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3D long-term monitoring of recent tectonic activity in the Branisko Tunnel (Eastern Slovakia)

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Abstract: This article presents the results of more than 24 years of monitoring of displacements along a Šindliar fault plane using a high-resolution 3D extensometer (TM-71), which was installed in the Branisko highway tunnel. This significant fault, striking NNE–SSW, separates the pre-Cenozoic basement of the Branisko mountain range and Cenozoic sediments. The micro-movements indicate a contemporaneous oblique dextral strike-slip, which is consistent with regional transtension/extension proved by previous geological studies. Furthermore, obtained results show that the displacements are permanent, very slow, and reflect the changes in the stress field. An average speed of movement reaches 0.11 mm a year. Jump-like changes correspond well with weak earthquakes as well. Our results prove that cracks in the reinforcement of the Branisko highway tunnel occur as a result of recent tectonics. The long-term monitoring may contribute to the safe operation of the tunnel and represent a warning system in future.

Keywords: Western Carpathians, Branisko Tunnel, Šindliar fault, recent tectonics, monitoring, 3D extensometer

Introduction

The most important Quaternary geodynamic phenomena or processes in Slovakia encompass slope movements (in particular landslides, less frequent falls, flows, creep), karstification, weathering, erosion, seismicity, and faulting. These reflect the geological structure, morphology, and climate of the Western Carpathians, covering the Slovak territory. Posing a threat to human life, the above phenomena also cause considerable damage to engineering constructions and economic activities. One way of protecting people and their property from geological hazards is through prevention by monitoring the manifestations and parameters of these phenomena. An extensive monitoring network for the detection of very slow movements or displacements on recent tectonic faults, rock block failures, and historical objects was created in Slovakia.

The network, which currently includes 36 localities (Fig. 1), is run by the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences and the State Geological Institute of Dionýz Štúr, Slovakia. Some monitoring works are carried out in collaboration with the Slovak Caves Administration (State Nature Conservancy of the Slovak Republic) and the Geophysical Division of the Earth Science Institute (Slovak Academy of Sciences). For 3D detection of fault slips, special TM-71 high-resolution 3D extensometers are primarily used (Fig. 2; Košťák 1969, 1991). The most interesting results from the sites in Slovakia were published by Petro et al. (1999, 2004a, 2011a, b, 2012); Wagner et al. (2000); Vlčko & Petro (2002); Vlčko (2004); Briestenský et al. (2007, 2018); Ondrejka et al. (2014). Detailed monitoring results from the monitoring network are presented in the form of annual reports and are available on the State Geological Institute of Dionýz Štúr website (https://dionysos.geology.sk/cmsgf/).

This paper presents the results of long-term 3D monitoring of micro-movements along a significant fault, crossing the Branisko highway tunnel (Eastern Slovakia) and their comparison with the results of geological and geodetic observations in the surrounding region. A long-term prediction of the safe operation of the tunnel is also presented.

Geology of the Branisko region

The Branisko mountain range is located in the eastern part of the Internal Western Carpathians (Fig. 3; Hók et al. 2014). The geological structure includes the Paleo-Alpine tectonic units of Veporicum and Hronicum. The Veporicum comprises crystalline rocks (granites, migmatites, gneisses, amphibolites) and autochthonous Mesozoic cover (quartzites, limestones). The Hronicum is a cover nappe composed of Upper

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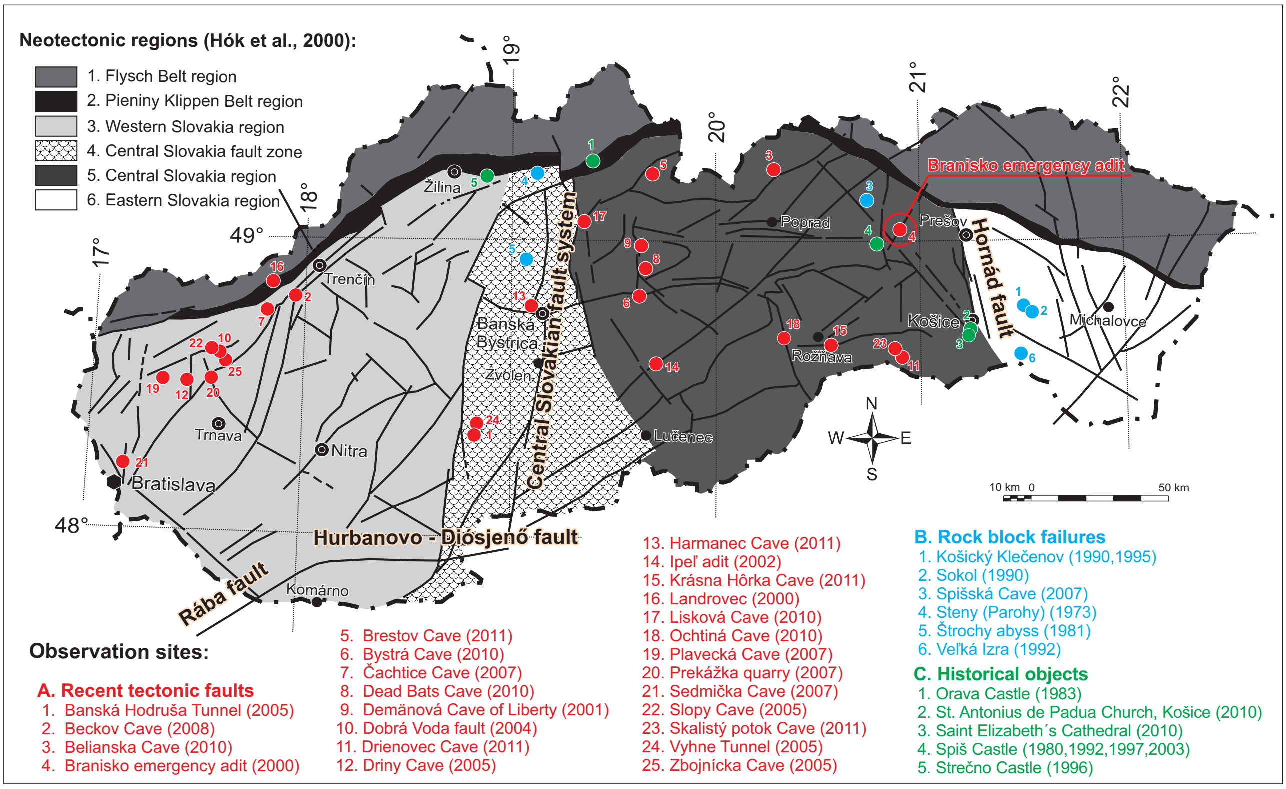


Fig. 1. Monitoring network for detecting micro-displacements on active tectonic structures, rock block faults, and historical objects using TM-71 extensometers in Slovakia, which is run by the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences and the State Geological Institute of Dionýz Štúr, Slovakia. The figure shows the observation sites along with their respective years of installation.

Paleozoic sediments and volcanic and Mesozoic carbonate sequences (Polák et al. 1996). Rock complexes of both tectonic units are unconformably and transgressively overlain by sediments of the Central Carpathian Paleogene Basin (Podtatranská – Sub-Tatric Group *sensu* Gross et al. 1984). The Branisko Mts. represents a morphologically prominent horst structure (Fig. 4), bounded by the Neo-Alpine Poľanovce fault on the west and the Šindiar fault on the east, which separate it from the Central Carpathian Paleogene Basin (CCPB) sedimentary formations.

Methodology

The TM-71 extensometer was chosen for the monitoring of micro-displacements on the Šindliar neotectonic fault inside the Branisko highway tunnel. The device can detect spatial (3D) changes, it has high measurement accuracy (rotations in the order of $8.7 \cdot 10^{-5}$ rad, displacements better than 5 μm), weather resistance (temperature, humidity, stray currents), simple handling and maintenance. It has also shown good results from its practical use all over the world (e.g., Avramova-Tacheva et al. 1984; Košťák & Avramova-Tacheva 1988; Košťák & Cruden 1990; Košťák et al. 2002, 2011; Štěpančíková et al. 2008; Gosar et al. 2009; Stemberk et al. 2010, 2015, 2016, 2018; Briestenský et al. 2015; Baroň et al. 2019, 2024; Šebela et al. 2021).

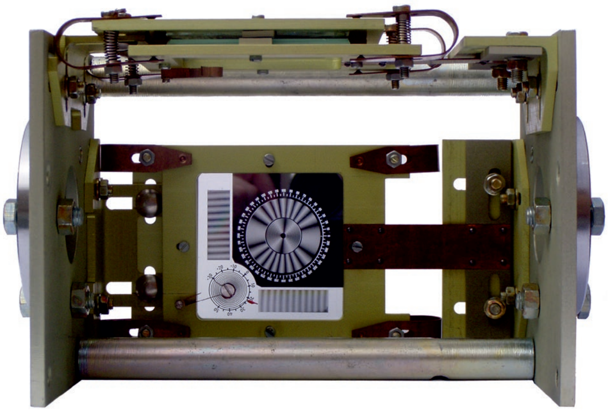


Fig. 2. TM-71 high resolution 3D moiré extensometer constructed by Košťák (1969). The vertical segment of the device displays the result of the movement recorded through optical interference – the number of stripes within the circle indicates displacement, while the number of stripes within the rectangles indicates rotation; the same applies to the horizontal segment.

