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ORIGINAL PAPER

PRESENT-DAY STRESS ORIENTATION AND TECTONIC PULSES REGISTERED IN THE CAVES OF THE SLOVENSKÝ KRAS MTS. (SOUTH-EASTERN SLOVAKIA)

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ABSTRACT

The fault displacement monitoring network EU-TecNet was established to define microdisplacements across faults in the territory of Central Europe (www.tecnet.cz) using three-dimensional optical-mechanical extensometers. The results of long-term neotectonic activity obtained from two caves localized in the eastern part of the Slovenský kras Mts. (SE Slovakia) show generally NE-SW oriented dilatation. This orientation is in a good accordance with the orogen-parallel extension monitored in the Western Carpathians. Differing short-lasting trends were distinguished in 2011–2012 and 2013–2015, which supports the significance of the tectonic pulse at the end of 2012 and the beginning of 2013. Moreover, simultaneous short-lasting faulting occurred at both sites under the transtensional tectonic regime, where the principal maximum compressional axis operated in a NW-SE direction (σ_1). The observed results were compared to data from monitoring points in distant areas of the European plate.

1. INTRODUCTION

The fault displacement monitoring network EU-TecNet was established to define displacements across faults with a higher accuracy than displacements obtained by the Global Navigation Satellite Systems (GNSS). To-date, the network has collected data from more than one hundred tectonic structures in Central Europe (www.tecnet.cz). Due to the fact that most of the sites are not situated within high seismic-prone regions, it represents the most appropriate data for analysis of fault microdisplacements (Stemberk et al., 2010), reflecting long-term displacement trends due to widespread redistribution of stress and strain within the shallow crust (Košťák et al., 2007, 2011; Stemberk et al., 2010; Briestenský et al., 2014a,b). Data on stress-field characteristics are absent in many of the regions and the observatories help to collect such data. The network is equipped with specially designed three-dimensional optical-mechanical extensometers (Košťák, 1969), usually installed in underground locations, enabling us to exclude seasonal massif dilatation (Briestenský et al., 2015).

The paper presents the first data concerning the orientation and character of the present-day stress field in the region of south-eastern Slovakia. It also highlights the tectonic pulses recorded using three-dimensional optical-mechanical extensometers, which are different from the long-term observations.

2. GEOLOGICAL SETTING

The selected study area is situated on the SE periphery of the Western Carpathians (Fig. 1) and belongs to the most tectonically complicated regions in the Western Carpathians. This is mainly due to the presence of a Jurassic–Cretaceous Gemericum-Meliaticum and Silicicum nappe stack and later effects of Cenozoic rifting of the Pannonian Basin (Hók et al., 2014; Plašienka, 1997).

Tectonic units of the Gemericum crystalline basement (Palaeozoic), the Meliaticum accretionary complex (Mesozoic), and the cover nappes of the Turnaicum and Silicicum are present in this region (Mello et al., 1996; Geological map of Slovakia, 2013). The Darnó Line or Darnó Zone (Petrik et al., 2016) is an important NNE-SSW trending structural element located in north-eastern Hungary, which reaches the southernmost part of Slovakia on the eastern periphery of the investigated area. The recent mechanism of the Darnó fault zone is assumed to be a sinistral strike-slip (Fodor et al., 2005). From the north, the study area is bordered by the Rožňava Fault (Mello et al., 1996), which cuts the Slovenský kras Mts. into two blocks (Fig. 1) with subsidence of the

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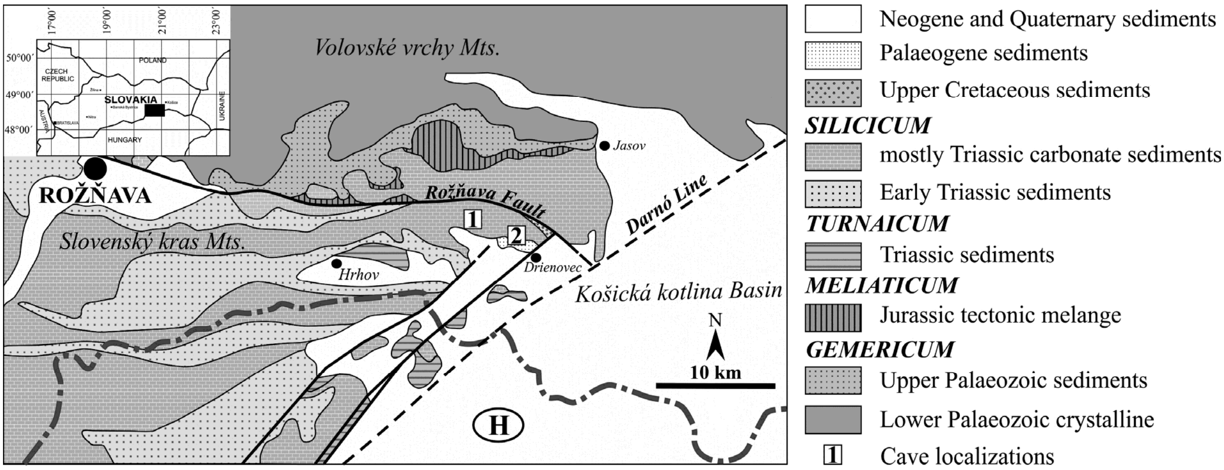

Fig. 1 Simplified geological map with position of the caves: 1) Skalistý potok Cave; 2) Drienovská jaskyňa Cave. Adopted from Fodor et al. (2005) and the Geological map of Slovakia (2013).

southern block (Zacharov, 2009; Maglay et al., 1999). The Rožňava Fault as well as the Darnó Zone show similar orientations to the main extension oriented in a NNE-SSW to NE-SW direction during the Late Miocene (Mello et al., 1996; Petrik et al., 2016). Orientation of the stress field extension component (Littva et al., 2015) yielded a NE-SW striking extension most probably during the Pliocene-Early Pleistocene, and a younger (Late Pleistocene-Holocene) WNW-ESE striking extension. Two caves were selected in the eastern part of the Slovenský kras Mts., close to a significant geomorphological contact with the Košická kotlina Basin (Fig. 1; Vass et al., 1994).

2.1. SKALISTÝ POTOK CAVE

The Skalistý potok Cave was formed in the Middle Triassic Wetterstein Limestones of the Silicicum (Mello et al., 1996), and represents one of the largest caves in Slovakia. The cave corridors are 7,107 m in length and have a vertical span of 336 m (Hochmuth, 2013). Between 1986 and 2000, cave divers led by Hochnuth and Hutňan discovered large spaces, numerous sets of siphons and lakes, as well as an ascending branch with rapids and waterfalls.

