FAULT SLIPS RECORDED IN THE STRAŠÍN CAVE (SW BOHEMIAN MASSIF)

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ABSTRACT

The paper presents the results of monitoring study undertaken during the period 2008 – 2010. The study recorded the displacement of tectonic structures in the Strašín Cave (SW Bohemian Massif). The derived results were compared, among others, with data recorded over the same time period across the Bohemian Massif in the EUTecNet (tectonic displacement monitoring net – see www.tecnet.cz), which is managed by IRSM ASCR.

The rate of recorded displacement is mostly in order of hundredths mm/year with maximal value recorded in vertical component at site Strašín 2, about 0,16 mm/2,5 years.

Whilst recorded displacement can indicate blocks subsidence into the cave empty space, the periods when displacement occurred correspond to periods of increased movement activity recorded for example at the opposite side of the Bohemian Massif, along the Sudetic Marginal Fault. Moreover, both periods are simultaneous with extraordinary earthquakes that affected western and southern part of the Bohemian Massif in 2008 and 2009.

KEYWORDS: Bohemian Massif, fault displacement, monitoring, Bohemian Forest, Strašín Cave

1. INTRODUCTION

During the last 10 years, regular and long-term 3-D monitoring of the fault displacement has started in many parts of the Bohemian Massif and other parts of Europe (e.g. Stemberk et al., 2010; Gosar et al., 2007; Stemberk and Košťák, 2007; Borre et al., 2003; Stemberk et al., 2003). Monitoring is organised preferentially under Earth´s surface, inside the caves and galleries (Stemberk and Štěpančíková, 2003). It can reduce or eliminate displacement induced by climatic variation (Briestenský et al., 2010). From our long-term monitoring of displacement, it has been possible to recognise periods of increased geodynamic activity (Stemberk et al., 2010). The suitability of this monitoring technique for the observation of geodynamic activity was confirmed by other geophysical methods (Košťák et al., 2011). As a part of the monitoring net, two spatial extensometers TM71 were installed in the Strašín Cave (49°10'57.16" N, 13°37'48.65" E) in SW Bohemia (Fig. 1). Regular monitoring has started in June 2008.

2. GEOLOGICAL AND TECTONIC SETTING

The Strašín Cave is situated in the Moldanubicum unit, a consolidated complex of mostly crystalline metamorphic and igneous rocks in the SW part of Bohemian Massif (Mísař et al., 1983; Chábera et al., 1985). The Moldanubicum is differentiated into several sub-units, of which the vicinity of Strašín cave belongs to so-called Varied series. It is mostly built by gneisses and mica schists with various degree of metamorphosis, but characteristically containing numerous insets and dykes of other rocks: erlans, crystalline limestones, aplites, etc (Babůrek et al., 2001; Müller et al., 1999).

The cave itself has developed in a small body of crystalline metamorphic limestone, and was partly formed by flowing water, as witnessed by numerous evorsion shapes on the ceiling (Kunský, 1930; Prosová, 1950). The cave consists of the main cavern, which is approximately 30 m long and 10-15 m wide, and of a maze of narrow passages on the eastern side, in total approximately 60 m. Climatic conditions are rather stable in the maze (yearly temperature oscillates between 5 - 7 °C), while in the main cavern the temperatures in winter may drop below 0°C. The cave is partly filled with clayey sediment, which was for the most part removed during mining activity in 1930ies, when local undertaker exploited the limonitic crusts for iron production (Kukla and Skřivánek, 1954).

Morphostructural analysis clearly showed differences in structural development between the Varied (where is located the cave) and Monotone Series (Hartvich and Valenta, 2011). The geological maps (Babůrek, 2001; Pelc and Šebesta, 1994) record few faults in the close surroundings of the cave, none, however, directly across. The situation is complicated by scarce occurrence of rock outcrop except for the cave and by vast floodplain of Strašínský brook.