The TM-71 extensometer is based on the moiré principle, which represents an optical interference effect (Fig. 2). When light passes through two specially prepared superposed glass

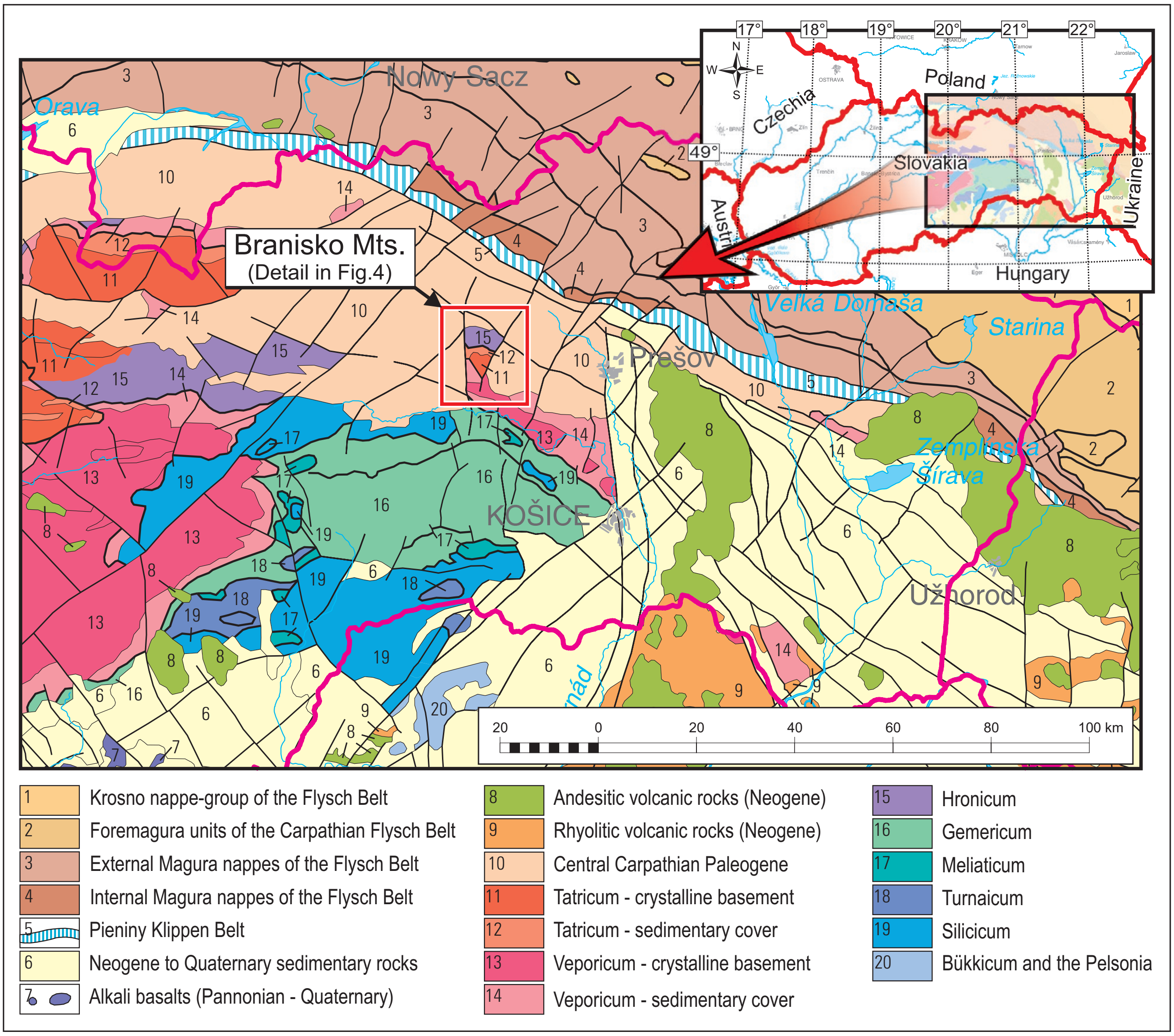
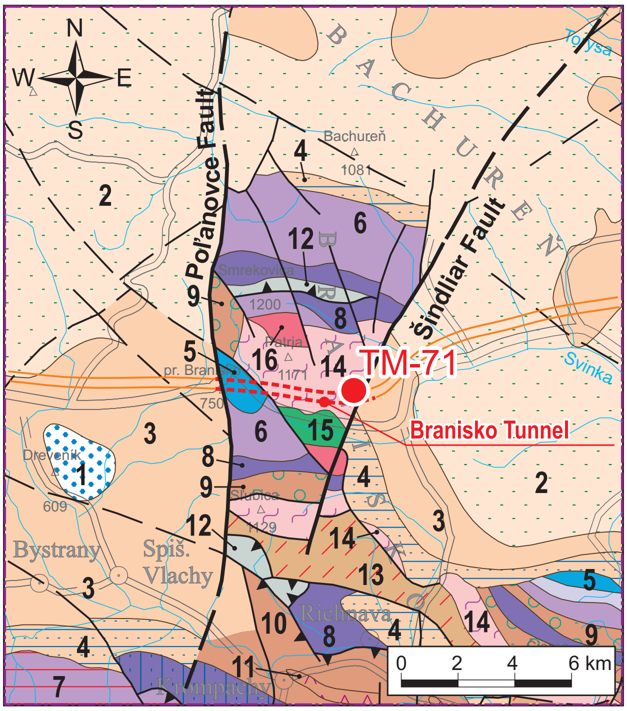


Fig. 3. Location of the Branisko Mts. among the principal Alpine tectonic units and the post-nappe formations of the Western Carpathians (adopted according to Lexa et al. 2000 and Hók et al. 2014).

plates, it creates a pattern of black and white fringes. The relative displacement of the plates causes a change in the number of fringes. The size of the movement is directly proportional to the number of stripes. The construction of the TM-71 allows not only displacements to be recorded, but also rotations in two mutually perpendicular planes. If the device is installed between two fault or crack walls, it is possible to obtain data in three Cartesian coordinates (X – crack width, Y – horizontal shift, Z – vertical displacement) from the recorded interference patterns. The recorded data may be taken visually; however, the use of photographic paper or digital cameras and images is more appropriate for the collection of data. In recent years, records from some extensometers have been captured continuously and computed automatically at a very high resolution (Marti et al. 2013; Rowberry et al. 2016; Stemberk et al. 2019; Briestenský et al. 2021).

The Branisko monitoring site and data collection

The Branisko site was selected for long-term monitoring using the TM-71 extensometer for several reasons, most notably due to the Neo-Alpine tectonic activity of the Šindliar fault, as confirmed by geological evidence. The mountain range is part of an elevated horst structure characterised by significant relative uplift on a regional scale (Maglay et al. 1999). The second reason was the penetration of the Branisko mountain range by a tunnel construction (1997–2003), which represents one of the most significant road constructions in Slovakia. The third reason was the launching of the multilateral international project COST Action 625 “3D monitoring of active tectonic structures” (02/2000–02/2006; https://www.cost.eu/actions/625/).



Lithology of the Internal Carpathian units – Quaternary: 1 – freshwater limestones travertines (Pliocene - Pleistocene); **Paleogene: 2** – sandstones, subordinate shales (Priabonian–Oligocene); **3** – sandstones, calcareous claystones, locally conglomerates: flysch, mostly claystones towards the base *–Zuberec, Huty and Zakopane Fms.* (Lutetian–Oligocene); **4** – conglomerates, sandstones, limestones, breccias, rare claystones – *Borové Fm.,* Súľov *Conglomerates, "Nummulitic Eocene" in Poland* (Lutetian–Priabonian); Mesozoic: **5** – limestones, sandstones, sandy and spotted limestones, nodular and radiolarian limestones, radiolarites – *"basinal facies" - Kőssen, Gresten, Allgäu, Adnet, Ruhpolding, Ždiar and Jasenina Fms.* (Rhaetian–Kimmeridgian); **6** – dark to light limestones - *Gutenstein and Wetterstein Lmst.* and dolomites - *Ramsau, Wetterstein Dol.* (Anisian–Carnian); **7** – limestones and dolomites *"carbonate platform" - Gutenstein, Steinalm, Wetterstein, Lmst.* (Anisian–Ladinian); **8** – quartzites, sandstones and shales – *Lúžna Fm.* (Induan–Olenekian); **9** – conglomerates, sandstones, shales, rhyolite/dacite volcanics – *Korytné Fm.* (Permian); **10** – conglomerates, sandstones, variegated shales, volcanics (*Malužiná, Knola, Petrova Hora Fms.*); **11** – rhyolite volcanics (Permian); **12** – conglomerates, sandstones, shales, acid volcanics, *Slatvina and Nižná Boca Fms.* (Late Carboniferous); **Variscan crystalline basement: 13** – mica schists, gneisses and products of their diaphtoresis; **14** – banded gneisses and augengneisses (mostly orthogneisses), migmatites; **15** – metamorphosed basic rocks (amphibolites, amphibole gneisses, chlorite-epidote schists, metagabbros); **16** – biotite tonalites to granodiorites, locally porphyritic

Fig. 4. The geological-tectonic structure of the Branisko Mts. with the location of the highway tunnel and the TM-71 monitoring site (adopted according to Bezák et al. 2004).

At present, the Branisko Tunnel is a one-tube-two-way design, almost 5 km long, and was constructed after the excavation of a parallel exploration gallery, which serves as an emergency adit in the event of a traffic accident inside the tunnel. The TM-71 extensometer was installed on 12 December 2000 directly between the footwall and the hanging wall of the Šindliar fault, approximately 300 m from the mouth of the emergency adit on the eastern side (Fig. 5). Data collection began immediately after its installation, e.g., before the completion and opening of the adjacent tunnel tube. Data were and are still being collected visually and/or photographically with a frequency of 3–6 times per year.

