004; Gibowicz, 1990; Lasocki, 1993a). The problems of tectonic stress and regional tremors were discussed, among others, in the works: (Gibowicz, 1996; Pilecka et al., 2005; Zuberek et al., 1997; Lasocki, 1993b; Zuberek et al., 1996; Mutke and Stec, 1997; Lasocki and Idziak, 1998).

The mechanism of mining tremors is largely determined by the geological structure and changes in the stress field existing in the rock mass (Gibowicz and Kijko, 1994). The problem of describing the mechanism of tremors is significantly complicated by multi-seam (multi-level) mining, where seismic phenomena are observed despite the lack of layers capable of accumulating elastic energy and its dynamic release (Majcherczyk and Niedbalski, 2017).

Changes in rock mass stress caused by mining operations are always associated with its displacement, which can lead to rock blocks moving along preexisting weakening planes in rocks, including discontinuity zones. Seismic tremors in the California region result from tectonic movements of rock blocks as a continuous process, though variable in time. Displacements result in a stress concentration that is dynamically released during shock. The majority of shocks occur in the fault plane, as does the movement of rock blocks indicated on the basis of measurements calculated with the use of the GNSS and InSAR techniques (Lohman and MacGuire, 2007; Hejmanowski et al., 2019). Also, in the case of the USCB area, the most common type of shock focus mechanism is the normal slip mechanism. Orientations of fracture planes for these phenomena are correlated with the extent and dip of faults located in their vicinity (Pilecka et al., 2005; Mutke and Stec, 1997).

Many years of research experience in the Polish mining industry have provided interesting results regarding tremors and rock bursts, but so far, there have been only a few studies in which this issue has been discussed in the context of deformations determined with the use of geodetic methods. Such analysis was performed for the copper mines in Poland (LGOM area), where the relationships between changes in the GNSS station position and the occurrence of high-energy seismic tremors were presented (Hejmanowski et al., 2019, Szczerbowski and Jura, 2015; Szczerbowski, 2016; Szczerbowski, 2019).

The research by Szczerbowski and Jura (2015) devoted to the characteristics of displacement of ASG-EUPOS stations in LGOM during high-energy seismic phenomena, and based on the analysis of time series of GNSS data, showed the relation between the amplitude of vertical displacements (including upheaval) observed at GNSS stations and the distance from the epicentre of the analyzed tremors. In the case of the LGOM area and the aforementioned GNSS data, a relationship between the occurrence of high-energy seismic tremors and the characteristics of horizontal components of the GNSS station positions has also been observed. Although their temporal characteristics largely reflect seasonal phenomena, a clear regularity exists between these events and shortened distances between stations, which were determined based on daily station positions (Szczerbowski, 2016). Thus far, there have been no significant studies on the conditions of Polish mining areas that would combine geophysical and geodetic observations in modelling rock mass deformations caused by mining tremors. Prospective research areas include the measurement zones at GPS/GNSS permanent stations, where analysis and interpretation of time series of numerical sequences as independent data from observation offers new possibilities for interpretation. These distributions are often the result of cyclical processes that do not manifest themselves in abrupt displacements in discontinuous (seasonal) measurements. The time distributions of data are often influenced by not fully explored phenomena and processes related to the kinematics of a given area. Furthermore, GNSS measurements only provide information about land surface kinematics for a relatively large area, and there is often no detailed information about the deformation parameters due to the limited resolution resulting from the distribution of permanent stations (Szczerbowski, 2016). This problem occurs in the case of the USCB area. In assessing possible relationships between the characteristics of time distributions of mutual positions of the GNSS stations and the time of occurrence of high-energy seismic events, the large number of these stations is not significant. This study was motivated by the observation of certain seasonal patterns in the occurrence of large tremors ($E \geq 3 \times 10^7$J).

The seismic data were obtained from European-Mediterranean Seismological Centre - EMSC. Figure 2 presents bar charts of their frequencies for each month. Occurrences of seismic events were initially analyzed for large tremors of energy $E \geq 3 \times 10^7$J. So, the number of events was increased in spring and autumn (Figure 2a). This remark is much better obvious for larger tremors of energy $E \geq 1.1 \times 10^8$J or the largest occurred in the area of energy $E \geq 2.8 \times 10^8$J (Figure 2b, 2c).