Morphologically, the cave consists of two different sections – a lower looping part and an upper ascending part with vertical steps and a subhorizontal corridor (pre-Quaternary paleolevel?). The lower entrance is a short artificial tunnel, built at the site of a karst spring, and the upper entrance is a longer artificial tunnel, which was opened by cavers in 2007. Two extensometric observatories were installed here. The first extensometer was located in the Skalistý potok Cave in October 2011 across the almost N-S-striking fault (080°/65°, dip direction/dip) close to the upper entrance (48°37'45.35" N; 20°52'15.62" E). The fault has an affinity to the Darnó Fault Zone and it is supposed to reflect its recent regime. The second gauge was installed in the lowermost entrance (Karst spring 48°37'23.6" N; 20°52'16.1" E) in May 2014 across the NW-SE striking fault (053°/85°), which creates a border between the Slovenský kras Mts. and the Košická kotlina Basin. It is assumed to reflect the subsidence of the basin.

2.2. DRIENOVSKÁ JASKYŇA CAVE

The cave (48°37' 27.38" N; 20°57' 8.9" E) is formed in the Upper Triassic (Carnian) grey and dark grey Tisovec limestones of the Silicicum, partly also in carbonatic conglomerate and breccias (the Drienovec conglomerate - Upper Oligocene). The main part of the cave is a fluvial modelled outflow corridor with lakes and cascades. The cave was developed in four levels; its total length reaches 1,348 m and has vertical span of 85 m (Zacharov, 2013). It was discovered in the 19th century. In October 2011, one extensometer was installed across the almost W-E striking fault (190°/80°) in the Rožňava Fault Zone.

3. METHODOLOGY

The TM-71 optical-mechanical extensometer (hereinafter TM71) was developed for monitoring very slow (some μm per year) three-dimensional displacements across active fault structures, which separate two rock blocks. Its most important advantage is its ability to record three-dimensional data (Fig. 2). The data reflect different types of fault microdisplacements: long-term trends or pressure pulses (in the sense of Stemberk et al., 2010), reflected in initialisation, oscillatory or reversal of the displacements (Fig. 2).

The principles and application of this instrument have already been described by e.g. Košťák (1991) and its accuracy has been tested by Marti et al. (2013) and Rowberry et al. (2016). Extensometers record data on the basis of optical-mechanical interferometry, i.e. by generation of moiré patterns (visible between two glass sheets), which are generated by the interference of light rays passing through two specially designed optical grids. Subsequently, the moiré patterns are mathematically transformed into three-dimensional displacement vectors as well as into angular rotations. Extensometers record displacements with an accuracy greater than 5 μm and rotations with an accuracy greater than $8.7*10^{-5}$ rad ($1.4*10^{-6}$ gon) (Rowberry et al., 2016). The data are usually collected manually using a digital camera with a frequency of once per month, although more than 46 sites have been

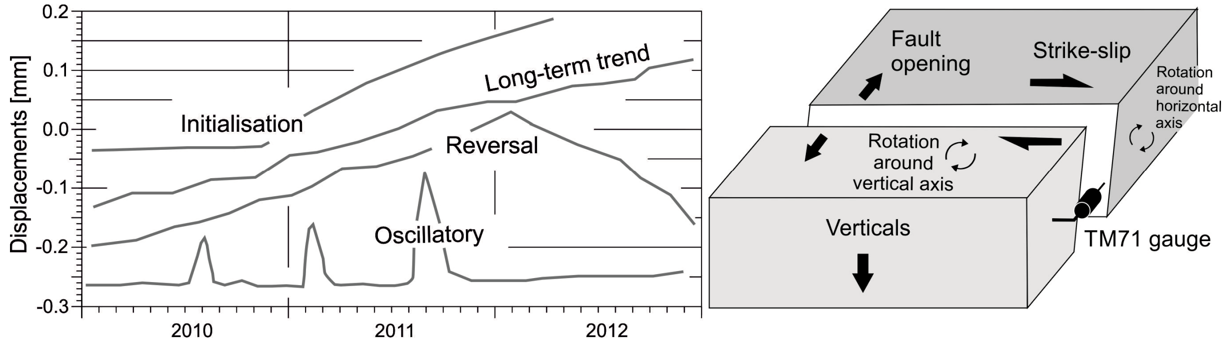

Fig. 2 Character of fault displacements (in the sense of Briestenský et al., 2015) and schematic block model showing all of the fault displacement components registered by the TM71 extensometric instrument.

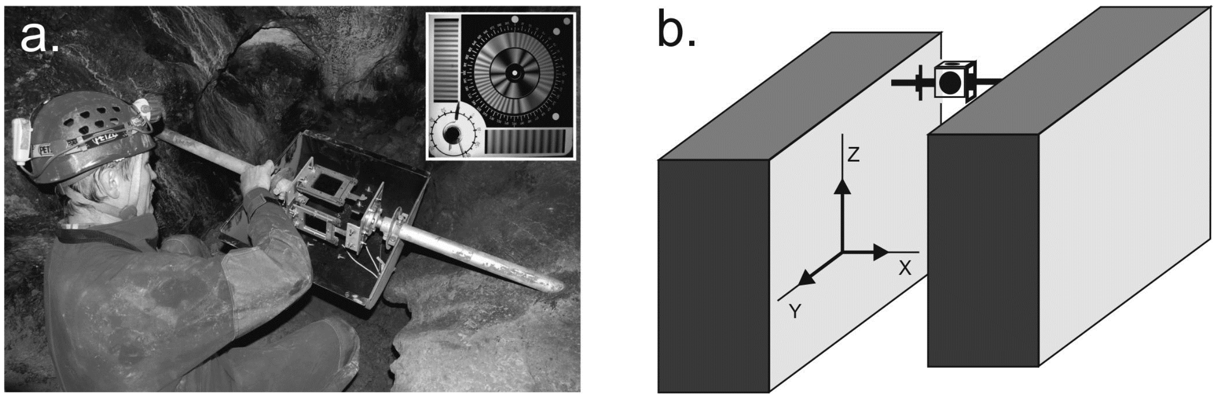

Fig. 3 The picture shows a common installation in the field: a) a TM71 instrument used to measure long-term deformations across a selected fault (photo: P. Staník). The inset shows an example of the moiré fringes registered on one pair of combined indicators; b) the coordinate system used by the TM71 instrument, showing the base vectors X, Y, Z. Axis X represents the crack opening (between two blocks), axis Y is the strike-slip (horizontal shift), and axis Z is the vertical component.

equipped with automatic dataloggers with a higher sampling rate since 2009 (Mladečské Caves, Czech Republic). The advantages, disadvantages, and limitations of the instrument have been studied from various points of view as a result of its protracted installation at a number of sites, for example, in the Czech Republic, Slovenia, Slovakia, Austria and Poland (Gosar et al., 2009; Baroň et al., 2016). Moreover, the obtained data have also been compared using other geophysical methods (Košťák et al., 2011). They show that seasonal and climatic variations can also be detected and separated from the recorded movement data (Briestenský et al., 2015).