Data processing and interpretation of results

All data acquired from the TM-71 extensometer, i.e., displacements along all three axes XYZ in both horizontal and vertical planes as well as rotations in the horizontal (XY) and vertical (XZ) planes, external temperatures, accurate date, and Central European Time (UTC+1), are processed using a special MSDilat computer program (MSDilat – application for computer processing of the TM71 3D measurements prepared by M. Stercz in Delphi language for MS Windows platform). The initial version of the software was developed in 2004 (Petro et al. 2004b), with a subsequently improved version employed in later stages. Mutual displacement and rotation of the tectonic blocks were determined based on the spatial relationship between the TM-71 extensometer and the fault plane, taking into account both coordinate systems. A schematic representation of the resulting motion vector, illustrated as a 3D model, is presented in Fig. 6.

Preliminary monitoring results and fresh cracks in the concrete reinforcement on both sides of the fault plane within the tunnel and the emergency adit (Fig. 5), suggest potential recent tectonic activity (Petro et al. 2004a). Almost twenty-four years of observations (from December 2000 to September 2024) have confirmed micro-displacements and relative rotations between the two tectonic blocks (Fig. 7). From a geotechnical perspective, the most significant finding is the long-term and progressive trend of shear displacements along the fault plane. The total displacement vector observed across the fault reached a magnitude of 2.64 mm, corresponding to an average displacement rate of 0.11 mm.year^{-1}. Analysis of the original XYZ data recorded by the TM-71 extensometer indicates that the Y-component accounts for approximately 83 % of the total movement. The remaining components of the displacement vector are nearly an order of magnitude smaller, with the X-component measuring 0.342 mm and the Z-component 0.178 mm.

Based on the installation parameters of the TM-71 device, the calculated azimuth of the movement vector of the hanging wall is 186°, indicating a general geographic movement in the NNE–SSW direction. From an interpretative standpoint, the spatial displacement can be characterised as a slightly oblique dextral slip of the SE block (hanging wall; Madarás et al. 2012).

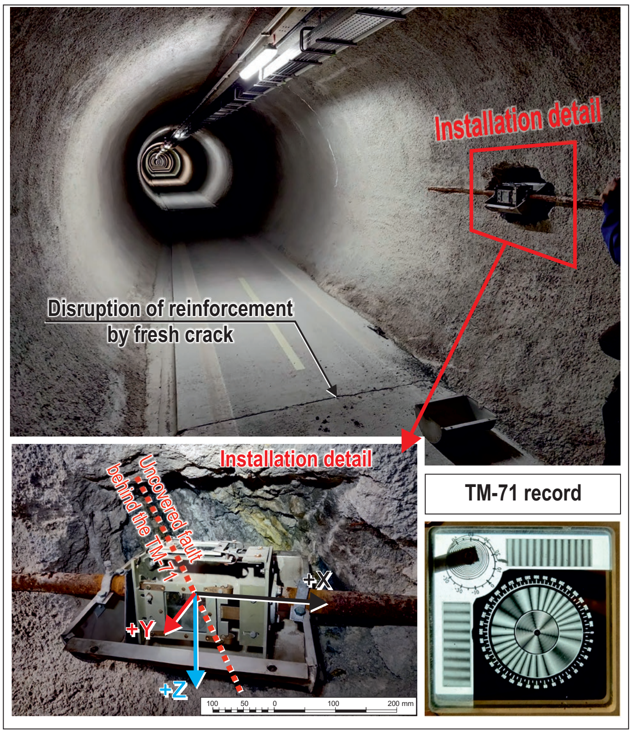


Fig. 5. TM-71 installation on the Šindliar fault inside the Branisko emergency adit. Measurements began on 12 December 2000.

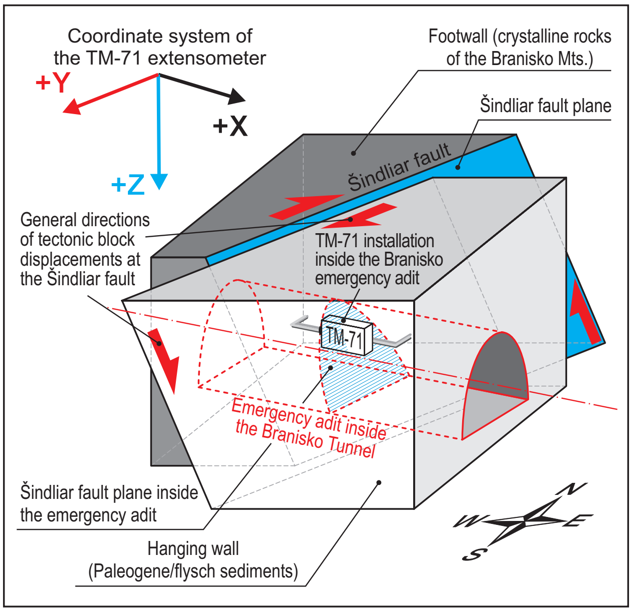


Fig. 6. 3D scheme of the TM-71 installation inside the Branisko emergency adit with directions of its coordinate system and directions of vectors X (crack opening), Y (strike-slip/horizontal shift), Z (vertical movement) and displacements of tectonic blocks on the Šindliar fault.

Moreover, in this work we used the approximate P-/T-axis method calculated and visualized by FaultKin7 software (cf. Marrett & Allmendinger 1990; Allmendinger et al. 2011). This method calculates the orientation of the principal axes as the mean of the clustered axes. The method had been adapted for use with a specific data input used for measurements with TM-71 extensometers, in contrast to the usual use of the structure geological method, where the orientations of the slickensides and the striae are used (see e.g., Stemberk et al. 2018, 2019, for further details). The 1-year XYZ displacement dataset adjusted to the fault plane was used as input data for the analysis. In this paper, the orientation of the main principal axes, individual 1-year fault slip data and were visualized as stereoplot.

Although the tectonic activity observed during the monitoring period can generally be described as relatively uniform, the entire timeframe may nonetheless be divided into several shorter intervals (Fig. 7), based on the characteristics of the measured components of the displacement vector and the recorded rotational values in the XY and XZ planes. This indicates the nature and manner in which the accumulated stress within the rock massif is progressively released over time.

Characteristics of the curves

The X-component of the motion vector represents a horizontal displacement in a direction close to the fault dip direction (the difference between the direction of the X-axis of the instrument and the fault dip direction is approximately 10°). Usually, according to the geometry of the device installation, the X-component represents the widening or narrowing of the gap between the measured blocks. In the case of the device installation in the emergency adit, the curve has a slightly decreasing character, which indicates the dilation of the fault. However, the total movement in this direction is relatively small (in the range of 0.34 mm over the entire monitoring period), and may therefore be considered negligible in comparison to the overall resultant movement. In terms of the temporal progression, the displacement curve exhibits a periodic component with an apparent annual cycle. This indicates a regularly occurring deformation of the rock massif, influenced by seasonal variations in the average outdoor temperature. A notable change in the trend was observed in the second half of 2011, marked by a slight shift in the displacement curve followed by a gradual deceleration of the movement. This trend change was also reflected in other measurement curves.

The Y-component represents the horizontal movement perpendicular to the dip direction of the monitored tectonic fault. This component exhibits a visually smoother trend with a clearly negative progression, indicating a right-lateral (dextral) sense of displacement. Notably, the periodic component with an annual cycle is completely absent from this time series. In the initial phase of the measurements (until the end of 2005), the course of the curve is restless, and the values oscillate significantly around the imaginary line of the trend. Later, this oscillation is less pronounced and certain periods with a change like a trend may be recognised. This indicates