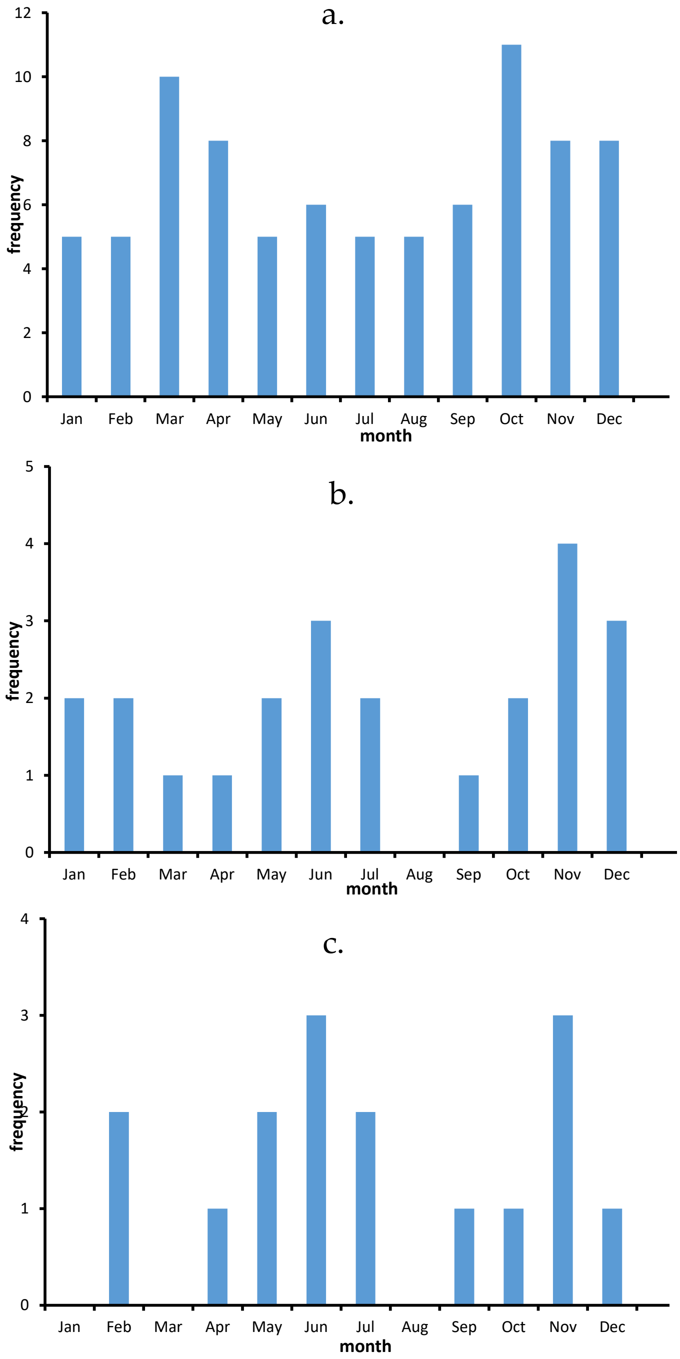

Figure 2. Frequencies of occurrence of large tremors in the period January 2008- December 2014 in the area of the USCB. Occurrence of tremors of energy: a. $E \geq 3 \times 10^7$J, b. $E \geq 1.1 \times 10^8$J, c. $E \geq 2.8 \times 10^8$J.

GNSS data analysis

The small number of permanent GNSS stations in the USCB area provides only a general view of the spatial-temporal distribution of terrain deformations. However, the GNSS data can be applied for some analysis of seasonal displacements or seasonal patterns in mutual positions of the stations of particular locations in the area. Our analysis includes changes in geodetic coordinates registered by KATO, KRAW, WOD1, ZYWI, CFRM stations of the ASG-EUPOS network and VSBO station (Ostrava, Czech Republic), which operates in Czech Reference Station Network – CZEPOS, trends of changes, displacements, linear deformations of baselines defined by the positions of these stations and their seasonal variation of the data. The changes in these deformations were analyzed in order to determine the time characteristics and to compare the values with occurrences of high-energy seismic tremors. It was assumed that the relations between the station positions might result from rock mass movement caused by natural factors or mining operations. These include, among others, natural ground movements resulting from hydrogeological effects. The coordinates and lengths of these vectors are affected by GPS malfunctions that affect the obtained characteristics of the distributions (including, in particular: trend and seasonality). The influence of mining operations on the rock mass and surface is lower than 2 km.

The analysis of the component changes of KATO, KRAW, WOD1, ZYWI, CFRM, and VSBO stations was made with reference to the values found in the measurements on June 1, 2008, i.e. from the date when ASG-EUPOS (Active Geodetic Network), the national precision satellite positioning system in Poland became fully operational (Bosy et al., 2007). One of the aims of his research was the scientific aspect - to study the movements of the Earth's crust in Poland. The use of the system in the study of land surface movements has been described in many studies both in terms of the geodynamics of the whole country and some regions (Bosy et al., 2007; Bogusz et al., 2014; Klos et al., 2015; Figurski et al., 2010). Registered changes in the position of the stations (coordinate changes) are characterized by a load influenced by several sources (including atmosphere, hydrology, etc.). In the analyzed case, in accordance with the general standards of the system, the accuracy of the daily station position is approximately 2 mm for each coordinate (Figurski et al., 2010). However, this value is actually estimated from the average value, and the accuracy for each station may vary. In the case of analysis of a large amount of data, e.g. for a period of several years, determining the regularity (trend) of changes in the position of a given station gives greater reliability.

