Acta Geodyn. Geomater., Vol. 7, No. 4 (160), 387–397, 2010

ACTIVE TECTONIC FAULT MICRODISPLACEMENT ANALYSES: A COMPARISON OF RESULTS FROM SURFACE AND UNDERGROUND MONITORING IN WESTERN SLOVAKIA

Miloš BRIESTENSKÝ [1)]*, Blahoslav KOŠŤÁK [1)], Josef STEMBERK [1)], Ľubomír PETRO [2)], Jozef VOZÁR [3)] and Lucia FOJTÍKOVÁ [4)]

[1)] *Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, v.v.i., V Holešovičkách 41, 182 09 Prague, Czech Republic*
[2)] *Geological Survey of the Slovak Republic, Jesenského 8, 040 01 Košice, Slovakia, Telephone: +421 556 250 045*
[3)] *Geological Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia, Telephone: +421 259 203 602*
[4)] *Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 845 28 Bratislava, Slovakia, Telephone: +421 259 410 611*
**Corresponding author's e-mail* briestensky@irsm.cas.cz

(*Received* January 2010*, accepted* October 2010)

ABSTRACT
This paper examines the results of fault microdisplacement analyses obtained from sites located both at the surface and underground in western Slovakia. The results of surface monitoring showed significant annual climatic effects on the various displacement components. In contrast, the results of underground monitoring in caves showed minimal climatic effects. It is seen that the influence of climate decreases markedly with depth. The yearly peak-to-peak amplitude of climatic variations may be as high as 1 mm at the surface but only 0.1 mm underground.
The amount of tectonic displacement can be determined once such climatic considerations have been taken into account. Our fault displacement measurements show horizontal strike-slip rates of tenths of mm or hundredths of mm per year. In addition, vertical displacements have been recorded at Prekážka Quarry, Driny Cave, and Slopy Cave. The network is sufficiently dense to identify changes in displacement activity recorded during recent, significant, earthquake events. Furthermore, three gauges have also helped to determine the local stress orientation in Driny Cave.

KEYWORDS: active faulting, microdisplacements, rock massif dilation, earthquakes, caves, extensometer

1. INTRODUCTION

Over the past five years a network of extensometric crack gauges has been established in western Slovakia. This region represents a significant contact zone between the Eastern Alps and the Western Carpathians. The network was constructed in order to observe the behaviour of rock massifs during seismic events and to establish the long-term tectonic trends that affect the region. Twelve significant fault structures have been selected for monitoring. Of these, eleven are located in the Malé Karpaty Mts and one is located in the Považský Inovec Mts. Ten of the monitored structures are sited underground with just two sited at the surface.

The monitoring of microdisplacements in natural underground spaces is comparatively rare. Some attempts to measure tectonic displacements have been undertaken in Italy (Mocchiutti, 2004; Mocchiutti and Dandrea, 2002) and Belgium (Tshibangu et al., 2004). More locally, certain studies have examined tectonic block stability within the caves of the Western Carpathians (e.g. Zacharov, 1984) or in the Bear Cave in Poland (Cacoń et al., 1994; Mąkolski et al., 2008). Unfortunately, many studies only measure one of the displacement components. The methods most commonly used in caves were described by Zacharov (1984). Of these methods, the most comprehensive instrument was developed by geologists working in Czechoslovakia. The device is an extensometric crack gauge, known as a TM71. It allows subsurface displacements to be measured in relation to three components (vertical, strike-slip, and crack opening or closing) and indicates rotations in two transversal planes. The first of these gauges to be installed in a karstic cave system was located within the Štrochy abyss in the Veľká Fatra Mts, Slovakia. It was installed in 1981 and continues to record displacements at the present day. In contrast to sites located at the surface, underground sites record almost stable temperatures throughout the year and therefore the effects on rock massif displacement are minimised (Košťák and Rybář, 1978).

Fig. 1 An example of the TM71 extensometric gauge installed in Hornsund, Spitsbergen (Photo: T. Nýdl).

We have searched for active tectonic structures over the past five years in order to measure fault movements within the most seismic part of western Slovakia. These movements are associated with the western Slovak neotectonic block. Twelve fault structures have been selected and equipped with extensometric gauges (TM71s). The first was installed in the epicentral area around Dobrá Voda in 2004, as reported in Briestenský (2005). Ten of these gauges are situated underground in natural caves whilst two are situated at the surface.

2. THE GEOLOGICAL AND CLIMATIC SETTING

The western part of Slovakia represents the country's most seismically active region (Hók et al., 2000; Hrašna, 2002; Cipciar et al., 2010). The region forms part of the important contact zone between the orogenic Eastern Alps & Western Carpathians and the cratonic North European Platform represented by the Bohemian Massif. The geological history of this region is complicated and this situation persists to the present day. The most significant tectonic structure in the region is the Mur-Mürz-Leitha-Dobrá Voda (MMLDV) sinistral strike-slip fault. This is, in fact, a continuation of the Vienna Basin Transfer Fault (Hinsch and Decker, 2003). It represents the topographic expression of the tectonic contact between the Eastern Alps and Western Carpathians. In the study area, the Vienna Fault Zone coincides with the Pieniny Klippen Belt (PKB) as a sinistral fault zone that forms the border between the Inner Western Carpathians and the stable North European Platform (Ratschbacher et al., 1993; Hók et al., 2000; Lenhardt et al., 2007). These authors have proposed that the Western Carpathians recently rotated to the northeast in an arc, in addition to the northward progression of the Alps. If this is the current situation, faults that trend NE-SW should presently be active. The aforementioned MMLDV and PKB both follow this NE-SW trend. Therefore these fault zones form the basis of this study.

Situated within central Europe, western Slovakia is characterised by a continental climate. In July the mean temperature reaches up to 21 ºC whilst in January the mean average temperature drops to -3 ºC. Such annual temperature variations are thought to affect rock massif dilation at the surface.