Due to the fact that the monitoring results are presented in Cartesian coordinates (X, Y, Z) (Fig. 3), we used the data to compute a deformation gradient (vector) and its spatial distribution (plunge and azimuth).

The vector can be computed using the following general formula:

|u|=root(X^2 + Y^2 + Z^2)

This vector shows the magnitude of the final displacement across the monitored failure. However, there are many circumstances where its size remains the same, but particular displacement components change. Therefore, individual displacement components still remain as the main indicators in our resulting graphs and papers.

The displacement vector can be defined by the spatial distribution of two angles: azimuth and plunge. Azimuth (δ) represents the dip direction of the vector. Its value is defined by the relationship between the coordinates X, Y (resulting in angle α) and by the orientation of the gauge in space (β) (Fig. 4). There are eight conditions to transform angle α into 360° horizontal space (Fig. 4). Plunge (λ) represents dip, the vertical component of the displacement vector. Its value is defined by the relationship between the coordinate Z and Hr (the horizontal resultant of coordinates X and Y).

There are five conditions to transform angle λ into 90° vertical space (Fig. 5). The horizontal resultant Hr can be computed using the following formula:

|Hr|=root(X^2 + Y^2)

Figures 4 and 5 show a schematic model of the azimuth and plunge computations in the case that the +X coordinate displays an extension, +Y dextral strike slip and +Z reverse. On the other hand, the real TM71 field situation (method of installation) provides two

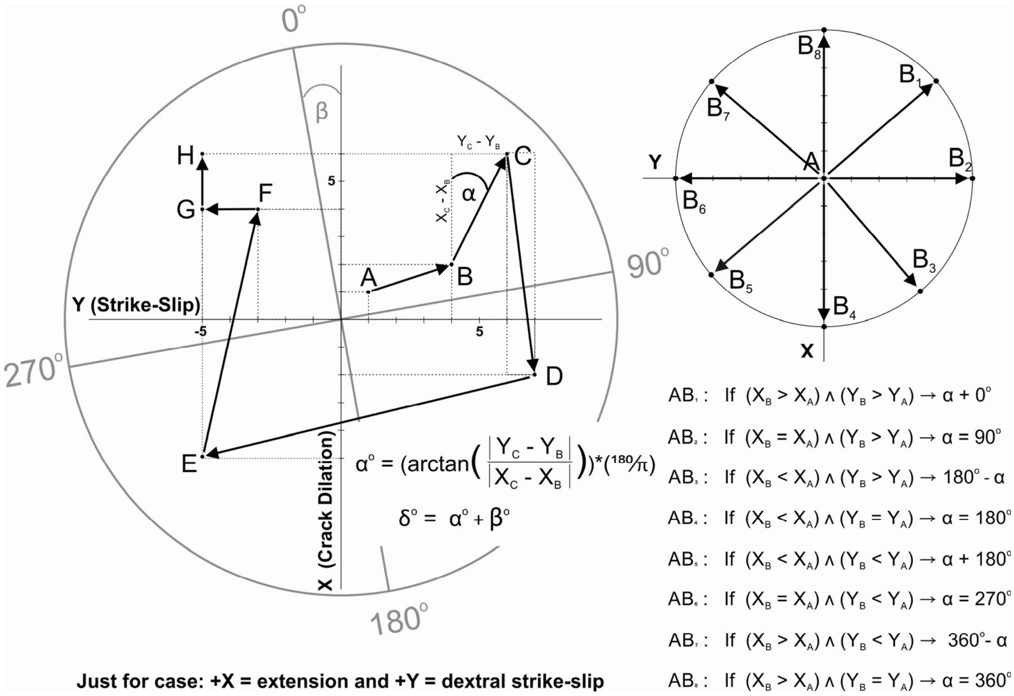

Fig. 4 Geometrical parameters used to compute the azimuth (δ), using the Cartesian coordinates X and Y (opening and strike-slip components). The alphabetical numbering shows the order of the observed horizontal fault displacements. Eight conditions represent the eight sectors defined by the X and Y relationship. Angle β represents the orientation of the TM71 instrument at the selected site.

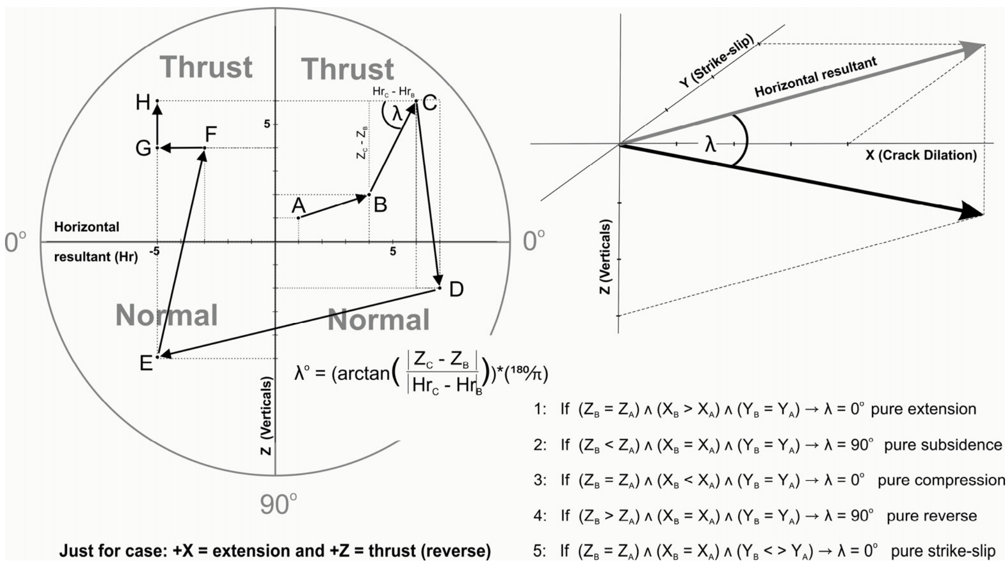

Fig. 5 Geometrical parameters used to compute the plunge (λ), using the Cartesian coordinates X, Y and Z (opening, strike-slip and vertical components). The alphabetical numbering shows the order of the observed vertical fault displacements. Five conditions represent the five thresholds in which the formula does not operate and the results should be substituted by the defined values.

versions of the calculation. These calculations were easy performed using MS Excel, whereby the sense of the microdisplacements is defined verbally. The data were subsequently plotted on a stereographic projection using the Stereo32 software (Röller and Trepmann, 2003). The fault plane was plotted as a large circle, whilst the discrete movement vectors were plotted as points (see Figs. 6, 7 and 8).