In this article, coordinates (X, Y, Z) are expressed in the European spatial datum ETRF2000, which is the realization of a reference frame. Geocentric coordinates (with its centre in the centre of the Earth) were transformed into a topocentric system (coordinate system with its centre in the place of observation). The transformation yielded station positions expressed by coordinates (N, E, Up), which allows for local analysis of both displacements (including altitude changes rather than changes in coordinate Z, directed along the axis of the Earth's rotation to the North Pole) and their azimuths. We used the ASG EUPOS data. ETRF2000 is the realization of ETRS89 that evaluated angular velocities of the Eurasia tectonic plate using an ITRF velocity field (see: http://etrs89.ensg.ign.fr/pub/EUREF-TN-1.pdf)

Another geodetic data was obtained from Nevada Geodetic Laboratory (NGL) (Blewitt et al., 2018). Calculated coordinates by the Geodesy Lab at the University of Nevada on a daily basis provided velocity vectors for analyzed stations with respect to stable Eurasia plate (time series are available at http://geodesy.unr.edu). The values of vector components determined for the stations are presented in Table 1.

Table 1. Velocities in the USCB and adjacent areas with respect to stable Eurasia plate (according to NGL and ASG EUPOS data).

station	**V_{north} [mm/yr]**	**V_{east} [mm/yr]**	**V_{up} [mm/yr]**
VSBO	0.61 ±0.14	0.53 ±0.13	0.12 ±0.59
WOD1	1.46 ±0.20	1.31 ±0.24	-1.93 ±0.68
KATO	-2.68 ±0.15	0.76 ±0.13	-1.17 ±0.55
CFRM	0.96 ±0.13	-0.06 ±0.12	-0.20 ±0.54
ZYWI	0.92 ±0.15	0.14 ±0.14	-0.05 ±0.66
KRAW	-0.69 ±0.24	-0.83 ±0.26	0.71 ±0.39

Figure 1 shows the horizontal displacement vectors of the following stations: WOD1, KRAW, ZYWI and KATO. The orientation of these stations' displacement is directed at the central axis of the USCB. Most of the stations have operated within the region for more than 5 years (the period normally adopted by GNSS for data analysis). KRAW and ZYWI are the stations located in the close vicinity of the area of the USCB. Changes in the horizontal positions of N (northward) and E (eastward) stations in the period from June 1 2008, to February 1 2014, were analyzed, followed by the analysis of changes in their mutual distances in that period (Figure 3). During this, approximately 60 large seismic events occurred, of which 11 took place within the area of KATO station (within a distance of approx. 20 km), and the others occurred in the rest of the area.

From the inspection of Figure 3, most of the stations located around the borders of the USCB show displacements towards the centre of the Upper Silesian Basin. The exception is a displacement of KRAW. As can be seen from N and E coordinates changes, they are subjected to seasonal changes, but these changes were regular until 2012 (Figure 3). At the same time, the KATO station shows a trend in moving southwards, which causes the distance between the ZYWI and WOD1 stations to shorten, to a lesser extent, with KRAW. It can be assumed that the area of the basin is compressed, and the pace of this process is quite fast - a maximum of 5 mm/year. In the next stage, linear deformations for the WOD1-KATO, the WOD1-ZYWI and the ZYWI-KATO baselines were analyzed.

The displacement vectors were obtained after transformation into a topocentric frame: and there were vectors in which tails and heads were just positions of pairs of the stations. So, in reference to the starting positions in the topocentric frame (with components: N - North, E - East and U - Up), vector magnitudes vary in time. As an example:

$$\vec{v}'_{WOD1-KATO} + \vec{d}_{WOD1-KATO} = \vec{v}_{WOD1-KATO}$$

What responds to adding of vectors **v'** (starting the vector WOD1-KATO on June 1, 2008) and *d* – displacement vector resulting from changes of components N and E between the stations in reference to their starting positions that make a resultant value in **v** - vector representing the stations' position in a moment of time. Thus:

$$dN_{WOD1-KATO} = N_{KATO} - N_{WOD1} \text{ and } dE_{WOD1-KATO} = E_{KATO} - E_{WOD1}$$

Strain as a linear deformation of baseline distance between the chosen GPS stations can be calculated from values of displacement vectors, for example:

$$\varepsilon = \frac{d_{WOD1-KATO}}{D}$$

where:

d – the magnitude of displacement vector and *D* – the initial distance between analyzed stations (length of baseline).

So, linear deformations were determined on the basis of station position changes. As shown in (Figure 4), distributions of deformations for individual baselines are also characterized by a clear trend and seasonal character of changes. However, the rate of the deformation process is clearly differentiated, and in terms of velocity, it corresponds with local displacement (i.e. in N, E system).

Geodetic strain analysis is typically inferred from GPS/GNSS velocities, that is, displacement rates determined for a time interval. This approach requires long time observations to determine the trend line of displacement data. This study presents an analysis based on day-by-day observations in the time interval 2008-2014, and seasonal variations are considered as well. The evaluations from varying coordinates baseline lengths are influenced by several sources that could not be identified precisely (GPS technique itself, effect of atmosphere, hydrology, equipment, variable environmental influences in the year). So, in consequence, the displacement evaluated on the basis of these varying coordinates in relation to the reference, initial length is a measure that should be regarded as "apparent strain". To be exact, with accepted professional standards, we use this term which can be described by operational definition as strain calculated from data affected by errors hard to be estimated.