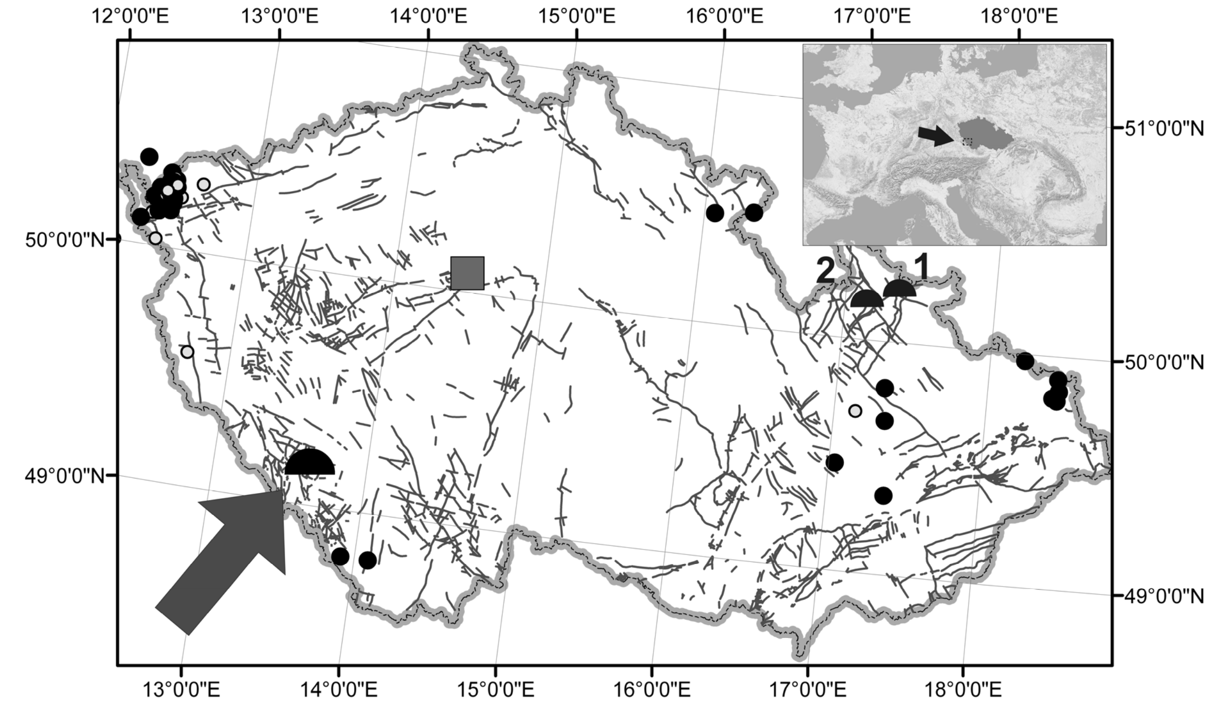

Fig. 1 Position of the Strašín cave site (indicated by grey arrow). No. 1 is Na Špičáku cave, No. 2 Na Pomezí cave. Grey solid lines are faults (based on geological map 1:500 000), black dots are earthquakes 2008-2010 above Mo > 2, grey dots Mo = 1-2 . Based on Regional seismic catalogue (IGP 2011).

The tectonic situation in the surroundings of the cave is analysed in detail by Hartvich and Valenta (2011), who tried to link the measured faults with the tectonic lines in the vicinity. The directions of monitored faults inside the cave (device Strašín No. 1: 60° and device Strašín No. 2: 120°) correspond both to the general tectonic directions of the Varied series and to the closest faults observed by Babůrek (2001).

3. GEODYNAMIC EVENTS DURING OBSERVATION PERIOD

During the monitoring period, several geodynamic phenomena affected the SW part of the Bohemian Massif. First event, the Cheb swarm (~50.19°N, 12.43°E), was recorded in October 6-12, 2008 with magnitude M = 2.5 – 4.3. It was the strongest swarm since 1980ies. The epicentres were approximately 140 km NW from the cave (Fig. 1). Second event were two earthquakes near Lipno Lake, recorded in May 2009 (May 5~~th~~, M=2.7, at 48.8° N 14.09°E and May 6~~th~~, M =2.2, at 48.8°N 13.91°E). The epicentres of these rather unusually located, unexpected earthquake events were only about 45 km distant to the SE from the cave (Fig. 1). The earthquake events were recorded by IG AS CR (Fischer and Zedník 2010, www.ig.cas.cz).

Third event was a flash flood, originating from the series of convective thunderstorms in the first decade of July 2009. The water level inside the cave raised about 5 m above the usual level in the small ponds at the bottom of the cave, with a result of flooding almost whole cave.

4. METHODOLOGY

On the studied site of Strašín cave, two TM-71 devices (cf. Košťák, 1991, Fig. 3) were installed in May 2008, crossing two most significant tectonic structures in the cave (Fig. 2). The optical-mechanical crack gauge TM-71 (Fig. 3) is a device for accurate, three dimensional measuring of relative movement between two blocks separated by a discontinuity. The principles underlying the function of the instrument were described by Košťák (1991). The device operation is based on optical-mechanical interferometry, i.e. optically registering the moiré patterns resulting from light rays bending and interfering between two special optical grids. Information about the movement value is represented by the moiré patterns, which are mathematically transformed into three-dimensional vector of displacement as well angular deviations (rotations).