Three basic modes of the vector displacement relative to the fault plane could be interpreted: normal or reverse displacement along the dip-slip, dextral or sinistral movement along the strike-slip, and movements related to the opening or closing of the fault fissure. Although the movement vectors usually contained a combination of these movements, the predominant sense of the movement on the vector

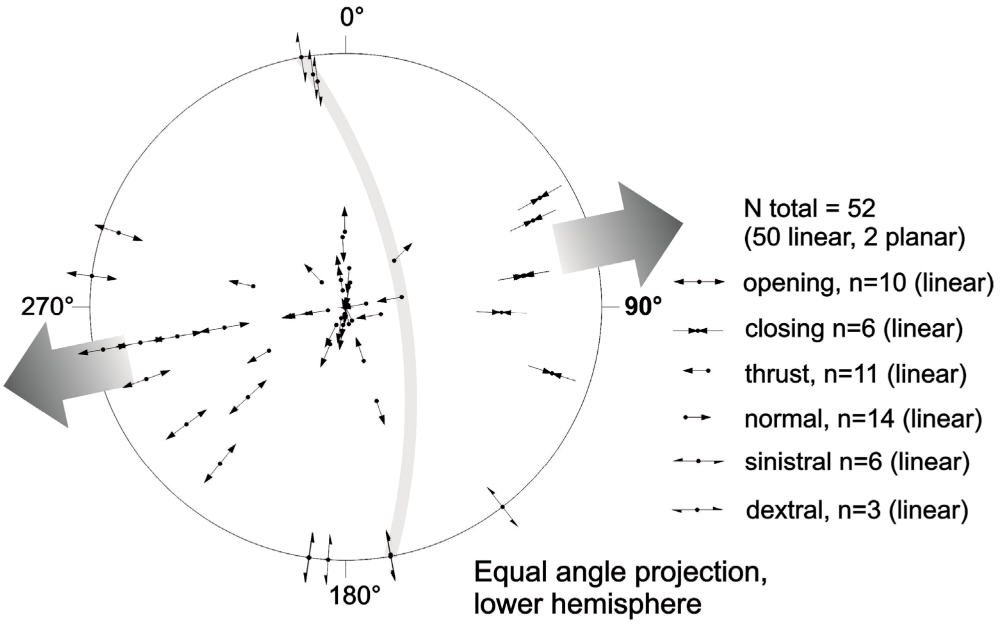

Fig. 6 Long term extension / transtension orientation (grey arrows) recorded in the Skalistý potok Cave.

could be inferred, and the corresponding linear features were marked accordingly. In general, vectors deviating more than 45° from the strike of the fault were classified as opening/closing, while vectors deviating less than 45° were classified as dextral/sinistral. However, due to the partial presence of the opening/closing component, which in its pure form is perpendicular to the fault plane (Fig. 2), some of the resulting linear features would be plotted outside of the projected fault plane.

4. OBTAINED RESULTS

4.1. SKALISTÝ POTOK CAVE – UPPER ENTRANCE

The recorded long-term displacements, 39 records in the period from October 2011 to January 2015, can be characterized as subsidence of the eastern block (12.5 μm/year) in an extensional regime, demonstrated by weak fault opening (12.5 μm/year, Figs. 6 and 7).

Moreover, the displacement components are not affected by the peak-to-peak amplitude caused by seasonal massif dilatation. Three significant events were registered, which changed some of the movement components. A notable tectonic pulse occurred at the end of 2012 and the beginning 2013, which is coincident with the pulse registered at many sites in Europe (Briestenský et al., 2015) and changed the displacement trends. A reversal in rotations is visible at this site as well. Different trends were observed in vertical as well as horizontal rotations before and after the event (rotation around the vertical axis: a counter clockwise 0.02 gon/year trend of the eastern block in the period 2011–2012 and a clockwise 0.012 gon/year trend of the eastern block in the period 2013–2014; a downward fault opening 0.02 gon/year trend of the eastern block in the period 2011–2012 and an upward 0.014 gon/year trend of the eastern block in the period 2013–2015). The second event had a very short duration and was opposite to the long-term trend. The fault closed at the end of 2014 and beginning of 2015 and was followed by a fault opening with a significant sinistral strike-slip (first half of 2015, Fig. 7). In the second half of 2015 there was a dextral strike-slip, probably a relaxation of the strike-slip, along the fault and no rotation around the vertical axis was observed (Fig. 7). The sinistral strike-slip is in good accordance with the sinistral strike-slip mechanism along the Darnó Fault Zone (Fodor et al., 2005).

4.2. SKALISTÝ POTOK CAVE – KARST SPRING

Due to the fact that the gauge was installed in 2014, it was not possible to define the long-term displacement trend (Fig. 8). Only the rotation around the horizontal axis shows a 0.04 gon/year downward fault opening tendency. The stereographic projection (Fig. 8) mainly shows alternating normal or reverse dip-slip and dextral and sinistral strike slips.

4.3. DRIENOVSKÁ JASKYŇA CAVE

The observed long-term tectonic activity shows a similar orientation to the main extension component of the present-day stress field as it was registered in the Skalistý potok Cave (Fig. 6 and Fig. 9).

The data (Fig. 10) display the same tectonic pulses as in the Skalistý potok Cave – upper entrance. A pulse was observed in 2013 (period B), which was accompanied by a strike-slip oscillation, southern block thrust and downward fault opening (Fig. 10). The second pulse caused initialization of southern block subsidence and counter clockwise rotation around the vertical axis in 2014. We have observed an initialization of the dextral strike-slip together with subsidence since the end of 2014, which shows oblique normal faulting. The stereographs also show the onset of increased dextral strike-slip movements in