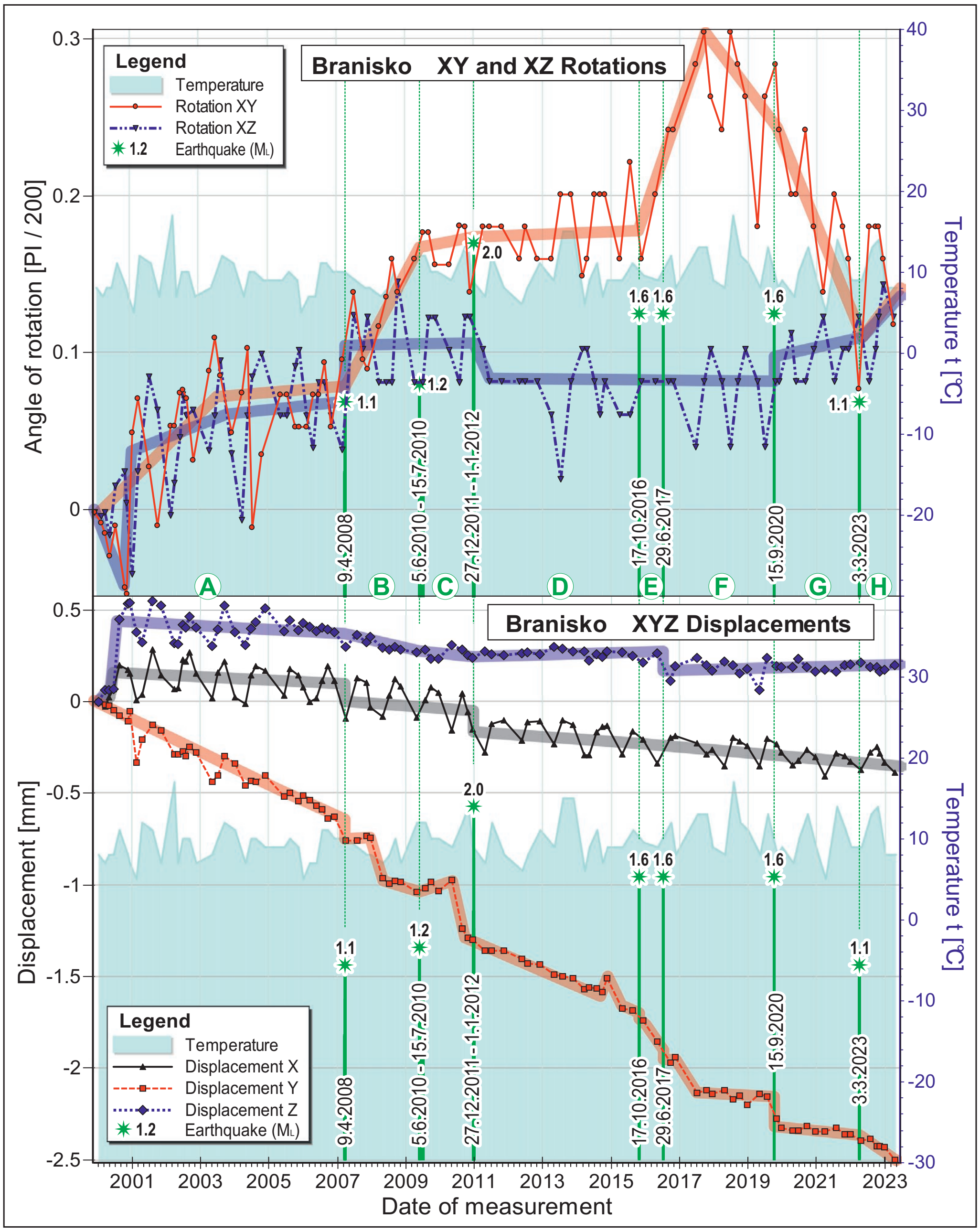


Fig. 7. Displacement records (XYZ) and rotations (XY – horizontal, XZ – vertical) of tectonic blocks detected by the TM-71 extensometer installed inside the Branisko emergency adit.

that the Y-component of the displacement exhibits a discontinuous, step-like character, with intervals of minimal or no movement alternating with periods of more rapid, and in some cases abrupt, displacement. The total amplitude of this component exceeds 2.6 mm over the monitoring period, representing the dominant portion of the overall motion vector.

The Z-component of the movement vector represents displacement in the vertical direction. The measured values for the entire measurement period represent only a tenth of a millimetre and indicate subsidence of the hanging wall, although the magnitude of the movement is almost negligible. In the initial period of measurements (until the end of 2001), the measured values had a significant positive direction (probably a settling of the apparatus at the beginning of the measurement), but from the beginning of 2002 the movement in this direction slowed down and there was a change in orientation of the trend to a negative one.

Figures 8 to 10 show the procedure for calculating the movements of geographic parameters from the measured XYZ data, i.e., direction of movement in the horizontal plane = azimuth (Fig. 8) and direction of movement in the vertical plane = magnitude of slope (Fig. 9 – XZ plane and Fig. 10

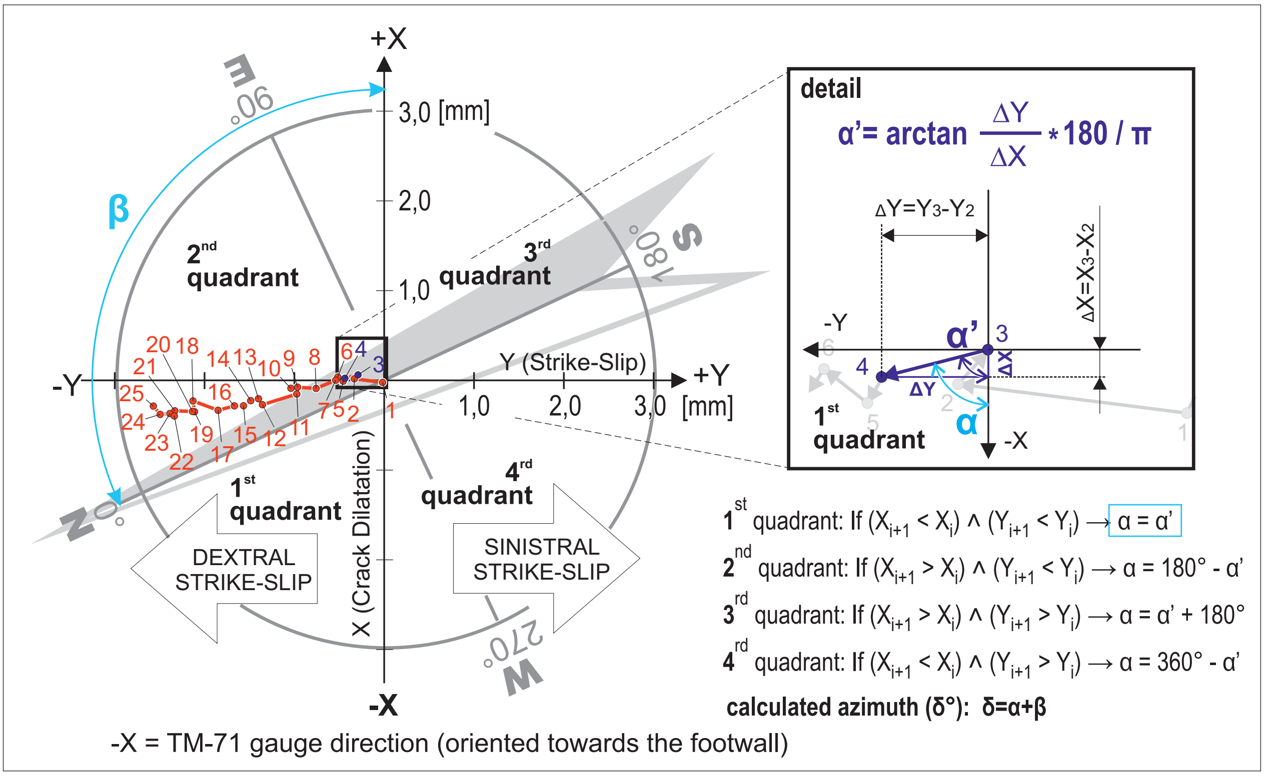


Fig. 8. Interpretation of data measured in the YX plane.

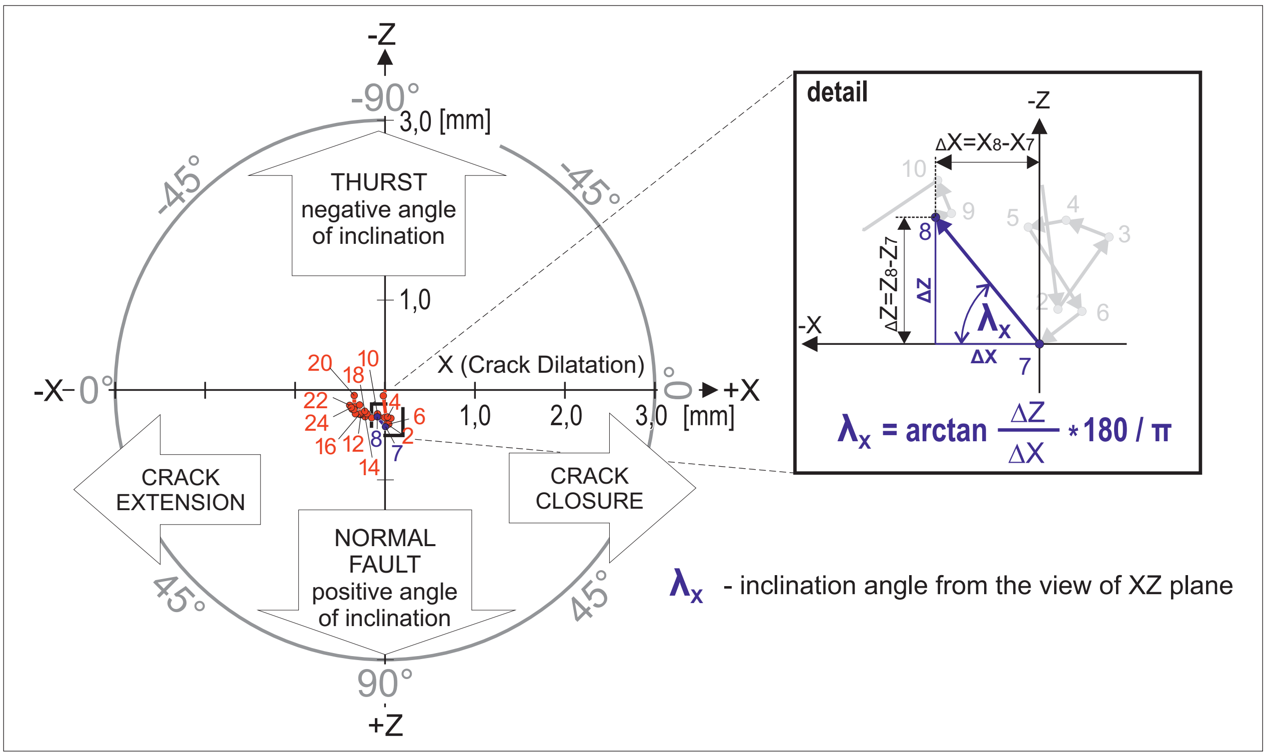


Fig. 9. Interpretation of data measured in the ZX plane.