The resolution of the installed device varies from 0.05 to 0.0125 mm depending on the particular type of the spiral grid. The devices in Strašín cave reach the accuracy of 0.0125 mm. The angular deviation between two blocks separated by a discontinuity -

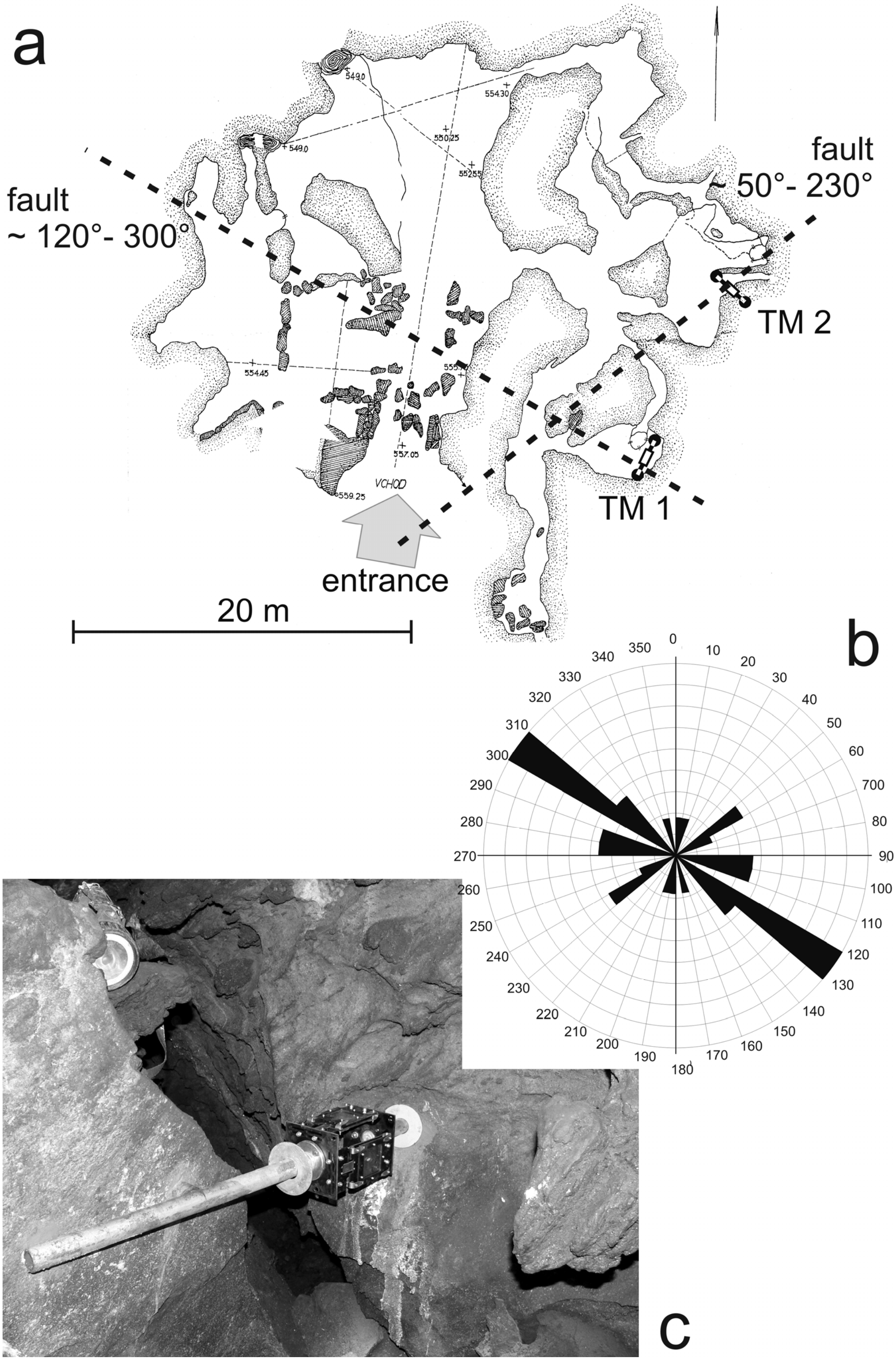

Fig. 2 A) Map of Strašín cave (after Kukla and Skřivánek, 1954, adapted) B) Rosette diagram of joint and fault system inside the Strašín cave. Measured by authors and additional data taken from Kukla and Skřivánek (1954) C) Photograph of TM-71 device No. 2 in the Strašín cave.