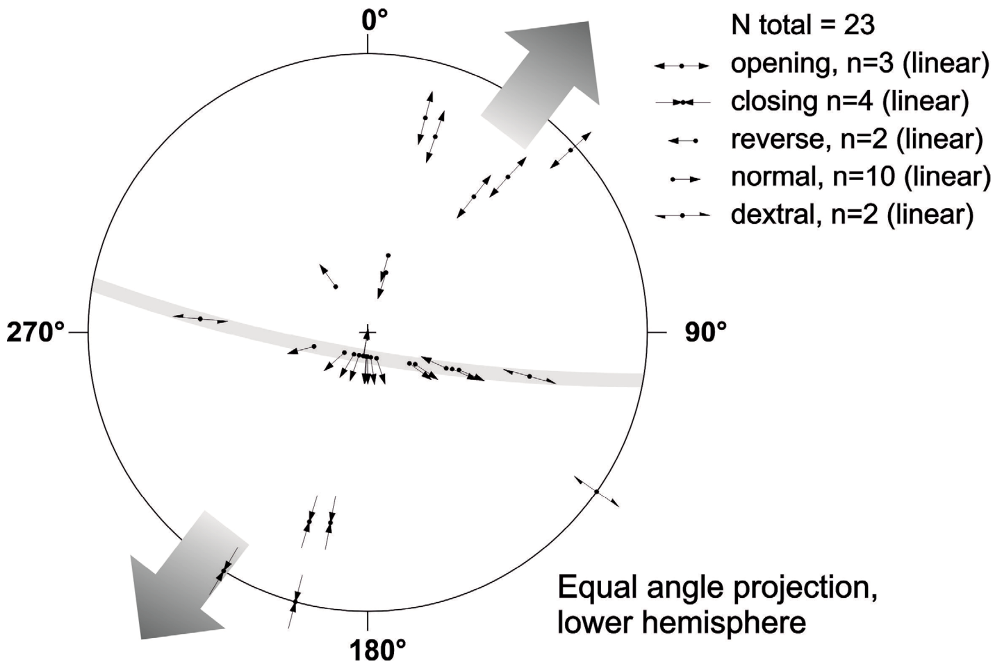

Fig. 9 Long term extension / transtension orientation (grey arrows) recorded in Drienovská jaskyňa Cave.

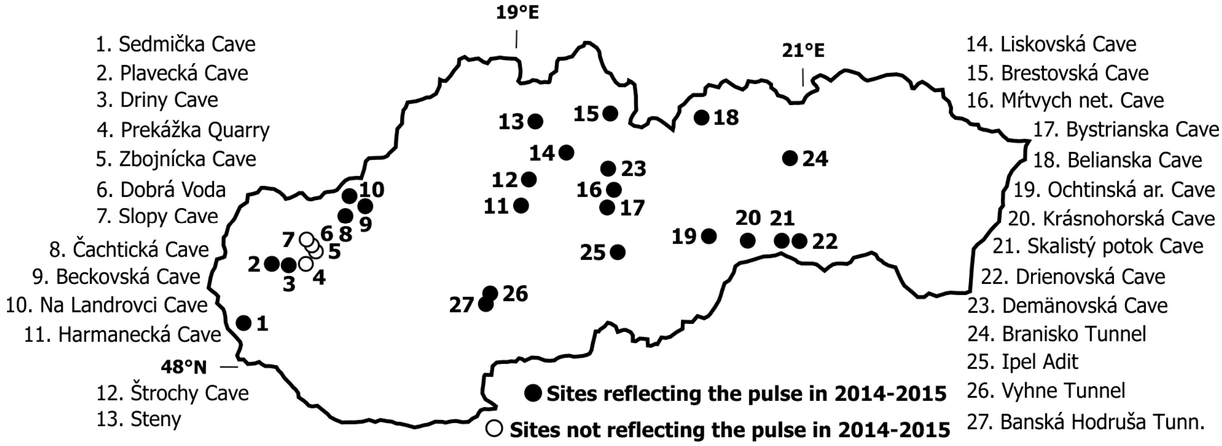

Fig. 12 The monitoring sites (of IRSM and SGIDS) in Slovakia: the black dots represent monitoring points demonstrating the proposed tectonic pressure of the 2014–2015 pulse, while the white dots represent the points that do not offer any evidence of the proposed pulse.

the last period (Fig. 10D). Normal faulting is in good accordance with the mechanism of the Rožňava Fault, separating the northern and southern Slovenský kras Mts. blocks, with southern block subsidence (Zacharov, 2009).

5. DISCUSSION

Two events with increased fault displacement or tectonic pulses were observed in the Skalistý potok Cave and Drienovská jaskyňa Cave. These disturbances were observed at many sites throughout Europe with different fault kinematics (Briestenský et al., 2015). The last tectonic pulse in the second half of 2014 was observed in e.g., Spitsbergen 3,172 km to the north and in Greece 1,156 km to the south (Fig. 11). It was also observed at most of the sites in the Slovak network (Fig. 12).

The pulse was one of the most powerful tectonic pulses registered by EU-TecNet (Stemberk et al., 2010, 2015; Briestenský et al., 2014 a, 2014 b, 2015). It was primarily registered as a strike-slip component, which proves its tectonic origin. This change closed the 2012/2014 period of sinistral strike-slip displacements in the Driny Cave (western Slovakia, Fig. 13), which reflects local tectonics and changes in faulting trends.

Due to the fact that many of the observatory points are only (manually) monitored once a month, it is not possible to accurately estimate the onset of the 2014 pulse. Generally, it began in July/August 2014. On the other hand, there are some sites that are now equipped with automatic dataloggers, which enables us to specify the exact start and the end of the tectonic pulse. Such a site is the 13C Cave (Moravian Karst, Czech Republic, www.tecnet.cz) with data acquired once a day (Fig. 14).

Generally, the event began here on the 9th of August 2014 and finished on the 1st of February 2015.

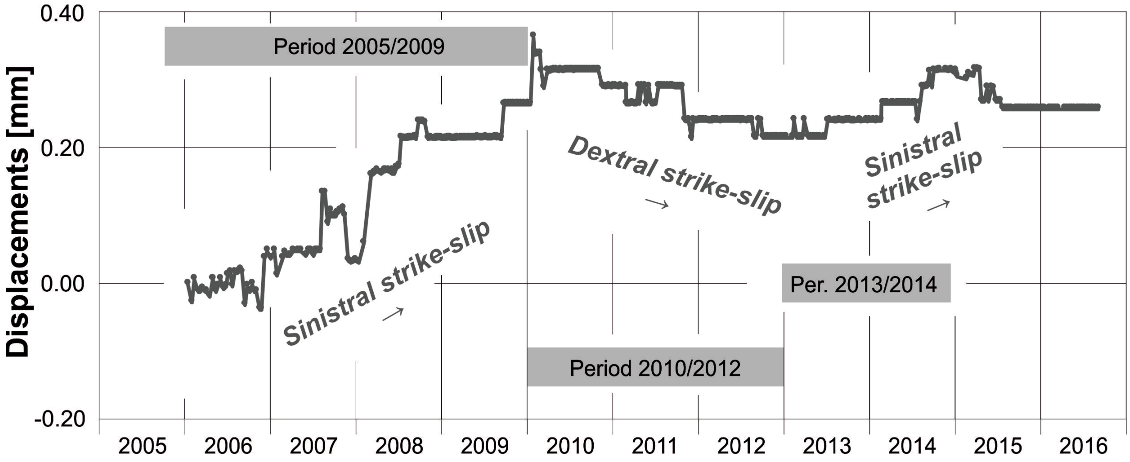

Fig. 13 Strike-slip displacements along the NNE-SSW striking fault in the Driny Cave (275 km westward) in the western part of the Western Carpathian Arc, which show four periods with different strike-slip mechanisms. The mechanisms changed at the end of 2009, 2012 and 2014. The last two reversals (2012/2013 and 2014/2015) correspond to rotation reversal in the Skalistý potok and significant faulting in the Drienovská jaskyňa and Skalitstý potok caves.