3. METHODOLOGY

To investigate three-dimensional microdisplacements in the field, we have employed the extensometric gauge TM71 (Fig. 1). This instrument has been used in numerous previous studies including Košťák (1991), Stemberk and Štěpančíková (2003), Šebela et al. (2005, 2009, 2010), Briestenský et al. (2007), Gosar et al. (2007, 2009), Stemberk and Košťák (2007, 2008), Briestenský and Stemberk (2007, 2008), and Stemberk et al. (2010). The gauge is an optical-mechanical instrument. It does not have any electrical components and is known to survive for tens of years in the field without any maintenance. The data are either collected manually or by camera approximately once a month. The gauge records three fault displacement components (vertical, strike-slip,

Fig. 2 Fresh shear cracks in speleothems associated with a fault plane at Autobus Dome, Čachtická Cave. These cracks reflect active fault displacements within the cave. The fissures are frequently healed by fresh white sinter (Photo: M. Briestenský).

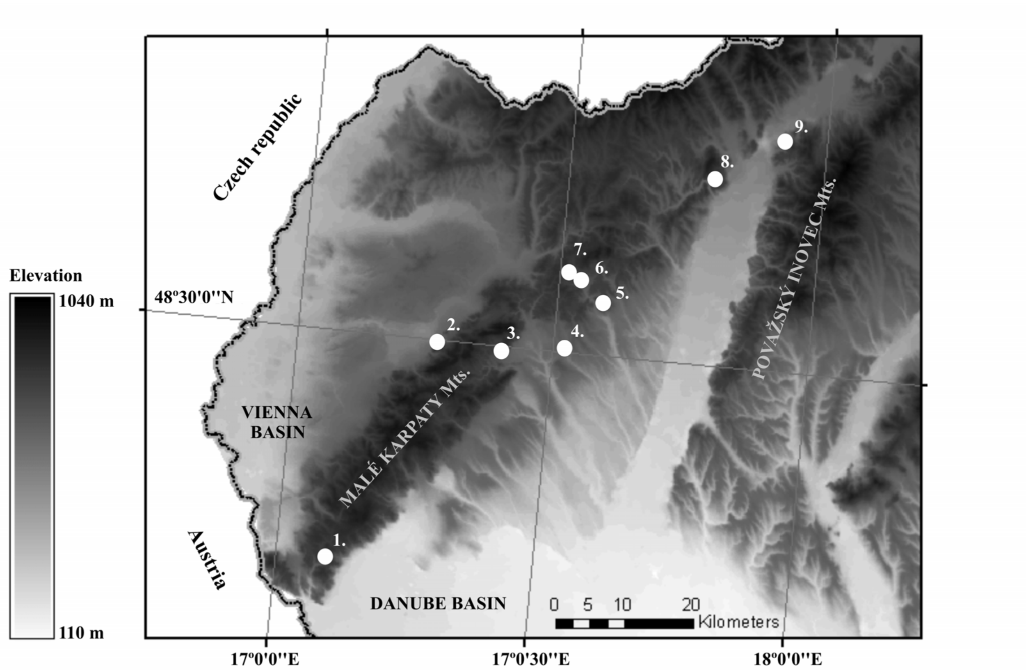


Fig. 3 The location of the monitored sites. 1: Sedmička Cave; 2: Plavecká Cave; 3: Driny Cave; 4: Prekážka Quarry; 5: Zbojnícka Cave; 6: Dobrá Voda Trench; 7: Slopy Cave; 8: Čachtická Cave; 9: Beckovská Cave.

and crack opening) and indicates rotations in two transversal planes. It is accurate to 0.01 mm per year.

It has frequently been observed that fresh shear cracks in sinter decoration (Fig. 2) were associated with rock failures, as documented by slickensides (Briestenský and Stemberk, 2008). This association allowed us to identify suitable sites for installing the gauges required for fault microdisplacement monitoring.

Six caves in the Malé Karpaty Mts. (Sedmička, Plavecká, Driny, Zbojnícka, Slopy, and Čachtická) were selected, as well as one cave in the Považský Inovec Mts. (Beckovská). The majority of these caves were equipped with only one gauge. However, two gauges were installed in Plavecká Cave and three were installed across an orthogonal fault system in Driny Cave. The gauges are located at a range of depths from the surface. The deepest is at Beckovská Cave, at a depth of 45 m, whilst the shallowest is at Slopy Cave, at a depth of 8 m. In addition, two gauges were installed across surface fault outcrops at the sites of Dobrá Voda and Prekážka (Fig. 3).

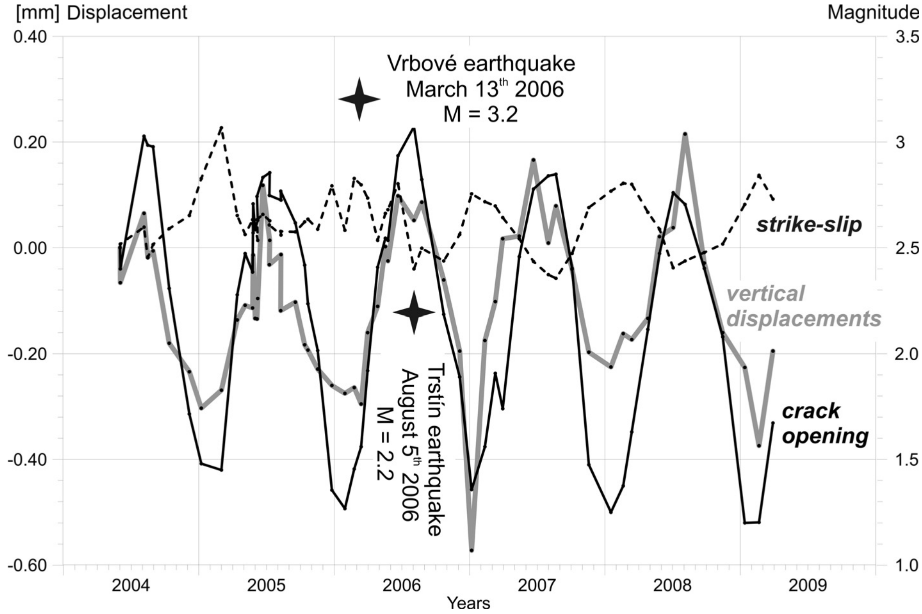


Fig. 4 A graph of microdisplacements recorded at the surface site of Dobrá Voda. The black stars indicate the two periods of heightened earthquake activity discussed in the text.