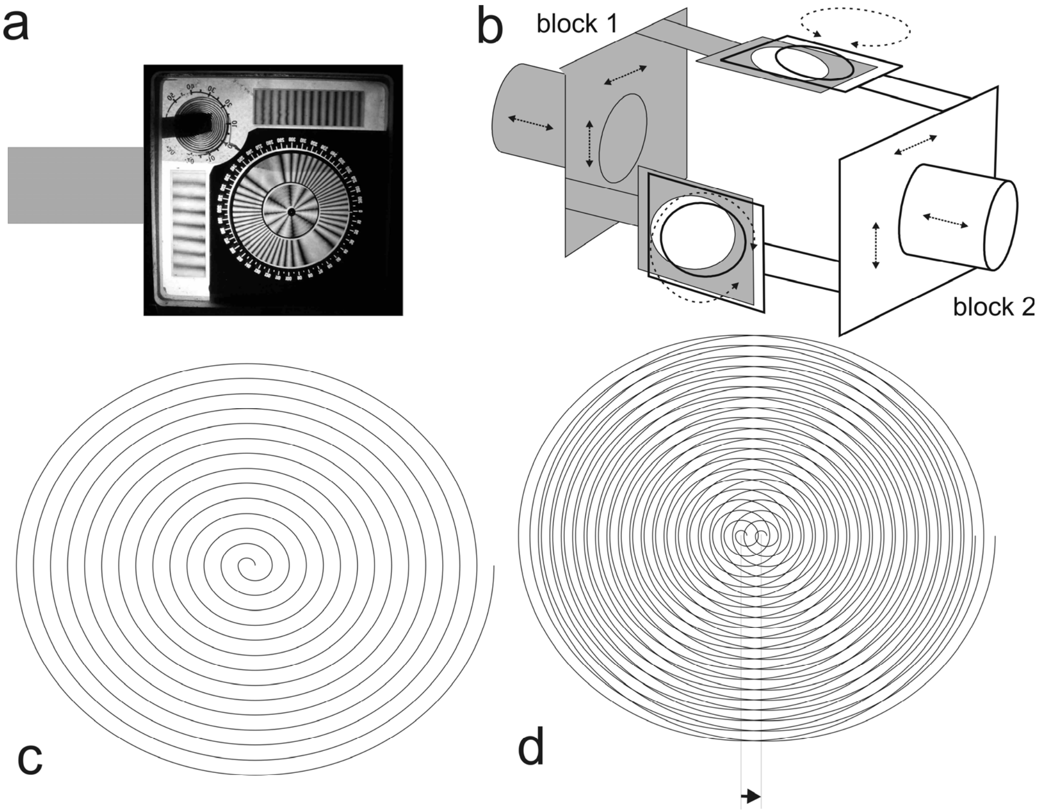

Fig. 3 A) Example of a photograph of moire pattern between two glass plates with fine engraved spirals B) Schematic drawing of the TM-71 device. All grey parts are attached to block 1, all white to block 2. Arrows indicate possible movements of the components C) Spiral similar to those engraved glass plate of TM-71 (much less dense) D) Two identical spiral as the one from C picture moved horizontally by the distance indicated by the arrow - now the moire effect is already observable.

i.e. their relative rotation – can be measured with a resolution of $3.2*10^{-4}$ rad (≈ 0.018°).

The records of the displacements and rotations are plotted into linear charts (Figs. 4 and 5). We can observe the trends and events directly from the charts, however, to have more precise markers of the significancy of the changes, we have created a summary plot of relative changes (Fig. 6). Each column represents relative percentual change (of either displacement or rotation) calculated between two following measurements per day. A sum of all changes is thus 100 %, and the values considered significant are those over 0,9 percentile (8%).

The ability to register both lateral and shear displacement as well as rotations of the blocks is a result of the three-dimensional operation of the instrument. This represents the fundamental methodical advantage of the TM71, as all possible relative movements of the blocks are measured with high accuracy. The particular advantages of using the TM71 in order to recognise seismic reflections and tectonic displacements were recently documented in the statistical study of Šebela et al. (2009), which examined displacement on the Dinaric Faults in Slovenia.

For several reasons, the underground monitoring in caves and artificial galleries is preferred. Firstly, the stable temperature allows avoiding the laborious removing of the temperature influence. Secondly, the stable conditions in the caves (temperature, moisture, heat flow) minimize the influence of other possible causes of the massif movements. And finally, the devices in locked underground cavities are much better protected both from the natural (weather, rockfalls) and from human-induced disturbances (tampering with the device, vandalism).

The specifics, advantages, disadvantages, limitations and possibilities of this instrument have been studied from various angles as a result of long-term application of the device on numerous sites e.g. in Czech Republic, Slovenia, Slovakia or Poland (Briestenský et al., 2010; Gosar et al., 2009; Šebela et al., 2009; Kontny et al., 2005). It was demonstrated that seasonal and climatic variations can be detected and separated from the total observed movements and thus obtain true tectonic activity. Therefore, long-term