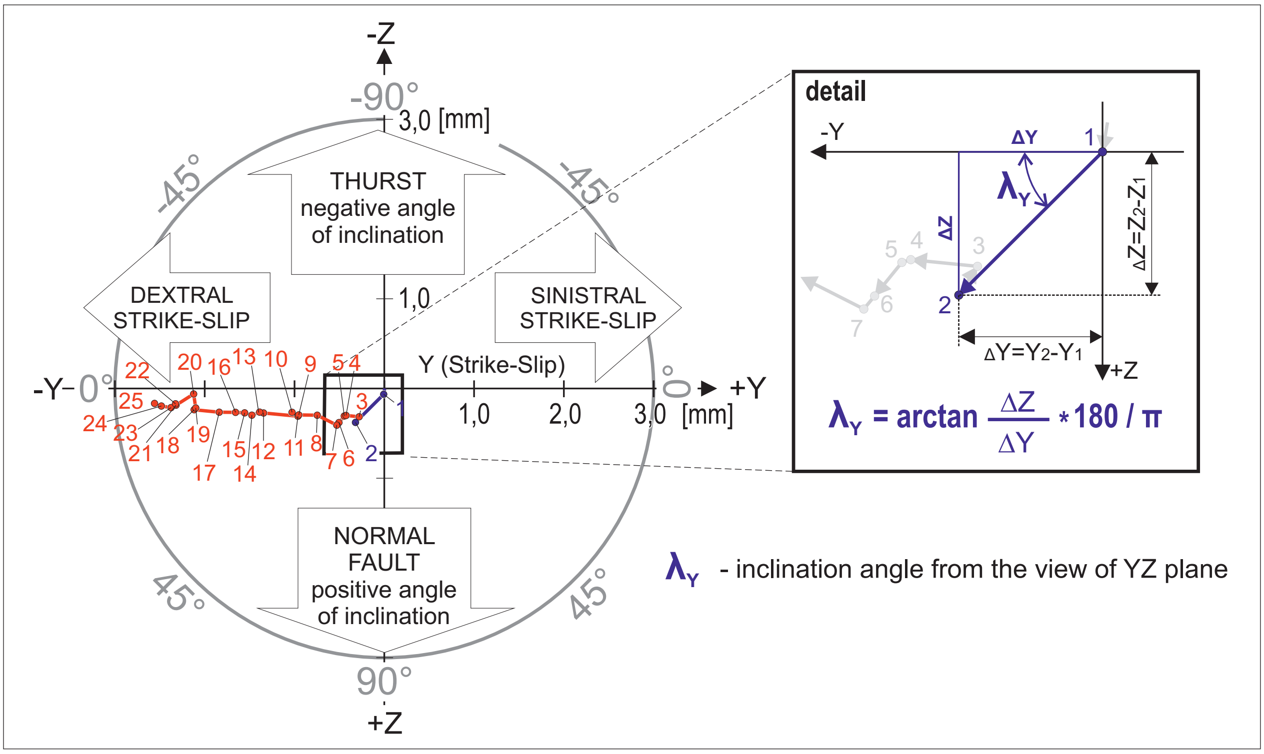


Fig. 10. Interpretation of data measured in the ZY plane.

– YZ plane). The input data for the movement parameter calculations have been simplified to 1-year periods and have the character of a movement vector for the specified period. The projections of the individual movement vectors onto the respective plane of the device are shown in red in the images. The horizontal direction, i.e., the azimuth of individual vectors, was calculated using goniometric functions (the formula for the calculation is shown in Fig. 8). The angle α for each motion vector represents the angle between the projection of this motion vector into the XY plane and the X-axis of the TM-71 coordinate system. The resulting azimuth δ is then the sum of angle α and angle β, which represents the horizontal deviation of the instrument's axis from the geographic north.

Calculation of the real direction of movement in the vertical plane is a little more complicated, as it is displayed in two mutually perpendicular vertical planes XY and XZ (Figs. 9 and 10). The actual size of the inclination angle λ for the general case may be calculated by combining the data for both planes:

$$\lambda = arctan \frac{\Delta Z}{\sqrt{\Delta X + \Delta Y}} * 180/\pi$$

In addition to measuring displacements, the TM-71 device also records rotations, i.e., the rotation of the measured blocks relative to each other in the horizontal (XY) and vertical (XZ) planes with an accuracy of hundredths of a grade (Rowberry et al. 2016). The measured values reflect the tension state of the rock massif on the fault and react quite sensitively to changes in tension but also indicate short geodynamic pulses and seismic events. According to the change in the course of curves at the Branisko site, it is possible to single out individual periods with similar characteristics within the measurement period (Fig. 7). From the beginning of the measurement to approximately the end of 2008, there is a slight increase in the angle of rotation on both curves, which may indicate a low tension increase in the massif. During the following period until the beginning of 2017, the rotation values remained relatively stable, exhibiting only minor short-term fluctuations in both positive and negative directions. In 2017 and 2018, the XY rotation curve experienced a significant increase. However, since 2019, the trend reversed, and the curve demonstrated a consistent decline through the end of the observation period. These variations were not significantly reflected in the XZ curve.

Correlation of the TM-71 measurements with seismic events

Seismic phenomena are observed and recorded in Slovakia by the National Network of Seismic Stations (NNSS), which was established and is operated by the Institute of Earth Sciences of the Slovak Academy of Sciences (ÚVoZ SAV) in Bratislava. Currently, NNSS consists of 14 seismic stations (https://www.seismology.sk/National_Network/national_network_A.html).

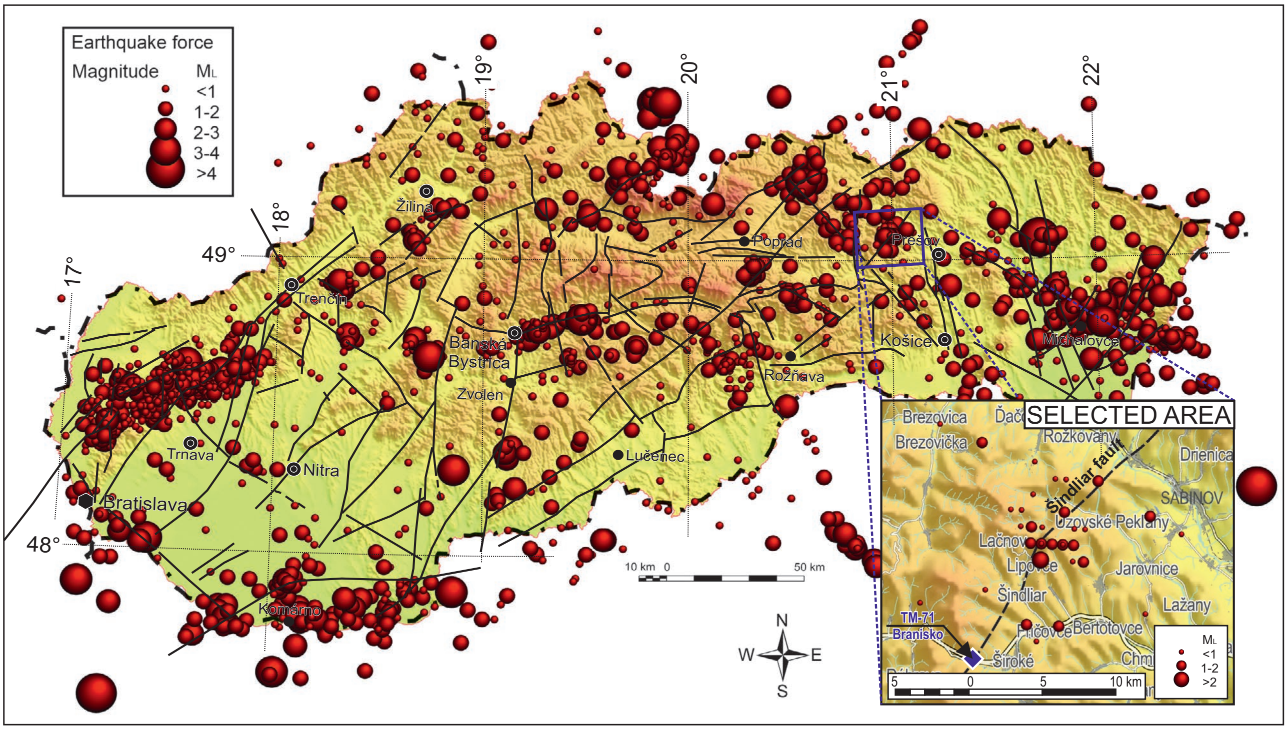


Fig. 11. Observed earthquakes in Slovakia the period between 2000 and 2023, with selected ones in the vicinity of the Branisko highway tunnel (processed using data from https://dionysos.geology.sk/cmsgf).

During the measurement period using the TM-71 device at the Branisko site, over 1600 earthquakes of varying magnitudes and with diverse epicentral locations were recorded in Slovakia and its immediate surroundings (https://dionysos.geology.sk/cmsgf/).

In this case, it would not be practical to search for temporal connections between the results of micro-displacement measurements at the Branisko site and all observed seismic events. Since the subject of these measurements is the Šindliar fault, monitored by the TM-71 device in the emergency adit of the Branisko Tunnel, only approximatelly 50 seismic events (earthquakes) since the year 2000, with a calculated epicenters close to this fault, were selected for the correlation analysis (Fig. 11). Although these earthquakes were of low intensity (local magnitude ML≤2.0), their relation to changes in the displacement and rotations curves is obvious (Fig. 7). A notable example is a cluster of earthquakes that occurred in late December 2011, with epicentres situated along the course of the Šindliar fault, approximately 10 km north of the monitored site. The observed changes are characterised either by abrupt shifts in the movement trajectory or by alternations in its overall trend. The entire monitoring period at this site may be subdivided into distinct time intervals, labelled A through H, based on seismic episodes and the nature of the measured data, within which the character of the movement generally exhibits consistent patterns (Fig. 7; https://dionysos.geology.sk/cmsgf/).