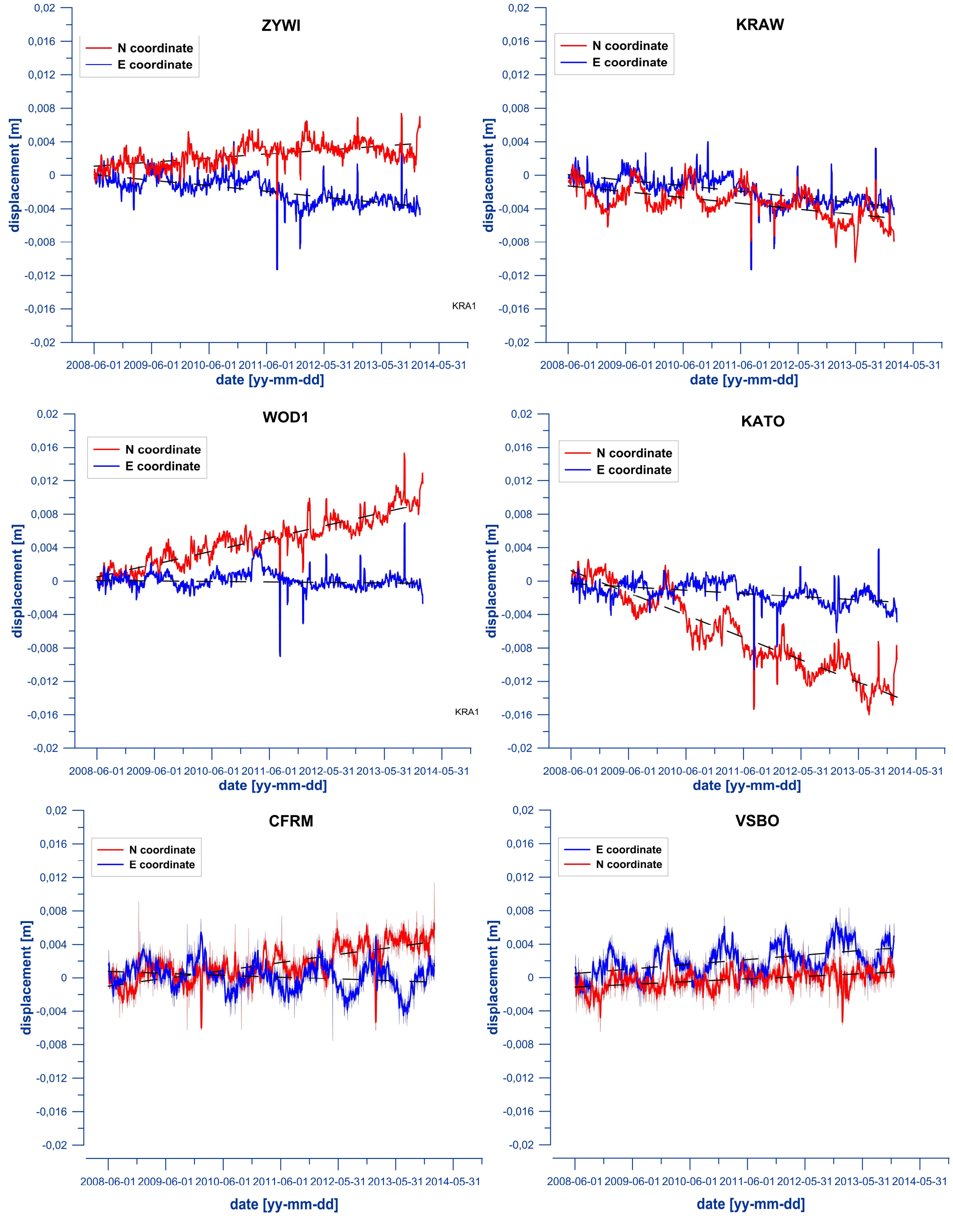

Figure 3. Horizontal displacements of the analyzed GNSS stations with trends (dashed lines) in 2008-06-01 – 2014-02-01.