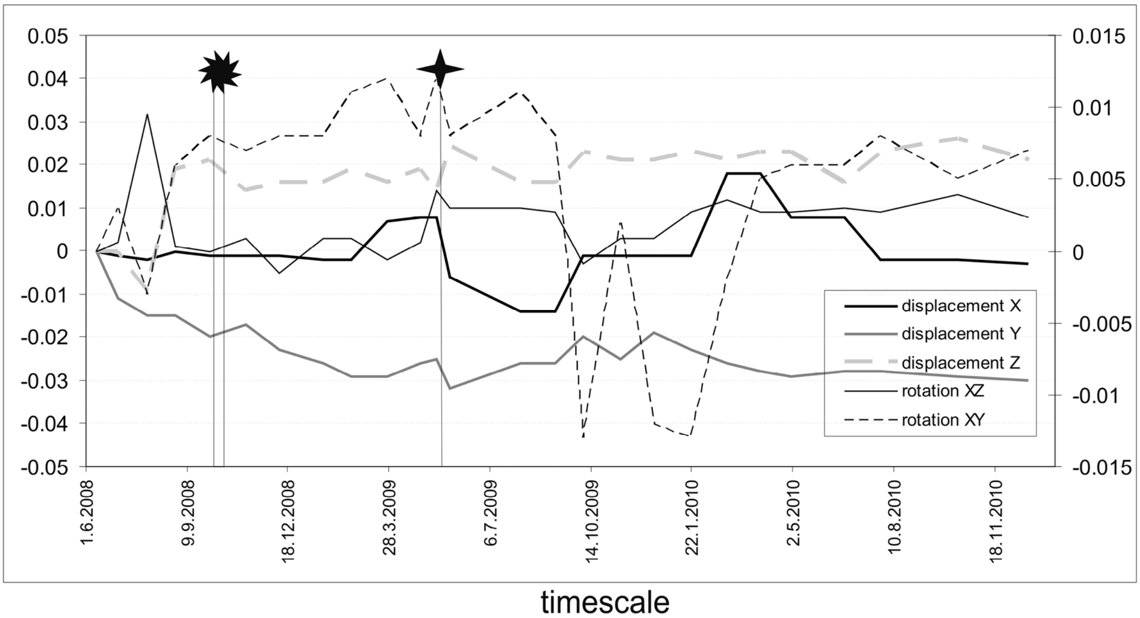

Fig. 4 Chart of displacements and rotations recorded by TM-71 device Strašín 1. The 10-spiked star indicates the Cheb swarm (6.-12.10.2008), 4-spiked star the Lipno earthquakes (5.-6.5.2009).

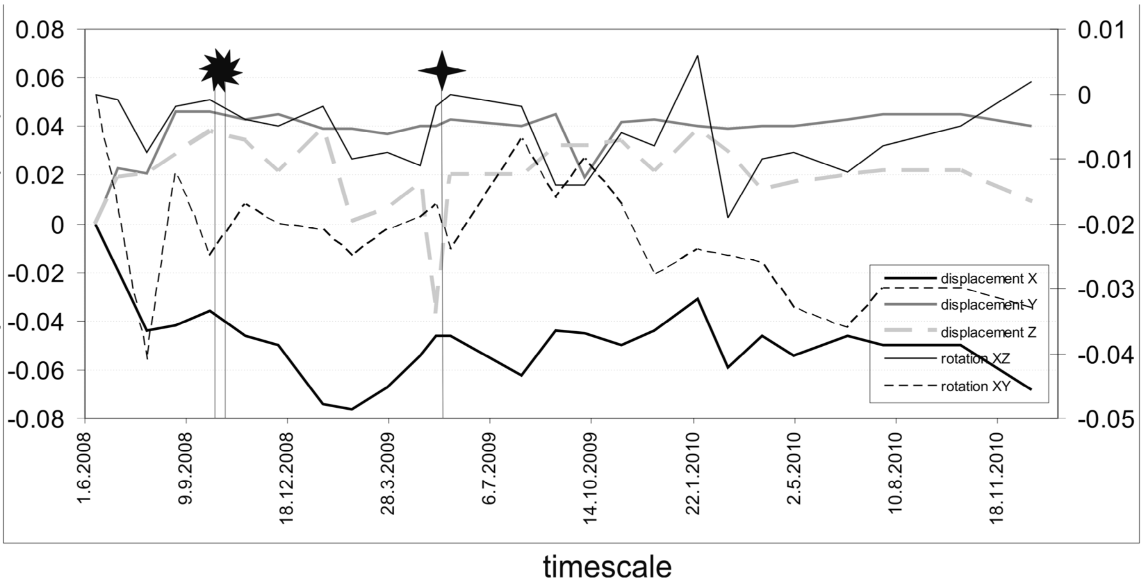

Fig. 5 Chart of displacements and rotations recorded by TM-71 device Strašín 2. The 10-spiked star indicates the Cheb swarm (6.-12.10.2008), 4-spiked star the Lipno earthquakes (5.-6.5.2009).

relative displacements on tectonic structures can be studied successfully.

5. RESULTS OF DISPLACEMENT MONITORING

Installation of TM-71s in the Strašín Cave, as a part of the EU-TecNet covering the Bohemian Massif, was finished during May 2008. Two devices TM71 were installed across two remarkable faults recognised in the eastern part of the cave. Device Strašín No. 1 was installed across fault 205°/75° (dip direction/dip angle) and device Strašín No. 2 across a fault 140°/60° (Fig. 2). Both devices are placed about 15 m below the surface. Regular monitoring has started in June 2008. Detailed site description and photo documentation is given also at www.tecnet.cz – Strašín Cave.