Seismic activity in the area has been monitored by the local seismic network, Malé Karpaty (MKNET). From these data, moment tensors of the events were calculated using amplitude inversion from the vertical components of the P waves. Moment tensors were decomposed into the double-couple (DC) and non-double-couple (ISO, CLVD) components (Vavryčuk, 2001; Vavryčuk, 2009; Fojtíková et al., 2010).

4. RESULTS

The results obtained from surface measurements at Dobrá Voda show significant fault displacements influenced by annual temperature dilations (Fig. 4). Movement variations appear as sinusoidal changes (changes in peak-to-peak amplitude) in all three fault displacement components, i.e. vertical, strike-slip, and crack opening. The annual peak-to-peak amplitude of these sinusoidal changes reaches a maximum of 1 mm (Fig. 4). This figure is comparable to the results registered at Spiš Castle by Jezný et al. (2007). It is, however, considerably less than the 2.5 mm registered between adjacent blocks of thickly-bedded sandstones in the Cretaceous Bohemian Basin (Zvelebil, 1995). The latter example is accompanied by significant slope deformation.

The dominant pattern of seasonal displacement obtained from surface measurements at Dobrá Voda does not allow us to monitor tectonic displacements. Kováč et al. (2001) calculated that the mean amount of fault displacement along significant tectonic structures within the study area has been ~ 0.01-0.1 mm/yr during the Pliocene-Quaternary.

Such low values suggest that tectonic trends would not be visible in a graph acquired from this surface locality, given that seasonal peak-to-peak amplitude ganges are far greater and reach up to 1 mm (or possibly more) during the course of a year. At Dobrá Voda, disturbances were registered in the smooth sinusoidal course of crack opening during a significant earthquake period during 2006 (Fig. 4). The effects of the tremors were reflected more sensitively in the rotation results than the displacement results at the site (Briestenský et al., 2007).

The results obtained from surface measurements at Prekážka also show fault displacements influenced by annual temperature massive dilations (Fig. 5). However, movement variations appear only as sinusoidal changes in the crack closing component. These seasonal variations reach a maximum of 0.25 mm. The other components are not sensitive to seasonal effects. Instead, these show some important tectonic relationships. Locally significant earthquakes in the region are well reflected in the course of the graphs (cf. e.g. Briestensky et al., 2007). The most remarkable quake, which caused significant displacement, occurred close to the town of Vrbové on 13th March 2006. This had a magnitude of M_L= 3.2 and almost certainly represents the most significant local event to have occurred during our observation period. The effect of the quake breaks the smooth course of the seasonal sinusoidal strike-slip component at the site of Dobrá Voda (Fig. 4). The seismic disturbances continued until the earthquakes registered around the village of Trstín

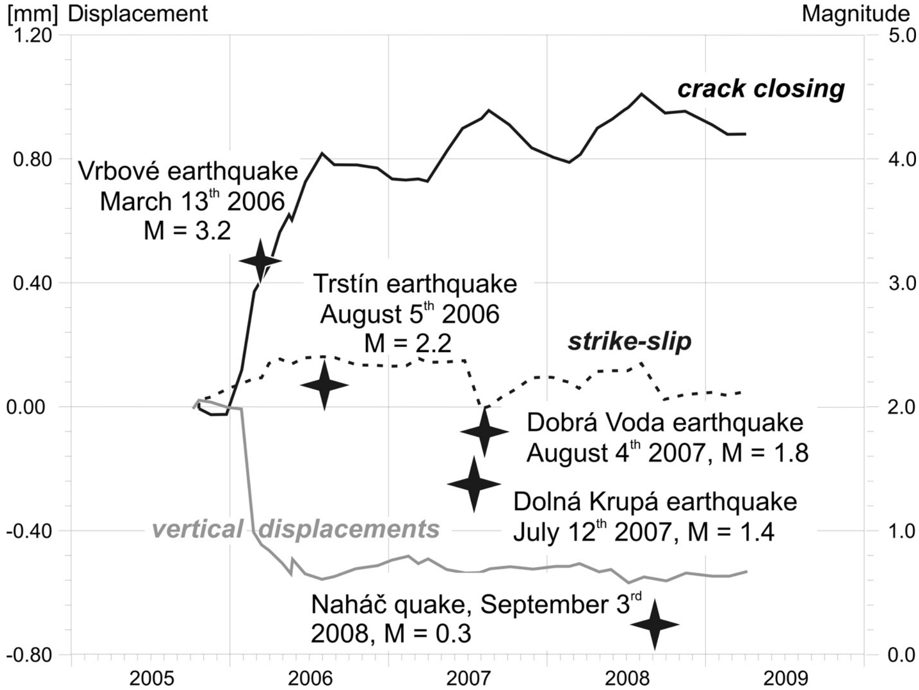


Fig. 5 A graph of the microdisplacements recorded at the surface site of Prekážka. The black stars indicate the most recent significant earthquakes to have occurred in the vicinity of the site.

between 5-8th August 2006. The maximum magnitude recorded was M_L= 2.2. Both quake periods also significantly affected the displacements at Prekážka (Fig. 5) (Briestensky et al., 2007). The final quakes terminated an overall increase in the strike-slip displacement trend (0.08-0.16 mm/yr). This can be explained either as a reversal in the sense of fault displacement or as increased movement on the opposite fault block (Fig. 5).

The gauge at Dobrá Voda was installed six metres above a narrow ravine or trench cut for a local railroad. The gauge at Prekážka was installed in a small quarry (width: 40 m) which exhibit relatively fresh outcrops. It was sited at the base of a conglomerate excavation 0.5 m below the surface, which causes the gauge to be permanently submerged underwater. Data are recorded once the water has been removed from the excavation. These two sites highlight the importance of both the location of the gauge in relation to the amount of sunlight it receives and the condition of the rock massif itself. With regard to the former, the site at Dobrá Voda is exposed more-or-less continuously to sunlight whereas the site at Prekážka is affected for just a short period during the day. Once a site has been monitored for at least three years, seasonal variations can be identified with confidence. It is then possible to remove these variations from the results to reveal tectonic displacement trends (Košťák et al., 2007).