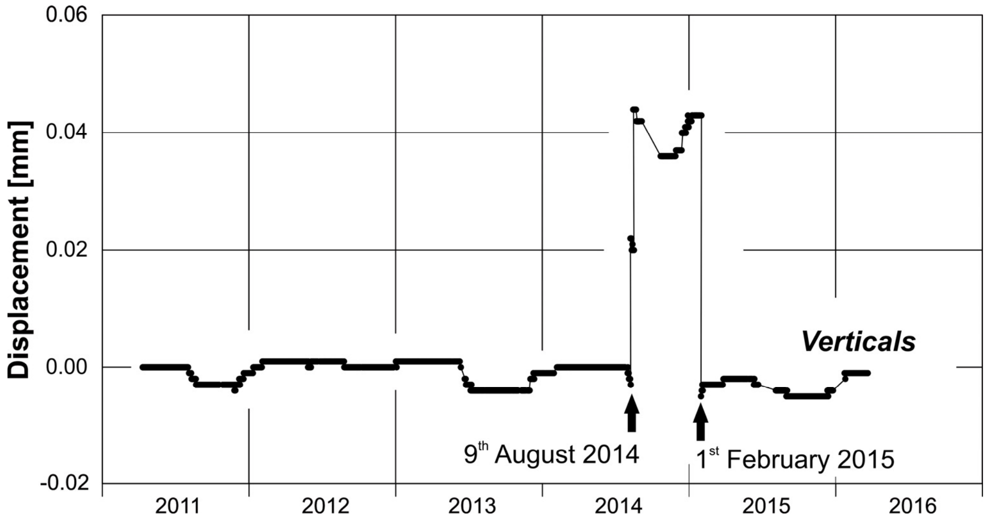

Fig. 14 The vertical displacement component registered along a N-S striking fault in the 13C Cave in the Moravian Karst (Czech Republic, 312 km west-north-westward from the Skalistý potok Cave). The site represents the second automated gauge with a data acquisition frequency of once a day, which helped to define the start and the end of the tectonic pulse at the end of 2014/beginning of 2015.

There are many studies that correlate distant post-seismic displacements (e.g. Bykov, 2005; Tregoning et al., 2013), but no significant seismic effect was found that could play a role in postseismic deformation affecting the whole of the European plate in the second half of 2014. The event was not preceded by any earthquake with $M_W>8$ (www.usgs.gov). On the other hand, the pulse occurred in a large seismic global cycle window with a high number of earthquakes with $M_W>8$, which caused far-field crustal deformation. This cycle started in 2000 (Tregoning et al., 2013).

There are other trigger mechanisms for active faulting like the change in the angular speed of the Earth's rotation (ASER), which is assumed to trigger the majority of earthquakes (Ostřihanský, 2012; Trofimenko and Bykov, 2017). The 13C Cave (Třináctka Cave) data (Fig. 14) indicate that the LOD (length of day), which represents a deceleration and acceleration of ASER, could correlate with the fault slips (Fig. 15).

Moreover, Riguzzi et al. (2010) presented a theory that a significant portion of tidal energy is also converted into tectonic processes. Kalenda et al. (2015) determined that microseims have the same annual distribution as LOD variations (changes in ASER) and they accompany a drift in the westward tectonic plates. Tidal torque decelerates the ASER (Scopolla et al., 2006); hence, it has a seasonal character. Figure 11 shows that changes between significant tectonic periods also finish at the end of the year. Furthermore, microdisplacements in the Drienovská Cave and the 13C Cave followed a short-lasting minimum LOD (maximum of the ASER) with a 2-day delay (in agreement with the 2-day earthquake delay published by Ostřihanský, 2012). Therefore, ongoing fault displacement monitoring should prove or rebut the role of ASER in active tectonics, not be

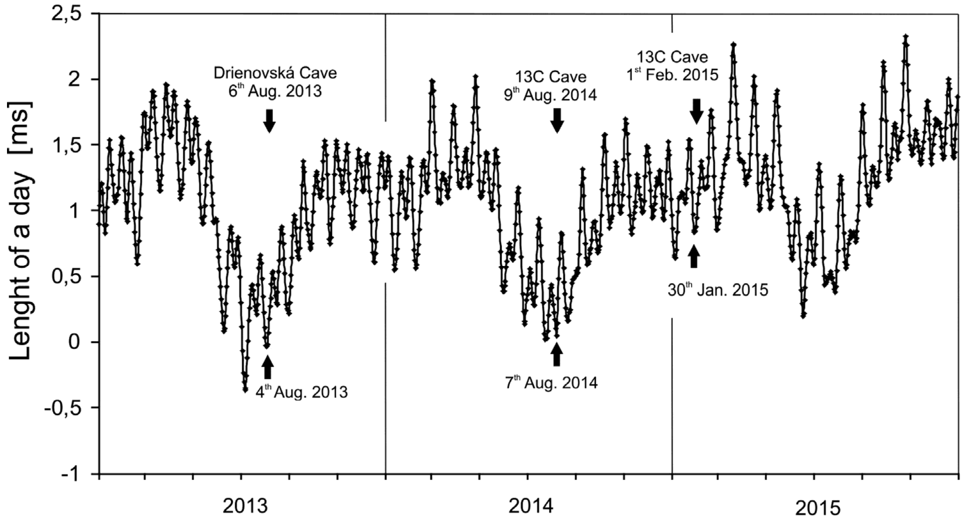

Fig. 15 The coincidence of the LOD (length of day, source: https://www.iers.org) and the discussed displacements with the accurate date in the Drienovská Cave and the 13C Cave in 2013, 2014 and 2015. The displacements followed a short-lasting LOD minimum (maximum of the angular speed of the Earth's rotation) with a 2-day delay (in agreement with the 2-day earthquake delay published by Ostřihanský, 2012). The lower arrows show the short-lasting LOD minimum and the upper arrows represent the beginning of the displacements.

regarded as the origin of the fault displacements, but as a triggering mechanism depending on the stress background.