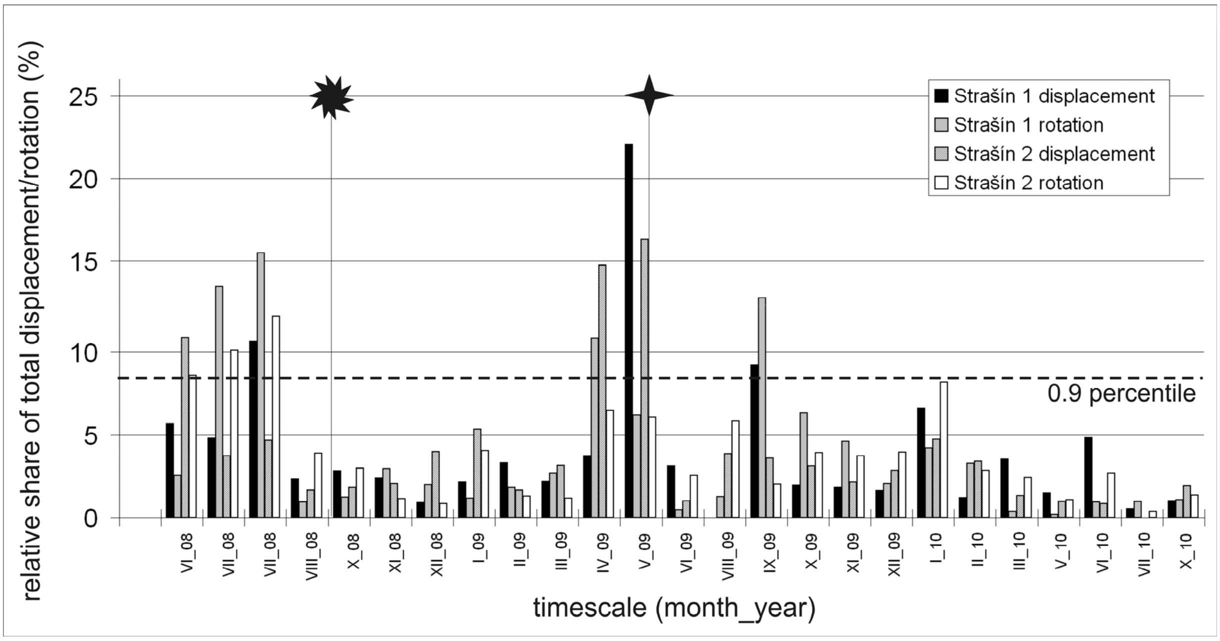

Fig. 6 Bar chart showing statistic significance of activation periods in summer 2008 and spring 2009 - during both events, the total percentual change exceeds 0.9 percentile. The percentual change of both displacement and rotation is calculated as sum of average daily change between two measurements, relativised by total observed change for each category. 10-spiked star indicates the Cheb swarm (6.-12.10.2008), 4-spiked star the Lipno earthquakes (5.-6.5.2009).

The principal characteristics of recorded movement may be summarised as follows:

1. At the site Strašín No. 1 (monitored fault 205°/75°), the main recorded trend is dextral oblique uplift of NE flank/subsidence of SW flank with approximately similar values of both vertical and horizontal components 0.04 and 0.05 mm (Fig. 4).
2. At the site Strašín No. 2 (monitored fault 140°/60°), recorded trend is sinistral uplift of SE flank/subsidence of NW flank with values of vertical and horizontal components 0.16 and 0.06 mm (Fig. 5).

It must be mentioned that the long term displacement (trend) consists of several short periods of increased velocity of displacement at both monitored sites. The major part of the displacement occurred between July 2008 and May 2009. This active period could be separated into two pulses – first occurred in July/August 2008 and second occurred in May 2009. It is clear that if we compare both pulses, the character of their trends is generally opposite. First pulse (July/August 2008) corresponds to uplifting of eastern block bordered by monitored faults and/or to subsiding of northern and southern blocks (see Fig. 7a). This pulse was probably connected with relaxation recorded at site Strašín 2.

The second pulse (May 2009) has a reverse pattern and corresponds to uplifting of the southern block and the northern block and/or to subsiding of eastern block (see Fig. 7b). This pulse was connected with clear pressure increases recorded at both monitored sites.

After second pulse, the movements practically stopped. During January/March 2010 new pressure increases was recorded, nevertheless without remarkable slips along monitored faults.

6. DISCUSSION

There were - as noted above - three events of activation of the movement recorded by both devices in the Strašín Cave – summer 2008 (must be mentioned that this period was observed just after installation of devices), May 2009 and beginning of 2010. Also three unusual geodynamic events occurred during monitored period as earthquakes and flood.

6.1. SEISMICITY

In the search for explanation of these events, we have used the earthquake databases to see if there are any seismic events, which might correlate in time with the observed periods of geodynamic unrest. The search has revealed two rather unusual events.

If we analyse the first seismic event, the Cheb swarm (October 6-12, 2008), we can observe that swarm occurred about 1 month after movement acceleration in the middle of 2008.