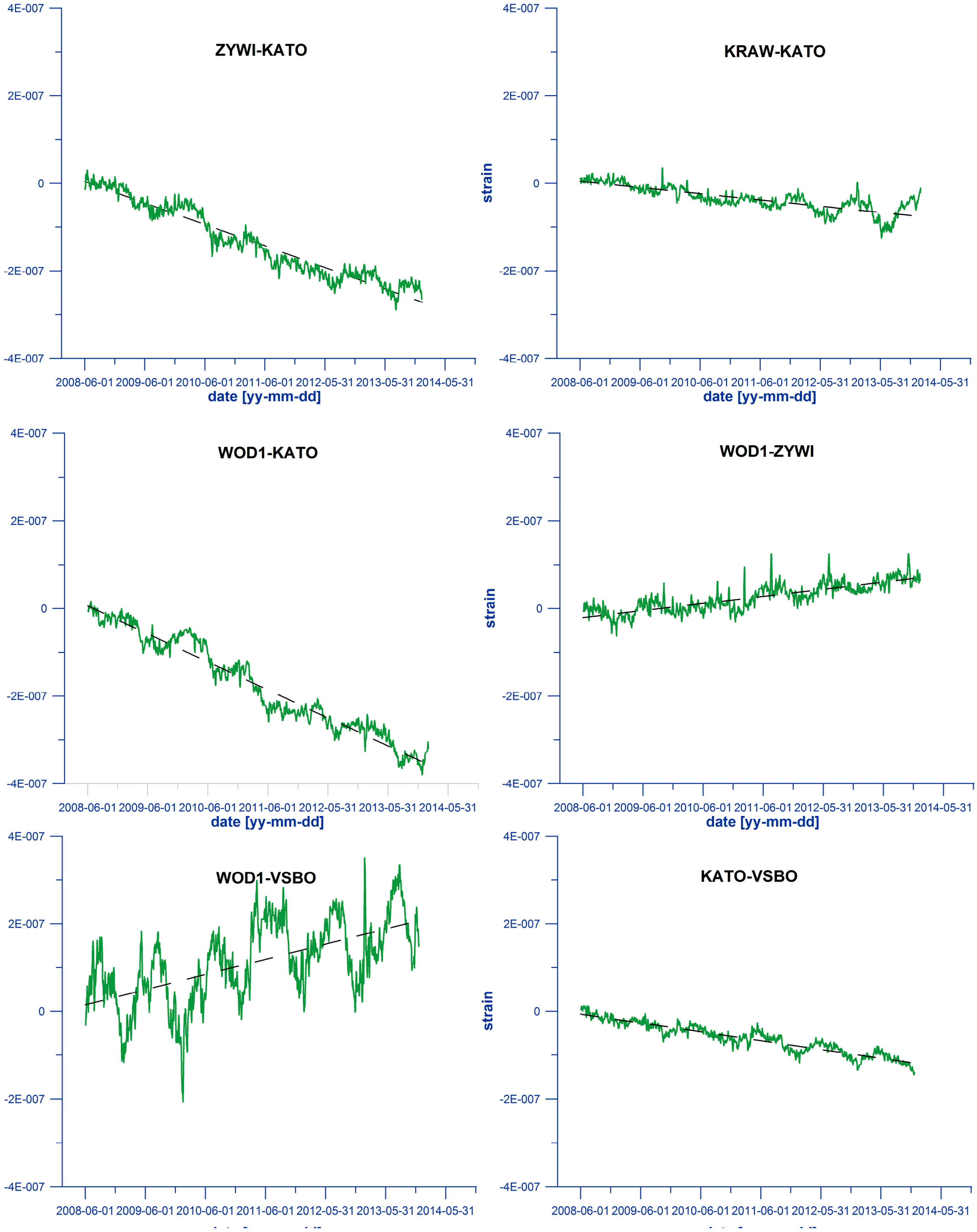

Figure 4. Temporal variations of apparent strain rates were evaluated for the analyzed baselines with the linear trends (dashed lines) depicting seasonal variations of the strain.

The highest rate is observed in the WOD1-KATO baseline, where compressions of -0.7 E-07/year occurred. It is oriented approximately perpendicularly to the axis of the Upper Silesian Basin and to the geological structures that form it. Small values of the displacements (1-3 mm/yr) suggest that they are free of direct mining effects in areas of the location of the station. Slightly lower apparent strain rates in comparison to the WOD1-KATO baseline are demonstrated by the ZYWI-KATO baseline, and the lowest rates are shown by the WOD1-ZYWI and the KRAW-KATO baselines. As can be seen, the value of annual deformations of baselines decreases as the baseline orientation changes. The WOD1-ZYWI baseline is the only one showing positive changes of deformations (apparent strain), which is related to the displacement of the ZYWI station to the east and lack of movement in this direction of the WOD1 station. Almost all baselines show seasonal variability of deformations, except the KRAW-KATO baseline, where this variability was insignificant during a specific period of time, and in subsequent years it began to increase. With regard to the majority of baselines, the amplitude of seasonal changes in apparent strain is approx. 5E-08. Also, in the case of the WOD1-KATO baseline, a seasonal variation is most clearly marked. This is much better seen on plots presenting detrended time series of the apparent strain distributions of baselines located in the area of the USCB: the KATO-WOD1, the WOD1-VSBO, and the KATO-VSBO (Figure 5).