Conversely, the analysed seismic data (Table 1) from this area show significant non-DC components (Fojtíková et al., 2010). These may reflect the physical properties of the earthquake source in the centre of the focal area. In addition, the ISO and CLVD components show positive correlations that may indicate of presence of tensile faulting. The positive values of ISO and CLVD are produced by the opening of faults while the negative values of ISO and CLVD are produced by the closing of faults (Vavryčuk, 2001, 2002).

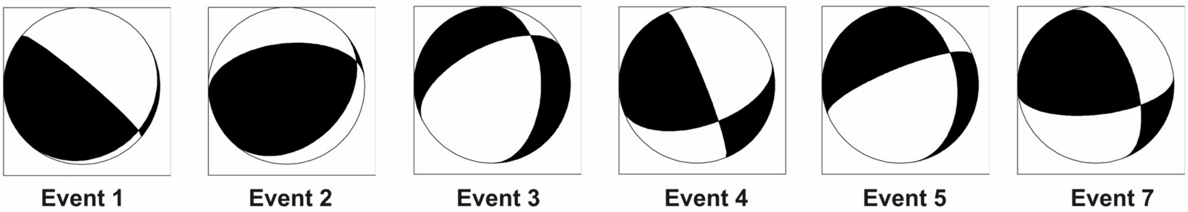
In addition to the surface sites, subsurface displacements have been recorded at sites that were supposed to be less affected by seasonal massif dilation. In Slopy Cave, the peak-to-peak amplitude of seasonal dilation reaches a maximum of 0.1 mm. At this site, the gauge is installed only 8 m below the surface. This dilation appears to only affect the horizontal crack opening component. Therefore, the vertical and strike-slip components are able to reflect the prevailing tectonic regime along the structure: increasing NW subsidence (0.04 mm/year) and growing dextral strike-slip (0.05 mm/year) during the earthquake period (Fig. 6). Moreover, tremors also affect the vertical displacements at this site. During the earthquake of August 2006 there was a noticeable change in the seasonal summer peak of fault opening (Fig. 6).

In general, the horizontal crack opening component shows a decreasing seasonal effect with increasing depth (Fig. 7 and Table 2). A similar relationship is also visible in the vertical component (Table 2).

Table 1 Descriptions of significant earthquake events registered during the study period and their focal mechanisms. The focal mechanisms were calculated using the polarities of P waves, the amplitudes of P waves, and complete waveforms. The lower-hemisphere equal-area projection is used.

Event	Place	Year	Month	Day	Time	Ml	Lat	Lon	Depth
1	Vrbové	2006	3	13	8:28:38	3.2	48.550	17.694	10.16
2	Trstín	2006	8	5	8:57:35	1.9	48.520	17.475	4.25
3	Trstín	2006	8	5	8:58:50	1.6	48.511	17.473	5.26
4	Trstín	2006	8	5	9:00:08	2.2	48.516	17.468	5.23
5	Trstín	2006	8	5	23:43:18	1.4	48.522	17.476	4.71
6	Dolná Krupá	2007	7	12	14:20:51	1.4	48.470	17.520	18.1
7	Dobrá Voda	2007	8	4	2:39:20	1.8	48.581	17.565	10.30
8	Naháč	2008	9	3	6:03:48	0.3	48.567	17.500	10.1

Event	DC	CLVD	ISO	strike	dip	rake	strike	dip	rake
1	46.6	-42.5	-10.8	310	85	113	51	24	12
2	8.7	61.8	29.5	46	39	59	264	58	113
3	46.8	45.8	-7.3	360	51	-141	242	60	-46
4	77.8	6.4	15.8	72	58	7	338	84	148
5	62.3	29.8	7.8	248	78	-48	351	43	-162
6	x	x	x	x	x	x	x	x	x
7	82.9	1.7	15.4	340	60	154	83	68	32
8	x	x	x	x	x	x	x	x	x



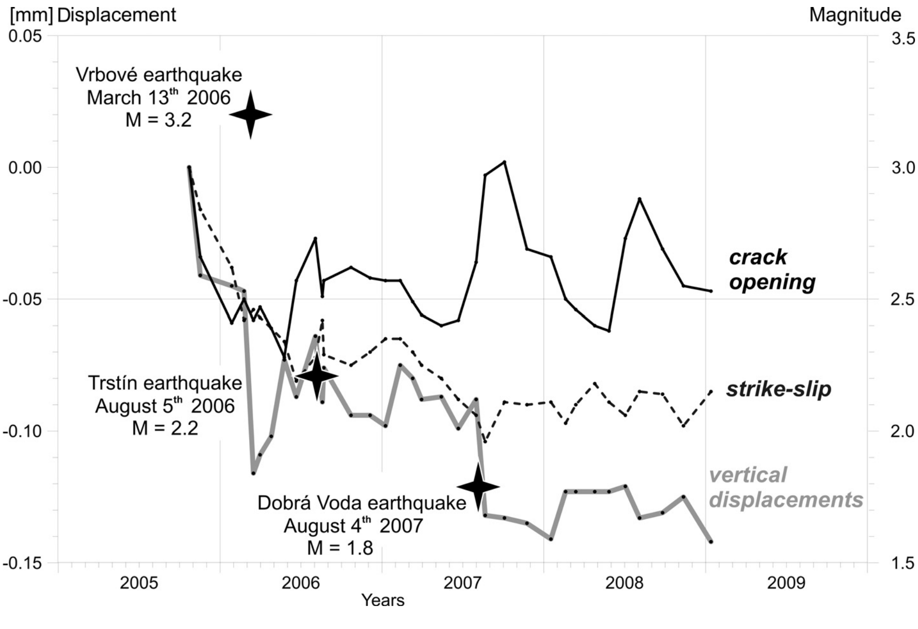


Fig. 6 A graph of the microdisplacements recorded in Slopy Cave. The black stars indicate the most recent significant earthquakes to have occurred in the vicinity of the site. These earthquakes are reflected in the course of individual components.