Both devices recorded sharp onset of movements during May 2009. At this time (May 5-6, 2009), two extraordinarily strong earthquakes (in the scale of this region's geological background, naturally) occurred near the Lipno Lake. This pulse was connected with evident compression recorded by both devices. From the data record we can recognise that during this pulse, the southern and northern blocks rose relatively to eastern block and about one month later the displacement development turns to “normal” observed trend. The sharp uplift of the southern block was recorded just around the Lipno earthquake events. Unfortunately, the focal mechanism was not assessed for these earthquakes (Fig. 7a).

The comparison of the displacement development and earthquake occurrence showed that the recorded pulses had reverse pattern, first conform to the long-term trend, second reverse. Moreover, it is clear that both periods of extraordinary displacement predate slightly the seismic events.

Interestingly, the position of epicentral areas of both groups of events (Lipno and Cheb) are situated in opposite directions from the cave; and both are situated approximately in NW – SE line corresponding to direction of main fault structures bordering the Šumava Mts. from NE (cf. Fig. 1; Hartvich and Valenta, 2011).

6.2. DISPLACEMENTS ELSEWHERE

As the monitoring in the Strašín Cave is a part of the EUTecnet network, focused on monitoring of displacement along faults all around the Bohemian Massif, we were able to compare the characteristics of the development of displacement both in time and space across the Bohemian Massif.

For comparison of displacement development we used records from the sites situated along Sudetic Marginal Fault Zone as a known indicator of tectonic activity in the Bohemian Massif (cf. Stemberk et al. 2010; Košťák et al., 2011). Moreover, the SMF follows approximately same direction as the main tectonic lines of Šumava (Hartvich and Valenta, 2011; Hartvich, 2004). Records published by Stemberk (2010) from Na Pomezí Cave and Na Špičáku Cave are shown in Figure 8. From the charts we can observe that:

- a remarkable vertical pulse was recorded in the Na Pomezí Cave (site Na Pomezí 2) in the middle of 2008, middle of 2009 and break of 2009/2010
- in the Na Špičáku Cave (site Na Špičáku 1) we observe significant reactivation of vertical movement since beginning of 2008, with a step-like development during first half of 2008, middle of 2009 and beginning 2010.

Simple comparison of displacement developments monitored in Sudetic Marginal Fault Zone (Fig. 8) and Strašín Cave (Figs. 4 and 5) show that remarkable displacements were recorded practically simultaneously.

6.3. OTHER POSSIBLE INFLUENCES

The above described remarkable timescale coincidences suggest that there might have been a common factor influencing both monitored areas as well as general geodynamic and seismic pattern, most likely of tectonic origin if we take into account the distance between the sites. However, it must be noted that there are other factors influencing the measured results.

The displacement trends recorded namely at site Strašín 2 might suggest possible subsidence of the blocks to empty spaces inside the cave, as the value of the subsidence is higher than other displacement components recorded at both devices. However, this explanation neither corresponds to the reverse character of the movements nor accounts for the recorded geodynamic events.

As the cave is rather shallow, the movements may be also influnced by thermal expansion of rock material due to outside temperature and insolation changes. Briestenský et al. (2010) analysed the influence of thermic volume changes on the TM-71 devices at various depths. It was found out that temperature-induced variation of displacement has an amplitude about 0.02 – 0.03 mm/year at the depth of 10 - 15 m under surface.

Aside from that, there are several indices that point to low influence of thermal volume changes:

- The temperatures inside the cave (in the part with TM devices) changes very little throughout a year (from +5° to +7°C)
- the rockface above the cave is covered with dense vegetation (trees, shrubs)
- a tell-tale sinusoid curve (typical for yearly thermal volume changes) cannot be distinguished in the records from Strašín cave

It was mentioned that the first activity period occurred shortly after monitoring installation. It is generally agreed that the initial measurements are less reliable due to such influences as massif reaction on hole-drilling, concrete hardening, etc. Nevertheless, our experience from other sites show that this "initial" behaviour is typically trend-like, without any reversal or relaxation. Moreover, the first event was recorded between 2nd and 3rd measurements (i.e. about 2 – 3 months after installation into the massif) and not between 1st and 2nd measurements which could be plausibly explained by a reaction on massif disruption. Thus, in combination with the fact that these events were simultaneously recorded on other sites, we tend to prefer the geodynamic explanation.

Finally, the cave was flooded during the monitoring period (July 2009). Flooding is generally considered as one of possible factors influencing the block movement inside the caves (decreasing of friction, changes in pressure and in weight distribution (e.g. Ford and Williams, 2007). However, the graphs do not indicate any observable during and after cave flooding (Figs. 4 and 5).