Discussion

The long-term monitoring results were compared with the results of geological research and geodetic measurements conducted within the Branisko Mts. and the eastern part of the Western Carpathians (Slovakia).

Neo-Alpine Tectonics

The compressional phase of the Paleo-Alpine tectonics within the Internal Western Carpathians region (IWECA) is characterised by Cretaceous nappe stacking. Subsequent Neo-Alpine nappe emplacement culminated during the Neogene in the accretionary wedge of the External Western Carpathians (EWECA), while the back-arc extension dominated in the IWECA (Nemčok et al. 1998). In the IWECA area, back-arc extension persisted during the Pliocene and early Pleistocene, but in the IWECA area, parallel orogen extension has been defined at several sites for the Late Pleistocene–Holocene (Littva et al. 2015; Hók et al. 2016; Bóna et al. 2024). Pliocene and Pleistocene stress orientation is characterised by extension to transtension, with the minimum stress component oscillating from WSW–ENE to WNW–ESE (Vojtko et al. 2010, 2012).

The Neo-Alpine tectonic evolution of the Branisko area may be traced back to the Miocene. The exhumation of the Branisko crystalline rocks occurred during the Early Miocene

(14.2±0.9–17.4±1.3 Ma) according to apatite fission track data (Danišík et al. 2012). The Badenian to Pannonian stress field in Eastern Slovakia is characterised by a stable orientation of the compressional component of the stress in the NNE–SSW to NE–SW direction and a perpendicularly oriented extension (Kováč et al. 1995; Nemčok et al. 1998; Jacko et al. 2021).

One way of determining the orientation of the stress field in the Holocene is by the presence of travertine to the west of the Branisko Mts. at the Dreveník site. The age of the travertine is considered to be Pliocene–Pleistocene (Němejc 1944; Holec 1992; Tóth & Krempaská 2008). The orientation of the Dreveník travertine ridge aligns with an NNW–SSE-striking fault in the underlying basement rocks. Consequently, the extension associated with the travertine formation was predominantly oriented in an ENE–WSW direction, i.e., perpendicular to the inferred extensional faults in the basement, which were active at least during the Pleistocene (Brogi et al. 2021). Similarly, the data obtained from the TM-71 high-resolution 3-D extensometer installed along the Šindliar fault reflect the prevailing stress regime within the rock mass. By processing these measurements using appropriate structural-geological software, it is possible to analyse the stress field, including the directional components of extension and compression. The results indicate a persistent orientation of the extensional stress component in a SSE–NNW direction (Fig. 12), characteristic of the ongoing transtensional to extensional tectonic regime.

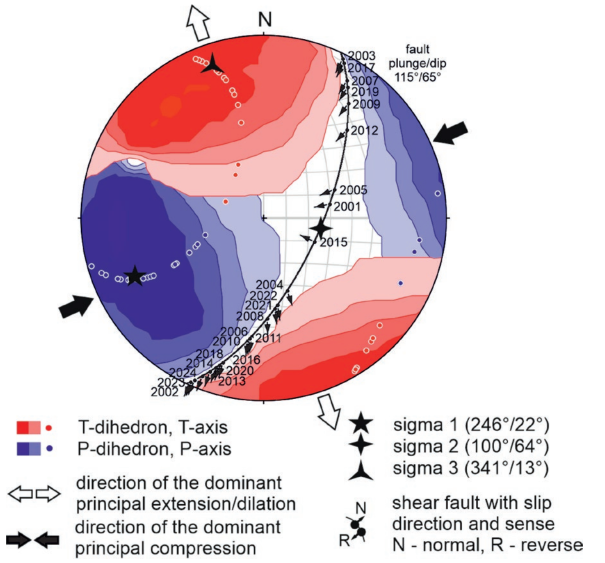


Fig. 12. Results of the P-/T-axis method applied displacement records detected by the TM-71 extensometer.

Geodetic measurements

The latest research on active tectonics of the Circum-Pannonian region, supported by updated GNSS network data, has confirmed the presence of slow positive dilatation (approximately 1 nanostrain a year) and ongoing transtensional deformation across much of the Western Carpathians (Porkoláb et al. 2023). Regional analyses indicate that geodetically derived strain rates cannot fully be explained by seismic deformation alone (Bus et al. 2009), thereby reinforcing the hypothesis that aseismic creep constitutes a significant deformation mechanism within the Pannonian Basin and its adjacent areas (Gerner et al. 1999).

Geodetically verified temporal variations in the terrain elevation, depending on the specific location of the measured points, are illustrated on the map of recent vertical movements (Majkráková & Janák 2019). At this study site, these changes exhibit a negative gradient oriented WSW–ENE (Fig. 13 – blue arrow), which aligns with the observed trend of subsidence on the eastern side, or conversely, uplift on the western side, of the tectonic line. This pattern is corroborated by measurements obtained using the TM-71 extensometer (Fig. 6).

The influence of tectonic activity on the operation of the Branisko Highway Tunnel

The confirmed progressive movement along the fault has resulted in deformations affecting not only of the internal reinforcement of the emergency adit but also the structure of the highway tunnel, manifested in the form of open cracks (Fig. 14). The initial appearance of such cracks at the monitored fault location was recorded in 2004 (Petro et al. 2004a), occurring on the sidewall of both the emergency adit and the motorway tunnel. The nature and number of cracks required the company overseeing the operation and maintenance of the tunnel to not only fill the cracks with a sealant but also to establish a local levelling network to monitor deformations in the internal reinforcement of the tunnel.

Based on almost 24 years of measurements, it is possible to assume that the current trend of block movement will continue in the future, encompassing further expansion of existing cracks or an increase in their number. Damage to or even disruption of the waterproof insulating sealing between the rock massif and the internal concrete reinforcement in the next 15 to 20 years cannot be excluded. The situation in the future may also be complicated by the planned construction of the second tunnel tube, which will certainly be required due to the increase in traffic density in the given section of the D1 highway.

Conclusions

The results of long-term monitoring (since the end of 2000) of the Šindliar fault using a special TM-71 3D extensometer indicate a continuing trend of relative movement between two tectonic blocks. To date, the total displacement of 2.64 mm has been recorded, interpreted as a dextral strike-slip displacement accompanied by a very slight oblique dip of the hanging wall. While the measured block rotations reflect variations in the tension state of the rock mass, the recorded values do not exceed 0.3 π/200 and are thus considered negligible from a practical engineering perspective.

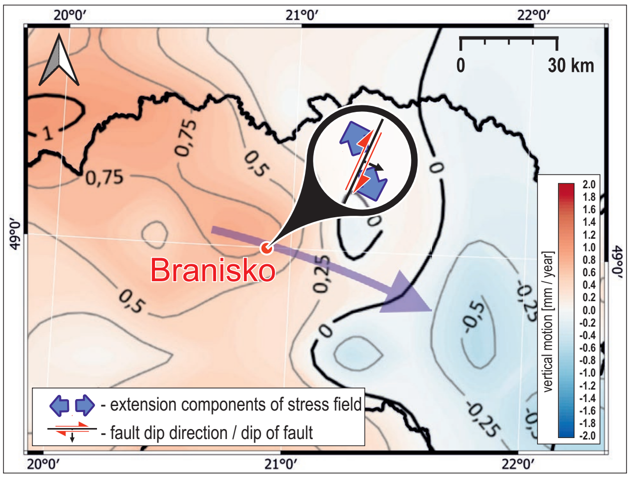


Fig. 13. The Branisko locality in the excerpt from the map of recent vertical movements of the Earth's crust surface in Slovakia for the period 1949–2017 (Majkráková & Janák 2019).

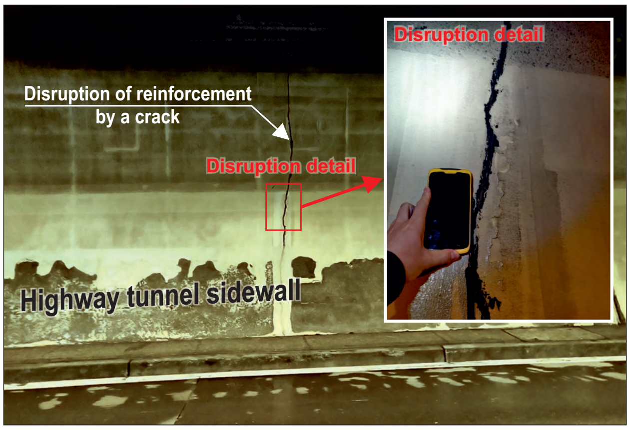


Fig. 14. Disruption of reinforcement by a crack on the highway tunnel sidewall with detail of the sealed and repaired crack (Photo: D. Grega).

Due to the absence of real-time measurements of micro-displacements, it is not possible to establish a precise causal relationship between seismic events (earthquakes) and movements on the Šindliar fault. It is more likely that the stress within the rocks massif, accumulated under the influence of regional tectonic processes, is released through micromovements along the fault, thereby generating seismic shocks, rather than seismic events unrelated to the Šindliar fault, including displacement along this tectonic zone. An illustrative example is the relatively strong earthquake that occurred on 9 October 2023, with epicentre near the village of Ďapalovce in eastern Slovakia, approximately 63 km from the monitored site, with a magnitude of M_L=4.9. This event exhibited no observable impact on the measured data. A more detailed analysis reveals that fault movement typically does not occur continuously, but rather in a series of abrupt shifts. These are characterised by alternating phases of increased and decreased activity, with transitions between these phases frequently accompanied by seismic events.