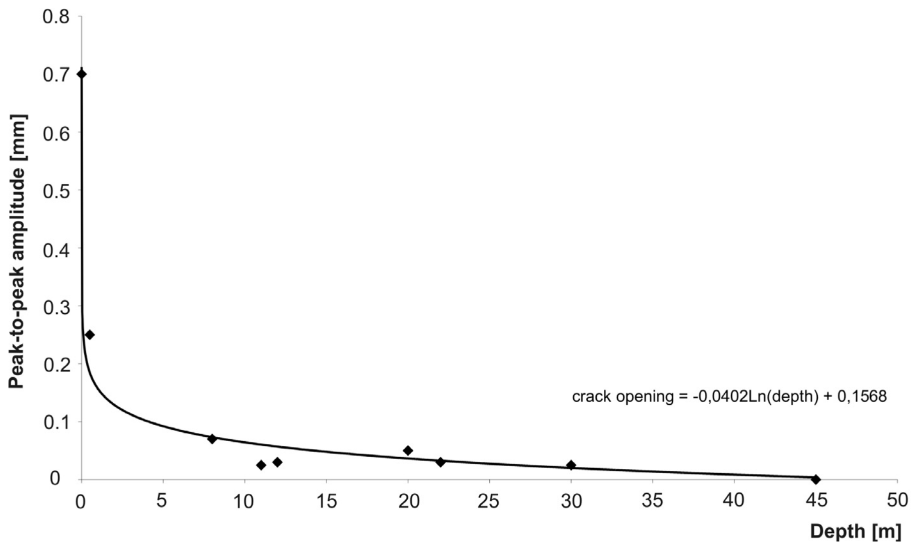


Fig. 7 The seasonal effect of temperature variations in the peak-to-peak amplitude of the vertical displacement component. It is seen that this effect decreases with depth.

Table 2 Description of the monitored fault structures and the peak-to-peak amplitude seasonal effect in fault displacements related to depth at the observed sites.

Locality	Previous fault activity	Fault structure		Monitoring	Gauge situation		Peak-to-peak amplitude [mm]		
		dip [°]	dip direction [°]	start [year]	surface	depth [m]	crack opening	strike-slip	vertical shift
Dobrá Voda trench	dextral /sinistral strike-slip	76	136	2004	x	**-**	**0.7**	0.2	0.7
Prekážka quarry	normal fault	75	140	2005	-	**0.5**	**0.25**	-	-
Slopy Cave	thrust fault	70	315	2005	-	**8**	**0.07**	-	-
Plavecká Cave 1	sinistral strike-slip	90	290	2007	-	**11**	0.025	0.03	-
Zbojnícka Cave	thrust fault	65	245	2005	-	**11**	-	-	-
Sedmička Cave	normal fault	89	80	2007	-	**12**	0.03	0.05	0.06
Driny Cave 3	strike slip	75	40	2005	-	**20**	**0.05**	-	0.1
Driny Cave 1	normal fault	70	290	2005	-	**21**	-	-	-
Plavecká Cave 2	normal fault	65	240	2007	-	**22**	**0.03**	-	0.09
Driny Cave 2	normal fault	70	110	2005	-	**25**	-	-	-
Čachtická Cave	sinistral strike-slip	80	270	2007	-	**30**	**0.025**	-	0.04
Beckovská Cave	normal fault	80	310	2008	-	**45**	**0.02**	-	0.03

In Slopy Cave and the nearby Zbojnícka Cave, a direct relationship has been noted between the recorded microdisplacements and the latest earthquakes to occur hereabouts during 2006-2007 (Briestenský et al., 2007). The effect is most clearly seen in the vertical displacements (Fig. 6). In particular, 2006 was a time of comparatively high earthquake activity. This activity decreases during the final third of 2007 (Fig. 8). The energy of the earthquakes was calculated using the following formula: $\log(E) = 9.05 + 1.96M_l$ (Energy in ergs) (Kanamori et al., 1993). The strike-slip components in both caves reflect this decreasing regional tectonic activity.

The long term measurements from Driny Cave, characterised by strike-slip components, allow trends in the data to be defined (Fig. 9). From these, it is then possible to constrain the local stress field orientation. Two gauges in Driny Cave showed sinistral strike-slip displacements along NNE-SSW striking faults, whilst a third indicated dextral strike-slip movements along a NW-SE striking fault (Figs. 9 and 10) (Briestenský and Stemberk, 2008). The resultant major principal horizontal stress ($\sigma 1$) has an approximately NNW-SSE orientation (Fig. 10), as defined by a regional 2D deformation model (McClay, 1987; Bahat et al., 2005). This stress field orientation, in addition to the rate of strike-slip calculated for the various faults, is in full agreement with previous geological ideas (e.g. Hók et al., 2000; Kováč et al., 2002). However the orientation of the major principal stresses determined from recent earthquakes in and around the Malé Karpaty Mts has recently been calculated to have an azimuth/plunge of $\sigma 1$ = 210-220°/5-25° (Fojtíková et al., 2010). These results are in direct contrast to the orientations calculated from microdisplacement observations in Driny Cave. The movements in Driny Cave were also indicated by damaged speleothems

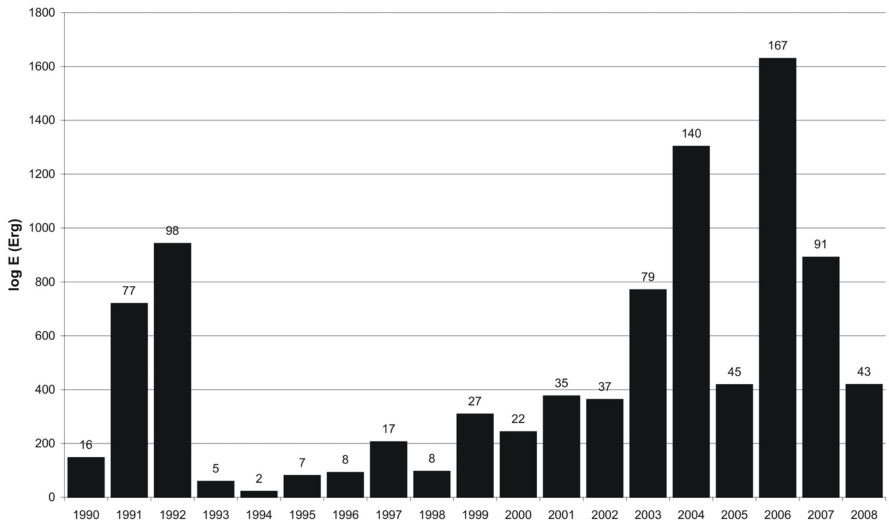


Fig. 8 The energy released by earthquakes in western Slovakia for the period 1990-2008. The number of quakes is shown on the peak of columns (data provided by the Geophysical Institute of the Slovak Academy of Sciences).