6. CONCLUSION

Long-term tectonic activity determined in the Skalistý potok and Drienovská caves is characterized by an extension of the transtension regime with the S_{hmin} orientation in a NE-SW to ENE-SWS direction. Orientation of the S_{hmin} is in good agreement with the results of the cavitonics obtained from the western part of the Slovenský kras Mts. (Littva et al., 2015) and also with orogen-parallel extension monitored in the Western Carpathian realm (Hók et al., 2016).

Block rotations in the Skalisty potok and Drienovská jaskyňa caves indicate a change in the long-term tectonic regime, which started in 2013 across the various regions of Europe (Briestenský et al., 2015).

The most significant fault microdisplacements occurred in first half of 2015, when the NNW-SSE sinistral strike-slip fault (in the Skalistý potok Cave – upper entrance) together with the WNW-ESE dextral strike-slip fault (in the Drienovská jaskyňa Cave) were reactivated under the transtensional tectonic regime, where the principal maximum compressional axis operated in a NW-SE direction (σ_1) during this short-lasting period.

The observed results were compared to data from monitoring points in other regions of the European plate, regarding e.g., the northern site in Spitsbergen and the south-eastern site in Greece. Many sites showed evidence of a simultaneous microdisplacement anomaly in the second half of 2014/ beginning of 2015, which is interpreted to reflect the occurrence of a tectonic pressure pulse towards the second half of 2014.

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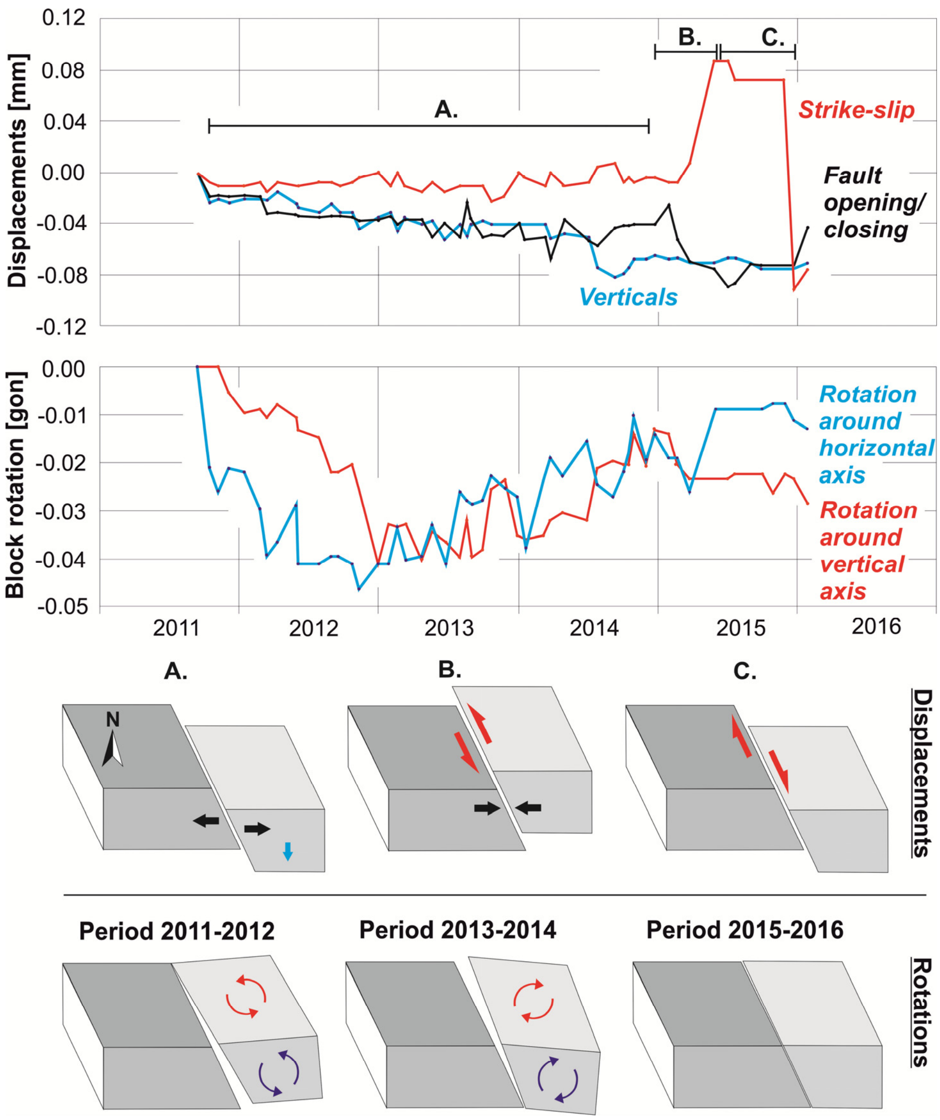

Fig. 7 The fault displacements and block rotations recorded in the Skalistý potok Cave – upper entrance. The block diagrams show a schematic model of the long-term block movements, significant faulting periods (blue arrow – verticals, black arrow – fault opening/closing, red arrow – strike-slip), block rotation and periods of block rotation changes (blue arrow – rotation around horizontal axis, red arrow – rotation around vertical axis).