From the approximate P-/T-axis method we can roughly conclude that the long-term orientations of the main principal axes are σ1=246°/22° (ENE–WSW compression), σ2=100°/64° and σ3=341°/13° (NNW–SSE extension). The slight variations in the orientation of the movements indicate that the stress field is evolving over time, and the year-to-year comparison shows slight changes in the orientation of the stress (see the positions of the P-axes and T-axes in Fig. 12).

Stress orientation calculated from the slickensides of brittle deformed geological objects in the eastern part of Slovakia indicates a transtensional to extensional tectonic regime with a generally E–W oriented extension for the Pliocene to Pleistocene. The results of long-term monitoring of fault slip confirm the persistence of this trend to the present day.

In the light of the aforementioned findings, it is necessary to continue monitoring at the Branisko site (tunnel) and to continuously inform the tunnel administrator about the measurement results. However, a reliable correlation with seismic events and to facilitate timely responses to extraordinary events (e.g., larger movements on the fault) will require an increase in the frequency of measurements to a daily basis or even continuous measurements.

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References

Allmendinger R.W., Cardozo N. & Fisher D.M. 2011: Structural Geology Algorithms: Vectors and Tensors. XII. *Cambridge University Press*, US, 1–302.

Avramova-Tacheva E., Vrablyansky B. & Košťák B. 1984: An attempt to detect recent movements along seismogenic faults. *Review of the Bulgarian Geological Society* XLV, 276–288 (in Bulgarian).

Baroň I., Plan L., Sokol L., Grasemann B., Melichar R., Mitrovic I. & Stemberk J. 2019: Present-day kinematic behaviour of active faults in the Eastern Alps. *Tectonophysics* 752, 1–23. https://doi.org/10.1016/j.tecto.2018.12.024

Baroň I., Melichar R., Sokol L., Rowberry M.D., Plan L. & Stemberk J. 2024: 3D active fault kinematic behaviour reveals rapidly alternating near surface stress states in the Eastern Alps. *Geological Society, London, Special Publications* 546. https://doi.org/10.1144/SP546-2023-32

Bezák V. (Ed.), Broska I., Ivanička J., Reichwalder P., Vozár J., Polák M., Havrila M., Mello J., Biely A., Plašienka D., Potfaj M., Žec B., Vass D., Elečko M., Janočko J., Pereszlényi M., Marko F., Maglay J. & Pristaš J. 2004: Tectonic map of the Slovak Republic 1:500,000 with explanations. *State Geological Institute of Dionýz Štúr*, Bratislava.

Bóna J., Gallay M., Macková A., Bónová K., Littva J. & Hók J. 2024: Travertine and calcareous tufa occurrences as an indicator of the ongoing tectonic activity of the Central Slovak Fault System inferred from airborne laser scanning data, geomorphometric, and structural analysis (Northern Slovakia). *Geomorphology* 466, 109420. https://doi.org/10.1016/j.geomorph.2024.109420

Briestenský M., Stemberk J. & Petro L. 2007: Displacements registered around March 13, 2006 Vrbové earthquake, M=3.2 (Western Carpathians). *Geologica Carpathica* 58, 487–493.

Briestenský M., Rowberry M.D., Stemberk J., Stefanov P., Vozár J., Šebela S., Petro Ľ., Bella P., Gaal Ľ. & Ormukov Ch. 2015: Evidence of a plate-wide tectonic pressure pulse provided by extensometric monitoring in the Balkan Mountains (Bulgaria). *Geologica Carpathica* 66, 427–438. https://doi.org/10.1515/geoca-2015-0035

Briestenský M., Hochmuth Z., Littva J. & Hók J., Dobrovič R., Stemberk J., Petro Ľ. & Bella P. 2018: Present-day stress orientation and tectonic pulses registered in the caves of the Slovenský kras Mts. (South-Eastern Slovakia). *Acta Geodynamica et Geomaterialia* 15, 93–103. https://doi.org/10.13168/AGG.2018.0007

Briestenský M., Stemberk J., Littva J. & Vojtko R. 2021: Tectonic pulse registered between 2013 and 2015 on the eastern margin of the Bohemian Massif. *Geological Quarterly* 65, 1. https://doi.org/10.7306/gq.1582

Brogi A., Capezzuoli E., Karabacak V., Alcicek M.C. & Luo L. 2021: Fissure Ridges: A Reappraisal of Faulting and Travertine Deposition (Travitonics). *Geosciences* 11, 278. https://doi.org/10.3390/ geosciences11070278

Bus Z., Grenerczy G., Tóth L. & Mónus P. 2009: Active crustal deformation in two seismogenic zones of the Pannonian region – GPS versus seismological observations. *Tectonophysics* 474, 343–352. https://doi.org/10.1016/j.tecto.2009.02.045

COST Association 2025: European Cooperation in Science and Technology – Action CA625. Available at: https://www.cost.eu/actions/625/ [accessed 3 December 2024].

Danišík M., Kohút M., Evans N.J. & McDonald J.B. 2012: Eo-Alpine metamorphism and the "mid-Miocene thermal event" in the Western Carpathians (Slovakia): new evidence from multiple thermochronology. Geological Magazine 149, 158–171. https://doi.org/10.1017/S0016756811000963

Gerner P., Bada G., Dövényi P., Müller B., Oncescu M., Cloetingh S. & Horváth F. 1999: Recent tectonic stress and crustal deformation in and around the Pannonian Basin: data and models. *Geological Society, London, Special Publications* 156, 269–294. https://doi.org/10.1144/GSL.SP.1999.156.01.14

Gosar A., Šebela S., Košťák B. & Stemberk J. 2009: Surface versus underground measurements of active tectonic displacements detected with TM 71 extensometers in Western Slovenia. *Acta Carsologica* 38, 213–226. https://doi.org/10.3986/ac.v38i2-3.123

Gross P., Köhler E. & Samuel O. 1984: Nové litostratigrafické členenie vnútrokarpatského paleogénu. *Geologické Práce, Zpravodaj* 81, 103 – 117.

Hók J., Bielik M., Kováč P. & Šujan M. 2000: Neotektonický charakter územia Slovenska. *Mineralia Slovaca* 32, 459–470 (in Slovak with English summary).

Hók J., Šujan M. & Šipka F. 2014: Tektonické členenie Západných Karpát – prehľad názorov a nový prístup. *Acta Geologica Slovaca* 6, 135–143.

Hók J., Kysel R., Kováč M., Moczo P., Kristek J., Kristeková M. & Šujan M. 2016: A seismic source zone model for the seismic hazard assessment of Slovakia. *Geologica Carpathica* 67, 273–288. https://doi.org/10.1515/geoca-2016-0018

Hók J., Pelech O., Teťák F., Németh Z. & Nagy A. 2019: Outline of the geology of Slovakia (W. Carpathians). *Mineralia Slovaca* 51, 31–60.

Holec P. 1992: Výliatky zubov mastodonta druhu Mammut borsoni (Hays, 1834) v dreveníckom travertíne pri Spišskom Podhradí. *Mineralia Slovaca* 24, 467–469.

Jacko S., Farkašovský R., Ďuriška I., Ščerbáková B. & Bátorová K. 2021: Critical Tectonic Limits for Geothermal Aquifer Use: Case Study from the East Slovakian Basin Rim. *Resources* 10, 31. https://doi.org/10.3390/resources10040031

Jarosiński M. 1998: Contemporary stress field distortion in the Polish part of the Western Outer Carpathians and their basement. *Tectonophysics* 297, 91–119. https://doi.org/10.1016/S0040-1951(98)00165-6

Jarosiński M. 2005: Ongoing tectonics reactivation of the Outer Carpathians and its impact on the foreland: results of borehole break-out measurements in Poland. *Tectonophysics* 410, 189–216. https://doi.org/10.1016/j.tecto.2004.12.040

Košťák B. 1969: A new device for in-situ movement detection and measurement. *Experimental Mechanics*. SESA (American Society for Experimental Stress Analysis) Journal 9, 374–379.

Košťák B. 1991: Combined indicator using moiré technique. In: Sørum G. (Ed.): Proceedings of 3rd Int. Symp. *Field Measurements in Geomechanics*, Oslo, Norway, Balkema, 53–60, Code 16264.

Košťák B. & Avramova-Tacheva E. 1988: A method for contemporary displacement measurement on a tectonic fault. *Journal of Geodynamics* 10, 115–125. https://doi.org/10.1016/0264-3707(88)90018-X

Košťák B. & Cruden D.M. 1990: The Moiré crack gauges on the crown of the Frank Slide. *Canadian Geotechnical Journal* 27, 835–840. https://doi.org/10.1139/t90-096

Košťák B., Vilimek V. & Zapata M.L. 2002: Registration of microdisplacements at a Cordillera Blanca fault scarp. *Acta Montana, Ser. A* 19 (123), 61–74.