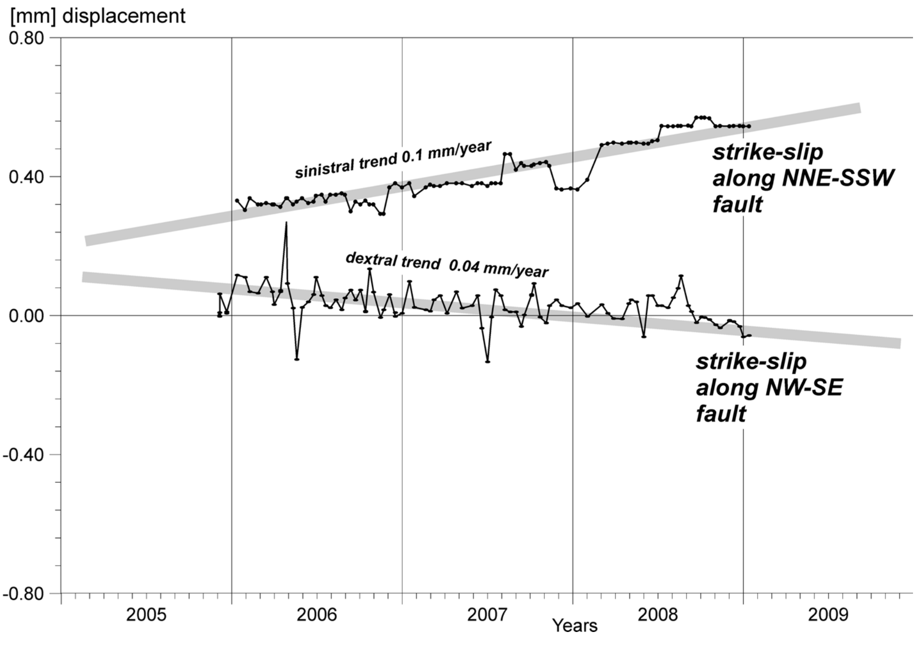


Fig. 9 The strike-slip displacement components recorded at two sites in Driny Cave. These sites are located at two differentially striking fault systems.

along the faults. Almost everywhere within the cave, freshly healed cracks cutting the sinter decoration appear in the close vicinity of fault outcrops (Briestenský and Stemberk, 2008).

5. DISCUSSION

The decision of where to locate gauges, either at the surface or underground, is of fundamental importance for studies of active fault movement. It is clear that caves and other underground sites are preferential as temperature is almost constant and the seasonal dilations that interfere with the identification of tectonic displacements are minimised. However, many caves around the world are associated with significant fluctuations of air temperature. Therefore, each cave system should be considered individually.

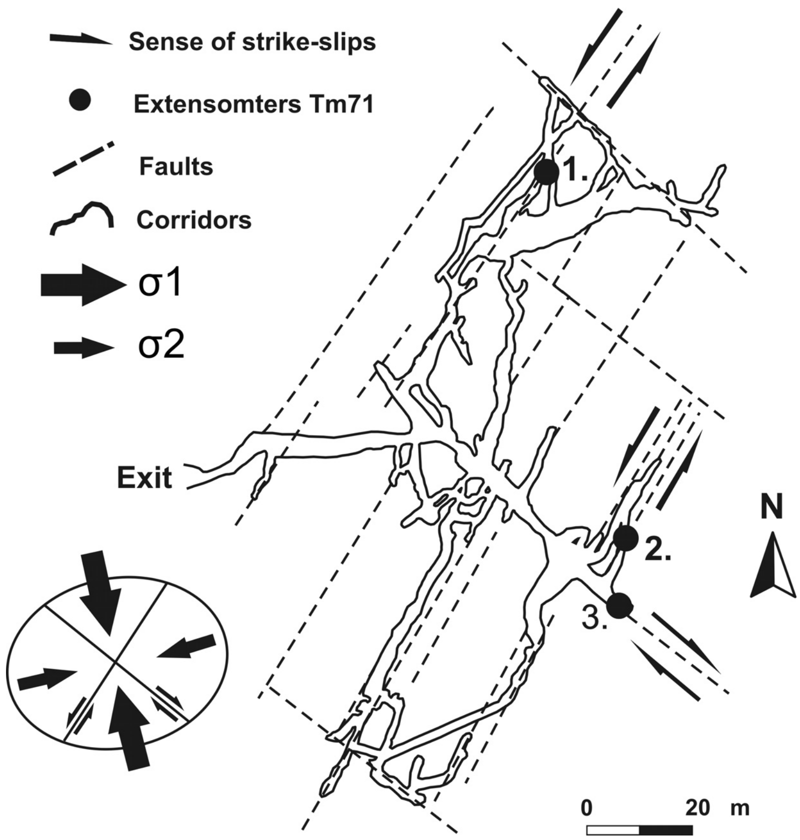


Fig. 10 The observed horizontal strike-slip fault displacements recorded along faults in Driny Cave, indicated by arrows. The stress diagram is shown in the bottom left-hand corner (modified after Briestenský and Stemberk, 2008).