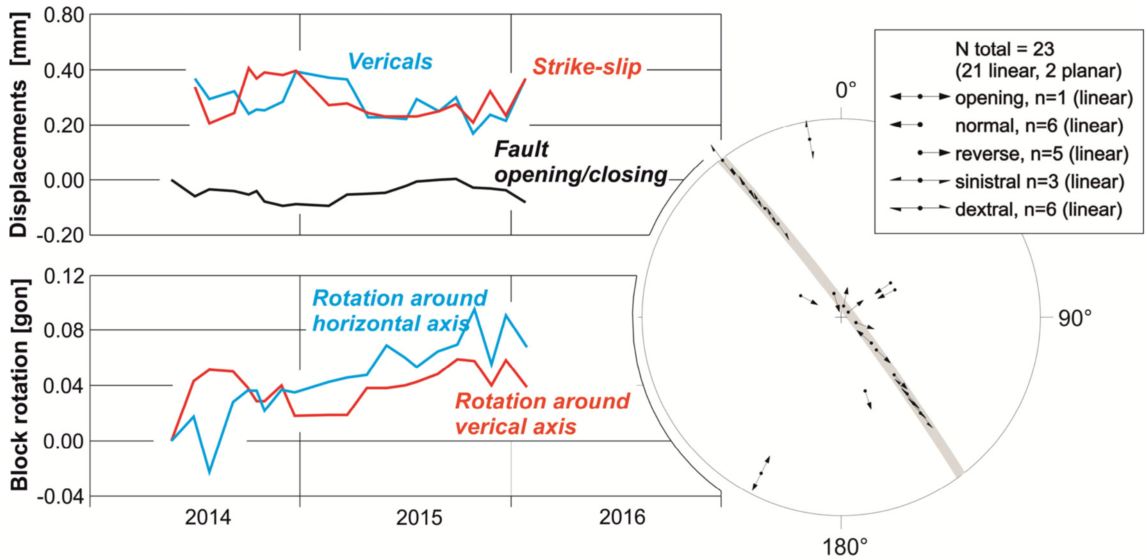

Fig. 8 The fault displacements and block rotations recorded in the Skalistý potok Cave – karst spring. The right image shows the stereographic projection of the plotted fault plane (thick grey great circle) and the displacement vectors projected as tangent lines.

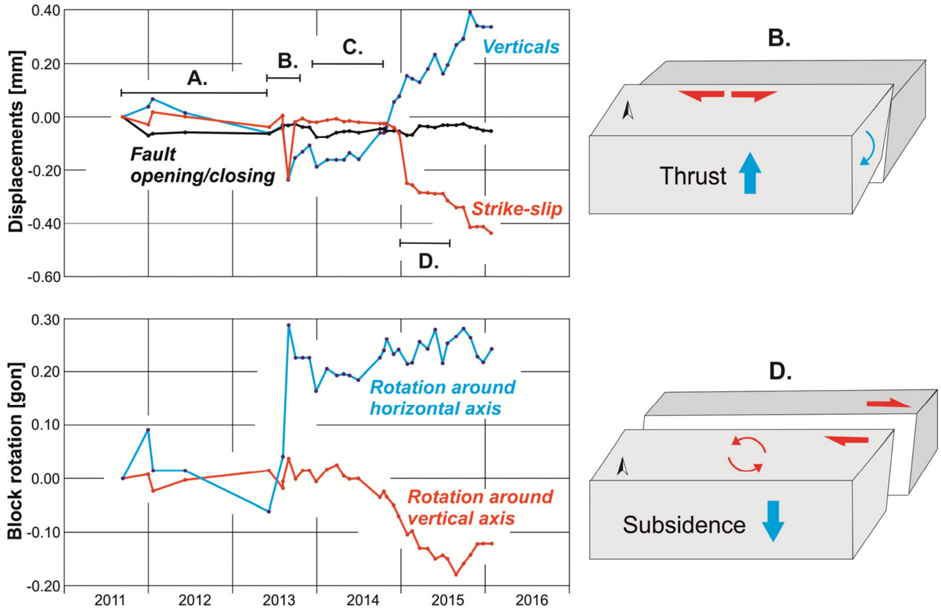

Fig. 10 The fault displacements and block rotations recorded in the Drienovská jaskyňa Cave. The block diagrams show a schematic model of the significant pulse in 2013 (B.) and displacement initializations in 2014/2015 (D.) (blue arrow – subsidence, thrust and rotation around horizontal axis, red arrow – strike-slip and rotation around vertical axis).

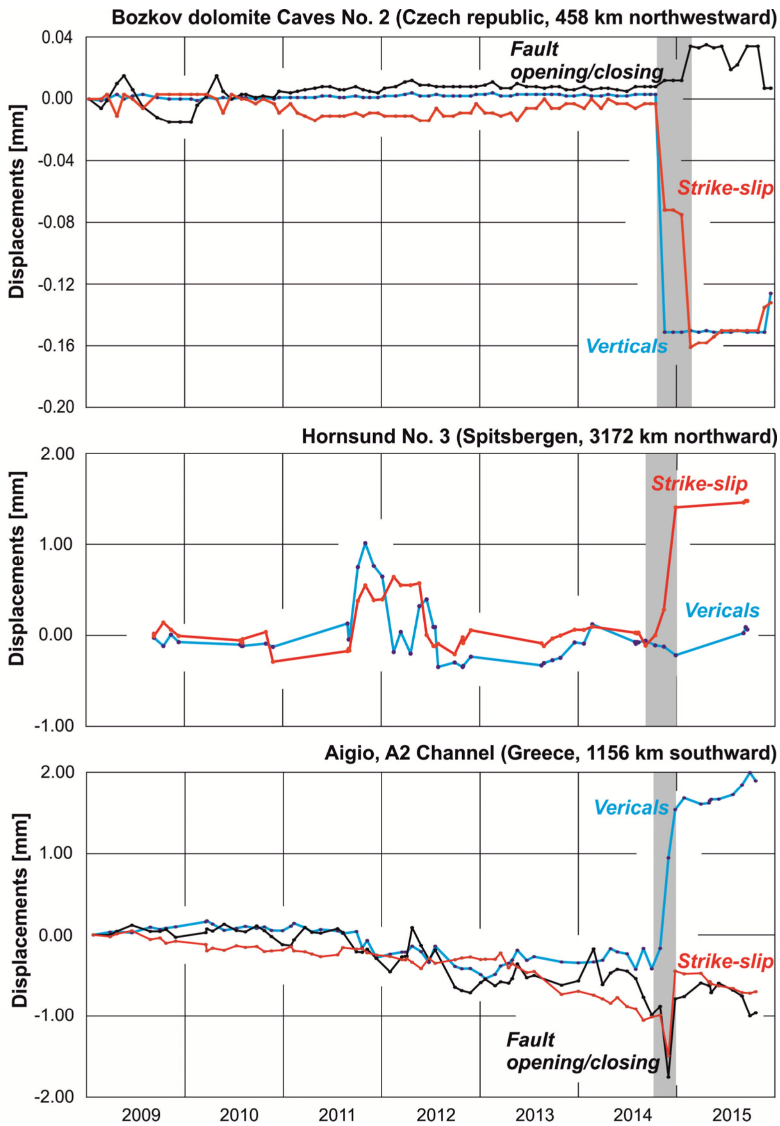

Fig. 11 Tectonic pulse (grey rectangle) that affected many fault displacement records with a plate-wide effect in the second half of 2014. The headings of the graphs show the distances from the Skalistý potok Cave. It is evident that the pulse affected the whole of the European plate and was simultaneously registered at the Skalistý potok and Drienovská jaskyňa caves. The sites belong to EU-TecNet (www.tectnet.cz).