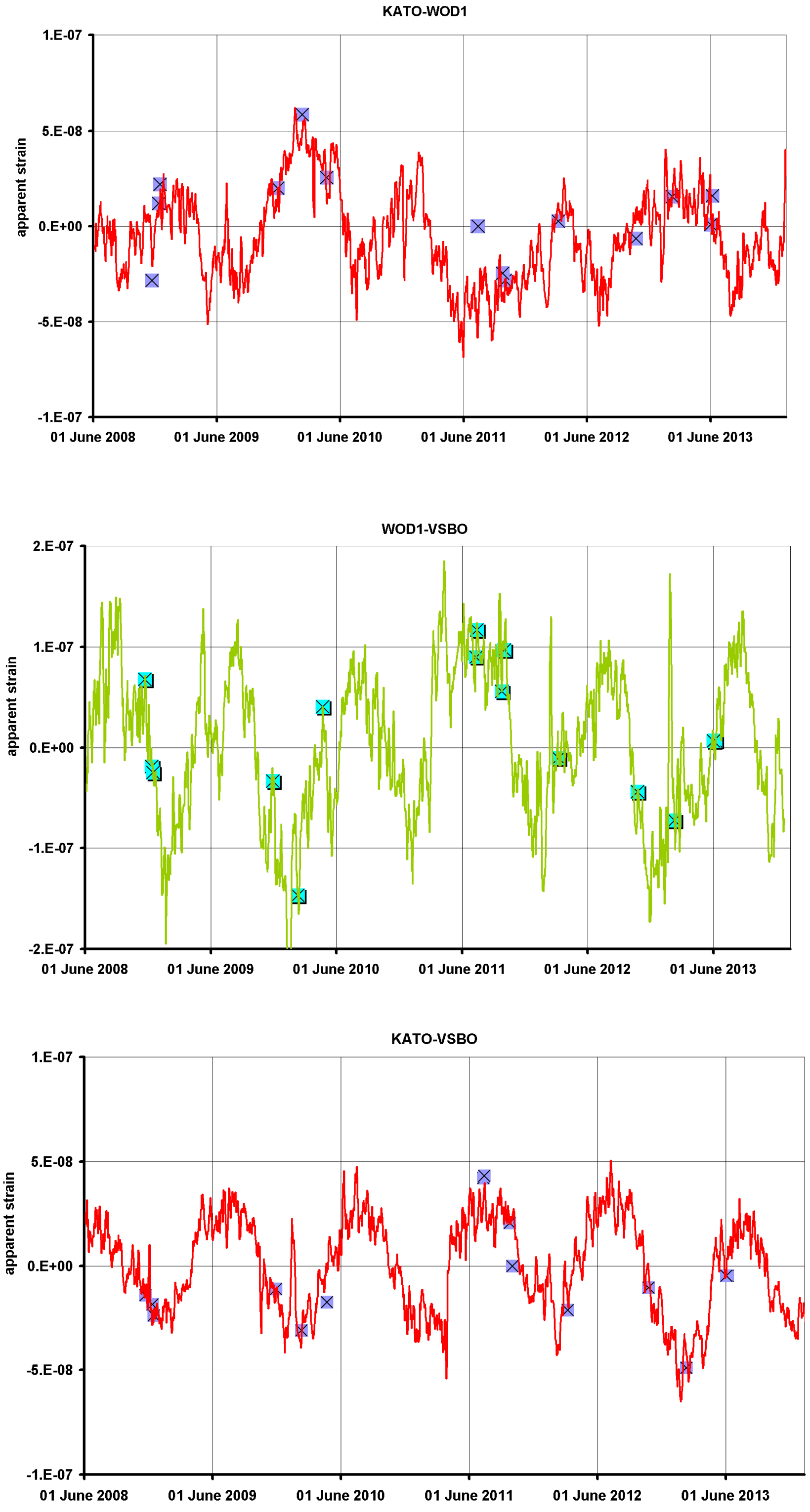

Figure 5. Detrened variations of apparent strain rates evaluated for the baselines in the area of the USCB: the KATO-WOD1, the WOD1-VSBO, the KATO-VSBO and the occurrences of the largest tremors of energy E ≥ 1.1 x 10^8J.

However, the time series of the WOD1-VSBO and the KATO-VSBO baselines are similar (in tensile and compression occurred nearly in the same seasons), and the amplitudes of the oscillations' apparent strain rates of the first baseline are much higher. Distribution of the KATO-WOD1 apparent strain rates is in opposite phases to the mentioned oscillations. Just before the beginning of winter or summertime, there are moments when apparent strain rates amount to extreme values in particular. As presented in Figure 5, most of the large tremors occurred in these time intervals: starting just before winter or summer and lasting up to the beginning of the next seasons (springs and autumn). The most regular seasonal oscillations are represented by the KATO-VSBO baseline, so it is chosen for further analysis.

So, as the next, occurrences of high-energy seismic tremors were analyzed with regard to the seasonal changes of the mentioned strain rates. As already mentioned, their origin is considered to be tectonic mining. The KATO-VSBO baseline shows a clear seasonal signal in changes in strain rates. However, it is evident that these changes are not perfectly regular. As can be seen in Figure 6, where removing the trend reveals the seasonality of changes in deformations is clearly visible: in autumn and winter, there are negative relative changes, and in spring and summer - positive changes occur. Although these changes commencement coincides somehow with calendar seasons, it is hard to assess the start of changes precisely due to the signal disturbances.