Caves are also able to preserve a record of fault movement through slickensides and damaged speleothems along fault planes. Such properties are helpful when selecting the most suitable sites for monitoring rock massif behaviour over protracted periods. Nonetheless, certain problems do exist. Underground monitoring is often strenuous for operators. For example, six of the localities in western Slovakia require climbing and the use of specialist caving equipment. Fortunately, suitable fault sites can also be found at the surface. The site at Prekážka shows that surface measurements may be viable once the record is sufficiently long to identify seasonal dilations. In contrast, the site at Dobrá Voda poses a number of interpretation problems.

Numerous factors dictate site suitability. Well defined and important fault structures may sometimes be inappropriate for monitoring depending on, for example, the condition of the rock massif, sun exposure, underground water table, depth of freezing, and gravitational slope deformations. The TM71 gauge is clearly capable being submerged underwater more-or-less continuously, as seen at Prekážka. The absence of electrical components and an anticorrosive finish allows the gauge to be used under extreme monitoring conditions.

Our results show that fault displacements do not develop consistently but are easy modified by stress changes. For example, in Slopy Cave two of the observed tremors affected vertical displacement components. Conversely, the second quake caused initiated only a change of the peak-to-peak amplitude of crack opening (see Fig. 6). Similar behaviour was also observed at Prekážka. If a sufficiently dense network of gauges can be constructed, these changes could be used in the future to discover the underlying earthquake mechanism.

The difference between the orientation of the major principal stress axes calculated from recent earthquakes in the Malé Karpaty Mts. (Fojtíková et. al., 2010) and the orientation calculated from our microdisplacement observations in Driny Cave probably reflects the tectonic complexity of Malé Karpaty Mts.: the local stress in the Driny Cave area can be quite different from the average stress computed from the large number of earthquakes scattered all over the Male Karpaty Mts.

6. CONCLUSIONS

From our data relating to the monitoring of fault microdisplacements in western Slovakia, the follow conclusions can be drawn:

- Sinter damage can be induced by active fault movements and therefore provides a useful indicator of ongoing tectonism. This damage enables localities for microdisplacement monitoring to be readily identified.
- Fault displacements seem to correspond to recent tectonic activity and probably to significant earthquakes in the vicinity of the study sites. The observed microdisplacements along differentially striking fault systems can provide data for determining local stress field orientations.
- The effects of seasonal dilation within the rock massif decrease rapidly with depth. In underground settings, the peak-to-peak amplitude of these seasonal displacements are either small or can not be recognised. This minimises problems associated with data interpretation.
- Seasonal dilations affect the horizontal crack opening component most clearly both at surface and underground. The ongoing monitoring program should provide further opportunities to evaluate these trends.

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the financial support provided by the Czech Ministry of Education, Youth, and Physical Culture (Project COST OC 625.10), the Czech Science Foundation (Projects Nos. 205/05/2770, 205/06/1828, & 205/09/2024), the Institute of Rock Structure and Mechanics at the Academy of Sciences of the Czech Republic (Code A VOZ30460519), the Grant Agency of the Academy of Sciences of the Czech Republic (No. IAA300120801), the Slovak Grant Agency (VEGA Grant 2/0072/08), the Slovak Research and Development Agency (No. APVV-0158-06 Project NEOTACT "Neotectonic activity of the Western Carpathians"), and the European Union (No. 230669 FP7 Consortium Project AIM "Advanced Industrial Microseismic Monitoring").

REFERENCES

Bahat, D., Rabinovitch, A. and Frid, V.: 2005, Tensile fracturing in rocks. Tectonographics and Electromagnetic Radion Methods, 187 pp.

Briestenský, M.: 2005, Tectonic displacements monitoring in the Dobrá Voda epicentral area. Mineralia slovaca 37, 490–491, (in Slovak).

Briestenský, M., Stemberk, J. and Petro, L.: 2007, Displacements registered around March 13, 2006 Vrbové earthquake, M=3,2 (Western Carpathians). Geologica Carpathica 58, 487–493.

Briestenský, M. and Stemberk, J.: 2007, Recent displacements registered in selected caves of Dobrá Voda karst area in Slovakia. Acta Geodyn. Geomater., 4, 1, 31–38.

Briestenský, M. and Stemberk, J.: 2008, Microdisplacement monitoring in caves of the Western Slovakia. Slovenský kras 46, 77–83, (in Slovak).

Cacoń, S., Košťák, B. and Mąkolski, K.: 1994, Anthropogeneous deformations in the Bear Cave Massif (in Polish). In: Jahn, A., Kozlowski, S., Pulina, M., „Masyw Śnieżnika", Rozdzial 6, 71-83, Polska Agencja Ekologiczna, Wydawnicrwa PAE, Warszawa.

Cipciar, A., Fojtíková, L., Bystrický, E., Kristeková, M., Franek, P., Gális, M., Kristek, J., Moczo, P. and Pažák, P.: 2009, Slovak Earthquakes Catalogue, Version 2010.

Fojtíková, L., Vavryčuk, V., Cipciar, A. and Madarás, J.: 2010, Focal mechanisms of micro-earthquakes in the Dobrá Voda seismoactive area in the Malé Karpaty Mts (Little Carpathians), Slovakia. Tectonophysics. 492, 213-229. doi:10.1016/j.tecto.2010.06.007

Gosar, A., Šebela, S., Košťák, B. and Stemberk, J.: 2007, Micro-deformation monitoring of active tectonic structures in W Slovenia. Acta Geodyn. Geomater., 4, 1 (145), 87–98.

Gosar, A., Šebela, S., Košťák, B., et al.: 2009, Surface versus underground measurements of active tectonic displacements detected with TM 71 extensometers in Western Slovenia. Acta Carsologica, 38, 2-3, 213–226.

Hinsch, R. and Decker K.: 2003, Do seismic deficits indicate an underestimated earthquake potential along the Vienna Transfer Fault System? Terra Nova 15, 343–349.

Hók, J., Bielik, M., Kováč, M. and Šujan, M.: 2000, Neotectonic character of the Slovak area (in Slovak). Mineralia slovaca 32, 459–470.

Hrašna, M.: 2002, Monitoring of tectonic and seismic activity of the Slovak area. Geologické práce, Správy 106, 103–114, (in Slovak).