Košťák B., Mrlina J., Stemberk J. & Chán B. 2011: Tectonic movements monitored in the Bohemian Massif. *Journal of Geodynamics* 52, 34–44. https://doi.org/10.1016/j.jog.2010.11.007

Kováč M., Kováč P., Marko F., Karoli S. & Janočko J. 1995: The East Slovakian Basin – a complex back arc basin history. *Tectonophysics* 252, 453–466. https://doi.org/10.1016/0040-1951(95)00183-2

Lexa J., Bezák V., Elečko M., Polák M., Potfaj M. & Vozár J. (eds.) 2000: Geological map of the Western Carpathians and adjacent areas. *Ministry of the Environment of the Slovak Republic and the Geological Survey of the Slovak Republic*, Bratislava.

Littva J., Hók J., & Bella, P. 2015: Cavitonics: Using caves in active tectonic studies (Western Carpathians, case study) *Journal of Structural Geology* 80, 47–56. https://doi.org/10.1016/j.jsg.2015.08.011

Madarás J., Ferianc D., Hrašna M. & Petro Ľ. 2012: Partial monitoring system of the geological factors of the environment of the Slovak Republic – Tectonic and seismic activity of the territory. *Annual report for the year 2011* (in Slovak). https://dionysos.geology.sk/cmsgf/files/Hodn_monitor_2011/02_Tektonicka_aktivita_2011.pdf

Maglay J. (Ed.), Halouzka R., Baňacký V., Pristaš J. & Janočko J. 1999: Neotectonic map of Slovakia 1:500,000. *Ministry of the Environment and Geological Survey of the Slovak Republic*, Bratislava.

Majkráková M. & Janák J. 2019: Určovanie fyzikálnych výšok na území Slovenska. *Dizertačná práca, SvF STU* Bratislava (in Slovak).

Marrett R.A. & Allmendinger R.W. 1990: Kinematic analysis of fault-slip data. *Journal of Structural Geology* 12, 973–986.

Marti X., Rowberry M.D. & Blahút J. 2013: A MATLAB® code for counting the moiré interference fringes recorded by the optical-mechanical crack gauge TM-71. *Computers & Geosciences* 52, 164-167. https://doi.org/10.1016/j.cageo.2012.09.029

Nemčok M., Hók J., Kováč P., Marko F., Coward M.P., Madarás J., Houghton J.J. & Bezák V. 1998: Tertiary development and extension/compression interplay in the West Carpathians mountain belt. *Tectonophysics* 290, 137–167. https://doi.org/10.1016/S0040-1951(98)00016-X

Němejc F. 1944: Výsledky dosavadních výzkumů paleobotanických v kvartéru západního dílu karpatského oblouku. *Rozpravy II, Třídy České Akademie* 53, 1–47.

Németh Z., Maglay M., Petro Ľ., Stercz M., Grega D., Pelech O. & Gaál Ľ. 2023: Neo-Alpine uplift and subsidence zones in the Western Carpathians: Product of kinematic activity on Cenozoic AnD3 (NW–SE and NE–SW) and AnD4 (E–W – subequatorial and N–S –submeridian) regional faults. *Mineralia Slovaca* 55, 103–116. https://doi.org/10.56623/ms.2023.55.2.1

Ondrejka P., Wagner P., Petro Ľ., Žilka A., Balík D., Iglárová Ľ. & Fraštia M. 2014: Main results of the slope deformations monitoring. *Slovak Geological Magazine* 14, 89–114.

Petro Ľ., Košťák B., Polaščinová E. & Spišák Z. 1999: Block movements monitoring in the Slanské vrchy Mts. (Eastern Slovakia). *Mineralia Slovaca* 31, 549–554 (in Slovak with English summary).

Petro Ľ., Vlčko J., Ondrášik R. & Polaščinová E. 2004a: Recent tectonics and slope failures in the Western Carpathians. *Engineering Geology* 74, 103–112. https://doi.org/10.1016/j.enggeo.2004.03.004

Petro Ľ., Bella P., Polaščinová E., Hók J. & Stercz M. 2004b: Monitoring of tectonic movements in the Demänovská Cave of Liberty. *Aragonit* 9, 26–29 (in Slovak with English Summary).

Petro Ľ., Košťák B., Stemberk J. & Vlčko J. 2011a: Geodynamic reactions to recent tectonic events observed on selected sites monitored in Slovakia. *Acta Geodynamica et Geomaterialia* 8, 453–467.

Petro Ľ., Bóna J., Kováčik M., Fussgänger E., Antonická B. & Imrich P. 2011b: The Cave under the Spišská hill: Preliminary results of the block movements. *Mineralia Slovaca* 43, 121–128.

Petro Ľ., Brček M., Vlčko J., Šimková I., Balík D. & Žilka A. 2012: Stability of selected historical objects in Slovakia: Monitoring results. *Mineralia Slovaca* 44, 403–422. (in Slovak with English summary).

Polák M., Jacko S. sr. (eds.), Vozár J., Vozárová A., Gross P., Harčár J., Sasvári T., Zacharov M., Baláž B., Kaličiak M., Karoli S., Nagy A., Buček S., Maglay J., Spišák Z., Žec B., Filo I. & Janočko J. 1996: Geological map of the Branisko and Čierna hora Mts. 1:50,000. *Geological Survey of the Slovak Republic*, Bratislava.

Porkoláb K., Broerse T., Kenyeres A., Békésil E., Tóth S., Magyar B. & Wesztergom V. 2023: Active tectonics of the Circum-Pannonian region in the light of updated GNSS network data. *Acta Geodaetica et Geophysica* 58, 149–173. https://doi.org/10.1007/s40328-023-00409-8

Rowberry M.D., Kriegner D., Holy V., Frontera C., Llull M., Olejnik K. & Marti X. 2016: The instrumental resolution of a moire extensometer in light of its recent automatisation. *Measurement* 91, 258–265. https://doi.org/10.1016/j.measurement.2016.05.048

Šebela S., Stemberk J. & Briestenský M. 2021: Micro-displacement monitoring in caves at the Southern Alps–Dinarides–South-western Pannonian Basin junction. *Bulletin of Engineering Geology and the Environment* 80. https://doi.org/10.1007/s10064-021-02382-4

Slovak Academy of Sciences, Earth Science Institute 2025: National Seismic Network of Slovakia. Available at: https://www.seismology.sk/National_Network/national_network_A.html [accessed 3 December 2024].

State Geological Institute of Dionýz Štúr 2024: Partial Monitoring System of Geological Factors. Available at: https://dionysos.geology.sk/cmsgf/ [accessed 3 December 2024].

Stemberk J., Košťák B. & Cacoń S. 2010: A tectonic pressure pulse and increase geodynamic activity recorded from the long-term monitoring of faults in Europe. *Tectonophysics* 487, 1–12. https://doi.org/10.1016/j.tecto.2010.03.001

Stemberk J., Briestenský M. & Cacoń S. 2015: The recognition of transient compressional fault slow-slip along the northern shore of Hornsund Fjord, SW Spitsbergen, Svalbard. *Polish Polar Research* 36, 109–123. https://doi.org/10.1515/popore-2015-0007

Stemberk J., Blahůt J., Hartvich F., Rybář J. & Krejčí O. 2016: Tectonic strain changes affecting the development of deep-seated gravitational slope deformations in the Bohemian Massif and Outer Western Carpathians. *Geomorphology* 289, 3–17. https://doi.org/10.1016/j.geomorph.2016.07.004

Stemberk J., Dal Moro G., Stemberk J., Blahůt J., Coubal M., Košťák B., Zambrano M. & Tondi E. 2018: Strain monitoring of active faults in the central Apennines (Italy) during the period 2002–2017. *Tectonophysics* 750, 22–35. https://doi.org/10.1016/j.tecto.2018.10.033

Stemberk J., Coubal M., Stemberk J. & Štěpančíková P. 2019: Stress analysis of fault slips data recorded within the Dědičná štola gallery in the Rychlebské hory Mts., NE part of the Bohemian massif. *Acta Geodynamica et Geomaterialia* 16, 315–330. https://doi.org/10.13168/AGG.2019.0027

Štěpančíková P., Stemberk J., Vilímek V. & Košťák B. 2008: Neotectonic development of drainage network in the East Sudeten and monitoring of recent displacements on tectonic structures (Czech Republic). *Geomorphology* 102, 68–80. https://doi.org/10.1016/j.geomorph.2007.06.016

Tóth C. & Krempaská Z. 2008: Pliocene Proboscidea remains from travertine Dreveník site (near Spišské Podhradie, Slovakia). In: Krempaská Z. (Ed.): 6th Meeting of the European Association of Vertebrate Palaeontologists, Spišská Nová Ves 2008. *Volume of Abstracts*, 116.

Vlčko J. 2004: Extremely slow slope movements influencing the stability of Spis Castle, UNESCO site. *Landslides* 1, 67–71. https://doi.org/10.1007/s10346-003-0007-8

Vlčko J. & Petro L. 2002: Monitoring of subgrade movements beneath historic structures. In: Van Roy J.L. & Jermy C.A. (eds.): Proc. of 9th International Congress IAEG, Durban, South Africa, 1432–1437.

Vojtko R., Tokárová E., Sliva Ľ. & Pešková I. 2010: Reconstruction of Cenozoic paleostress fields and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Východné Tatry Mountains). *Geologica Carpathica* 61, 211–225. https://doi.org/10.2478/v10096-010-0012-5

Vojtko R., Petro Ľ., Benová A., Bóna J. & Hók J. 2012: Neotectonic evolution of the northern Laborec drainage basin (northeastern part of Slovakia). *Geomorphology* 138, 276–294. https://doi.org/10.1016/j.geomorph.2011.09.012

Wagner P., Iglárová Ľ. & Petro Ľ. 2000: Methodology and some results of slope movement monitoring in Slovakia, *Mineralia Slovaca* 32, 359–367.