The beginning of the highest values of relative tensile was observed in different time intervals in particular years: from the end of June to the beginning of July. Similarly, the highest values of compressions were observed in different years from January to February. The time intervals of extreme values of apparent strain were preceded by intervals of 2-3 months when smaller but significant strain values were observed. It should be noted that the transition from tensile to compression or from compression to tensile underwent in a short time interval (i.e. in 2011).

As seasonal changes take place within the framework of pressing deformations trend, there are periods of relative (i.e. with regard to linear trend) tensile and compression. Seasonal variability includes the duration of these periods and the rate of deformation buildup. To examine the relationship between their occurrences with values of apparent strain rates, they were placed on the line of detrended time series according to moments of seismic events.

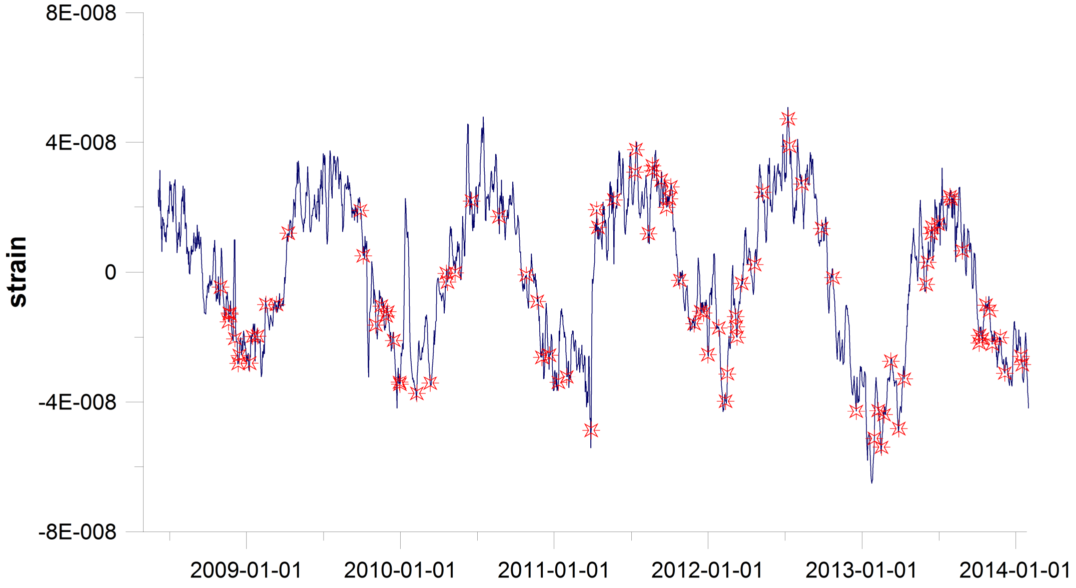

Figure 6. Seasonal variation of the apparent strain of the KATO-VSBO baseline in the period 2008-06-01–2014-02-01 with the occurrence of high energy tremors of $E \geq 3 \times 10^7$ J.

The threshold of energy $E \geq 3 \times 10^7$ J includes a large population of 96 seismic events. Locations of the tremors presented were presented before in figure 1. As shown in Figure 6, most occurred in time intervals of extreme values of determined apparent strain rates. This relation between the occurrence of the tremors and values of strain rates is a much more illustrative form of the histogram, which is presented in Figure 7.

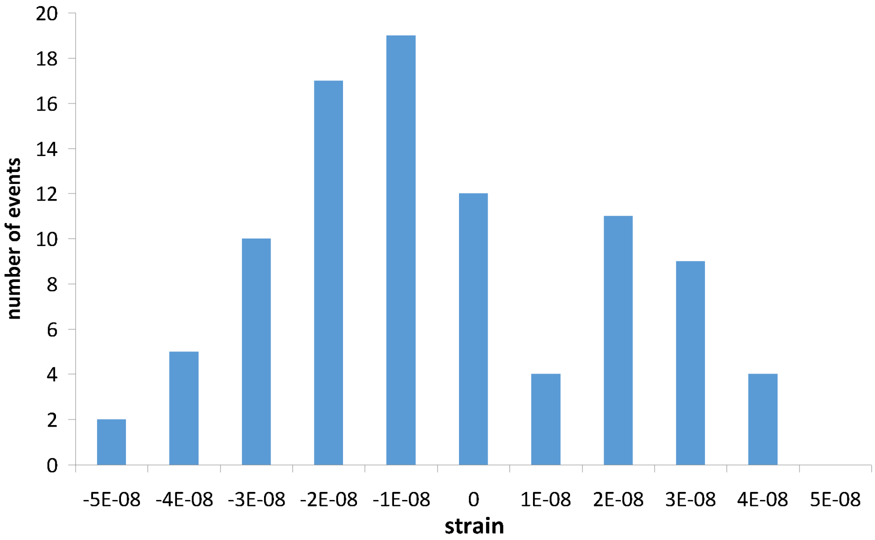

Figure 7. The number of high-energy tremors per given value of apparent strain.