Jezný, M., Vlčko, J. and Hvožďara, M.: 2007, Temperature as a factor of the structural rock massif weakening. Geotechnika 3, 8–15, (in Slovak).

Kanamori, H., Mori, J., Hauksson, E., Heaton, T.H., Hutton, L.K. and Jones, L.M.: 1993, Determination of earthquake energy release and ML using TERRAscope. Bull. Seism. Soc. Am. 83, 330–346.

Košťák, B.: 1991, Combined indicator using Moiré technique. Proc. 3rd Int. Symp. on Field Measurements in Geomechanics, 9-11 Sept. 1991 Oslo, 53–60.

Košťák, B. and Rybář, J.: 1978, Measurements of the activity of very slow slope movements. Grundlagen u. Anwendung d. Felsmechanik, Trans Tech Publications, Clausthal, 191–205.

Košťák, B., Cacoń, S., Dobrev, N., D., Avramova-Tačeva, E., Fecker, E., Kopecký, J., Petro, L., Schweitzer, R. and Nikonov A.: 2007, Observations of tectonic microdisplacements in Europe in relation to the Iran 1997 and Turkey 1999 earthquakes. Izvestiya, Physics of the Solid Earth 43, 503–516.

Kováč, M., Baráth, I., Halouzka, R., Joniak, P., Sliva, Ľ. and Vojtko, R.: 2001, Neotectonic development of the Považský Inovec Mts. horst and the Blatné depression „slip rate analysis". Manuscript, Archive EQUIS Ltd., Bratislava, 85 pp., (in Slovak).

Kováč, M., Bielik, M., Hók, J., Kováč, P., Mozco, P., Plašienka, D., Šefara, J. and Šujan, M.: 2002, Seismic activity of the Western Carpathians (Slovakia). EGU Stephen Mueller Special Publication Series, 3, 167–184.

Lenhardt, W.A., Švancara, J., Melichar, P., Pazdírková, J., Havíř, J. and Sýkorová, Z.: 2007, Seismic activity of the Alpine-Carpathian-Bohemian Massif region with regard to geological and potential field data. Geologica Carpathica 58, 397–412.

Michalík, J., Reháková, D. and Marko, F.: 1992, Stratigraphy and tectonics of lower Cretaceous limestone sequence in a profile from Driny Cave (Vysoká Unit, Small Carpathians). Mineralia Slovaca 24, 235–243, (in Slovak).

Mąkolski, K., Cacoń, S., Jamroz, O., Košťák, B. and Kaczałek, M.: 2008, Investigations regarding Bear Cave Massif (Lower Silesia) long-term stability. Acta Carsologica 37, 279–290.

McClay, K.R.: 1987, The Mapping of Geological Structures. Milton Keynes, Open University Press, 161 pp.

Mocchiutti, A.: 2004, Evidenze morfologiche di movimenti tettonici recenti ed attuali nelle cavita delle Alpi Carniche. Il fenomeno carsico dell Alpi Carniche Mem. Ist. It. Spel., S. II, XV, 47–50.

Mocchiutti, A. and Dandrea, A.: 2002, Evidenze morfologiche di movimenti tettonici recenti ed attuali, stazioni di monitoraggio in alcune grote delle Prealpi fruilane (Nord-East Italia). Mem. Soc. Geol. It. 57, 487–491.

Šebela, S., Gosar, A., Košťák, B. and Stemberk, J.: 2005, Monitoring of active faults in Slovenia. Acta Geodyn. Geomater., 2, 1 (137), 45–57.

Šebela, S., Turk, J., Mulec, J., et al.: 2009, Statistical evaluation of the 3D monitoring of displacements of Dinaric fault zone in Postojna Cave, Slovenia. Acta Geodyn. Geomater., 6, 2 (154), 163–176.

Šebela, S., Vaupotic, J., Košťák, B. and Stemberk, J.: 2010, Direct measurement of present-day tectonic movement and associated radon flux in Postojna Cave, Slovenia. Journal of Cave and Karst Studies, 72, 1, 21–34.

Stemberk, J. and Štěpančíková, P.: 2003, Tectonic setting and monitoring of recent tectonic deformation in the Rychlebské Hory Mts. Acta Montana, Ser. A, 24, 153–161.

Stemberk, J. and Košťák, B.: 2007. 3-D trend of aseismic creep along active faults in western part of the Gulf of Corinth, Greece. Acta Geodyn. Geomater., 4, 1 (145), 53–65.

Stemberk, J. and Košťák, B.: 2008, Recent tectonic microdisplacements registered in Bedřichov Tunnel „A“ in the Jizerské Hory Mts. (N Bohemia). Acta Geodyn. Geomater., 5, 4 (152), 377–388.

Stemberk, J., Košťák, B. and Cacon, S.: 2010, A tectonic pressure pulse and geodynamic activity recorded from long-term monitoring of faults in Europe. Tectonophysics. 487, 1–4, 1–12.

Tshibangu, J.P., Ruymbeke, M., Vandycke, S., Quinif, Y. and Camelbeeck, T.: 2004, Studying underground motions in the Ramioul's Cave, Belgium. Engineering Geology for Infrastructure Planning in Europe 104, 614–623.

Vavryčuk, V.: 2001, Inversion for parameters of tensile earthquakes. J. Geophys. Res. 106 (B8), 16339–16355: doi:10.1029/2001JB000372.

Vavryčuk, V.: 2002, Non-double-couple earthquakes of 1997 January in West Bohemia, Czech Republic: evidence of tensile faulting. Geophys. J. Int. 149, 364–373.

Vavryčuk, V.: 2009, The Amplitude Moment Tensor Inversion - program AMT. Computer Codes Library, Institute of Geophysics, Prague.

Zacharov, M.: 1984, Research of the geological-structural circumstances and deformations in Jasovská Cave. Slovenský kras 22, 69–94, (in Slovak).

Zvelebil, J.: 1995, Determination of the characteristic features of slope movements present-day activity by monitoring in thick-bedded sandstones of the Bohemian Cretaceous basin. Acta Univesitas Carolinae, Geographica, XXX, Supplementum, 79–113.