Frequencies of the tremors show a certain pattern: occurrences correspond to moments of particular values of strain rates. In general, the occurrences are "preferred" when compressions were attributable to strain rates -3E-08, -2E-08 (50% of all cases). However, a significant increase in frequency concerns tensile strains: about 25% of all cases were attributable to the rates 3E-08 and 2E-08. Gradual distribution of frequency suggests that occurrences are not related to particular values of strain but rather to their changeability. It should be read as an increase in the probability of seismic events due to the accretion of the strain. The statistical probability of the occurrence of high-energy seismic tremors within the area of the USCB in the autumn and winter periods is clear. This probability of these occurrences in moments of time intervals determined by compression or tensile observed as the variation of apparent strain rates is even more evident.

The release of seismic energy from tremors, which are believed to have a partially tectonic origin in certain periods of time, is hardly accidental, especially since these periods of time are related to the temporal characteristics of the deformation of the land surface, which is determined by means of the geodetic method. What is more, this characteristic has a special character of continuous compression, which can be assumed to be a decrease in the length of the KATO-WOD1 or the KATO-VSBO baselines, which means that the distance between the GNSS permanent stations is accompanied by seasonal fluctuations: periodical decrease and increase in compression stresses.

These seismic events are related to the periodical reduction of these stresses. Similar results were obtained for natural seismicity in the Himalayas, where seismic tremors are strongly influenced by seasons and hydrological strain on the lithosphere as a result of rainfall and snowfall, which is reflected in geodetic deformation measurements (Bollinger et al., 2007; Borchers et al., 2014).

Discussion and conclusions

The paper presents the relationships between the occurrence of high-energy seismic tremors within the area of the USCB and the seasonal changes in the positions of the GNSS stations located there. The 2008-2014 shocks were analyzed, and 90% of these shocks occurred in periods when the stations were seasonally shifted significantly. Such a temporal relationship may be accidental, and it is more important whether the possible seasonal changes observed at the GNSS permanent stations are of a regional nature, which could explain the change in the stress field as the reason for inducing the analyzed shocks. Determining the physical indicator, rather than only the kinematic indicator, is also important in describing seasonal changes. One such indicator may be linear deformations observed at the GNSS permanent stations. In many studies, analyses of relationships between characteristics of surface displacements and the occurrence of seismic tremors induced by mining exploitation were undertaken (Szczerbowski and Jura, 2015; Szczerbowski, 2016; Milczarek, 2019). Local displacements do not necessarily reflect the effects of in-depth processes and may be due to various local causes, such as changes in the geotechnical conditions of the rock mass. A more reliable parameter is linear deformation, preferably on a local scale. Analysis of the mutual position of two or more stations gives a higher probability of reflecting the in-depth causes of surface deformation.

Linear deformations were determined on the basis of changes in the position of GNSS permanent stations of ASG-EUPOS in the area of the USCB to investigate possible links with the occurrence of high-energy tremors. So, this combined analysis involves seismic data (occurrence of tremors releasing high elastic energy) and geodetic data (seasonal changes in baselines whose lengths were determined on varying positions of the stations). As shown, there is a time relationship between seasonal changes in deformations of the KATO-VSBO baseline, analyzed as an exemplary case and high-energy seismic events. The analyzed seismic events mostly took place during the time intervals when the relative seasonal changes in deformations (relative to the trend line) showed extreme values. Assuming that the observed changes reflect physical displacements of stations, they can be adapted to reflect changes in stress characteristics that could influence the rock mass's tendency to release larger energy during tremors induced by mining operations.

Simplified binary classification of seismic events distinguishes between natural and artificial origin (Bormann et al., 2013). Unnatural energies released during large seismic events triggered by mining in the USCB area can be explained by the tectonic setting. Their seasonal occurrence also should be considered as conditioned by environmental factors. So, high energy events, in this case, are just combined effects of human impact (mining activity) and tectonic stress.

We show velocity vectors of the GNSS stations in the area of the USCB, which orientation is directed at the central axis of the USCB. This characteristic suggests a compressional regime. The most recent geophysical investigations of large seismic event mechanisms in a particular location in the USCB exhibited a pattern indicating that seismicity was tectonic and mining-triggered rather than induced (Mendecki et al., 2020). The investigations provided the conclusion that natural hazards corresponded to regional tectonics and residual stress accumulation. This stress could be the effect of differences between the velocity/strain rate fields depicted by geodetic observations. Considering small values of the presented displacements and long-term trends as seasonal oscillations of displacements of the stations, their origin should be presumed as a result of natural origin. The presented seasonality of high-energy tremors may confirm that as well. The work presented here is a contribution to seismic studies on the seasonality of seismic events in many areas. It is the first time that geodynamics theory about the tectonic activity of the area was used to analyze the cause of high energy tremors in USCB.

The search for new solutions in assessing rock mass and surface deformations, including the use of permanent GNSS data, is a basis for a detailed characterization of the creation of phenomena and processes occurring in the rock mass, including large-area movements and related hazards.

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