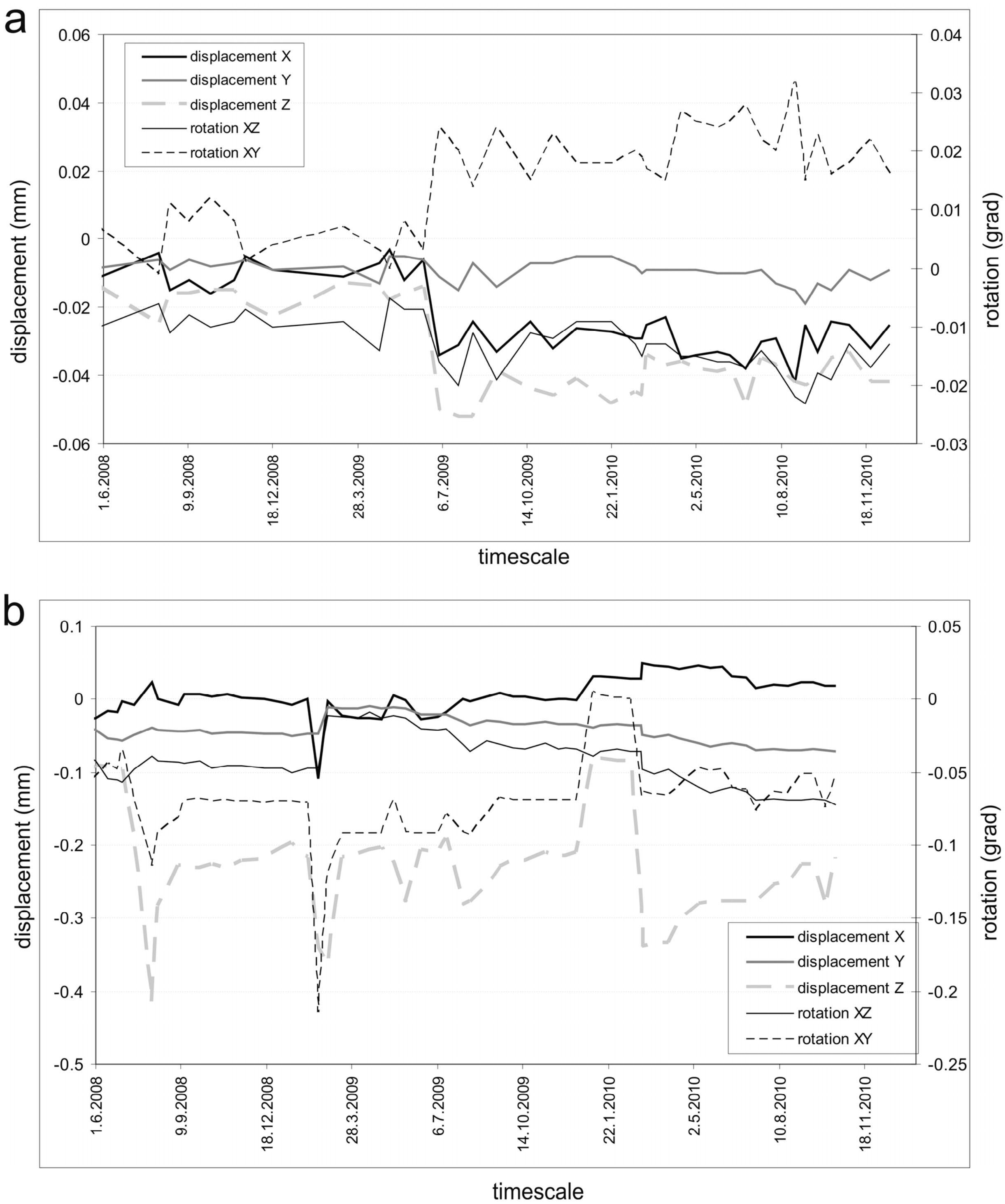

Fig. 8 Chart of displacements and rotations recorded by TM-71 at the Na Pomezí Cave (A) and Na Špičáku cave (B).

7. CONCLUSIONS

During monitoring period, the fault displacements were recorded on both TM-71 devices (Strašín 1 and Strašín 2) installed inside the Strašín cave. The rate of recorded displacement is mostly in order of hundredths mm/year with maximal value recorded in vertical component at site Strašín 2 about 0.16 mm/2.5 years.

However, during the observed 2.5 years we have also recorded two significant, temporarily limited periods of increased displacements. These movements occurred simultaneously with periods of increased movement activity recorded in EUTecNet across Bohemian Massif. Moreover, both periods can be parallelized with extraordinary seismic activity recorded in southern and western part of the

Bohemian Massif (October 6-12, 2008 – Cheb swarm and May 5-6, 2009 – Lipno), when the diplacements predate closely both seismic events.

The striking temporal coincidence of all these recorded events may indicate common geodynamic cause. We suggest that this cause could be the reconfiguration of stress and strain within Bohemian Massif. Moreover, as the earthquake swarms were a result of the upflow of magma, it may even indicate that this reconfiguration results from the processes which have their origin deep within the lithosphere/asthenosphere. This is in accordance with conclusions of Stemberk et al. (2010) describing periods of increased geodynamic activity and numerous, unusual earthquakes recorded in central Europe during the period of early 21. century.

On the contrary to the geodynamic coincidences, we have observed no remarkable displacements during and after flooding of the cave during July 2009.

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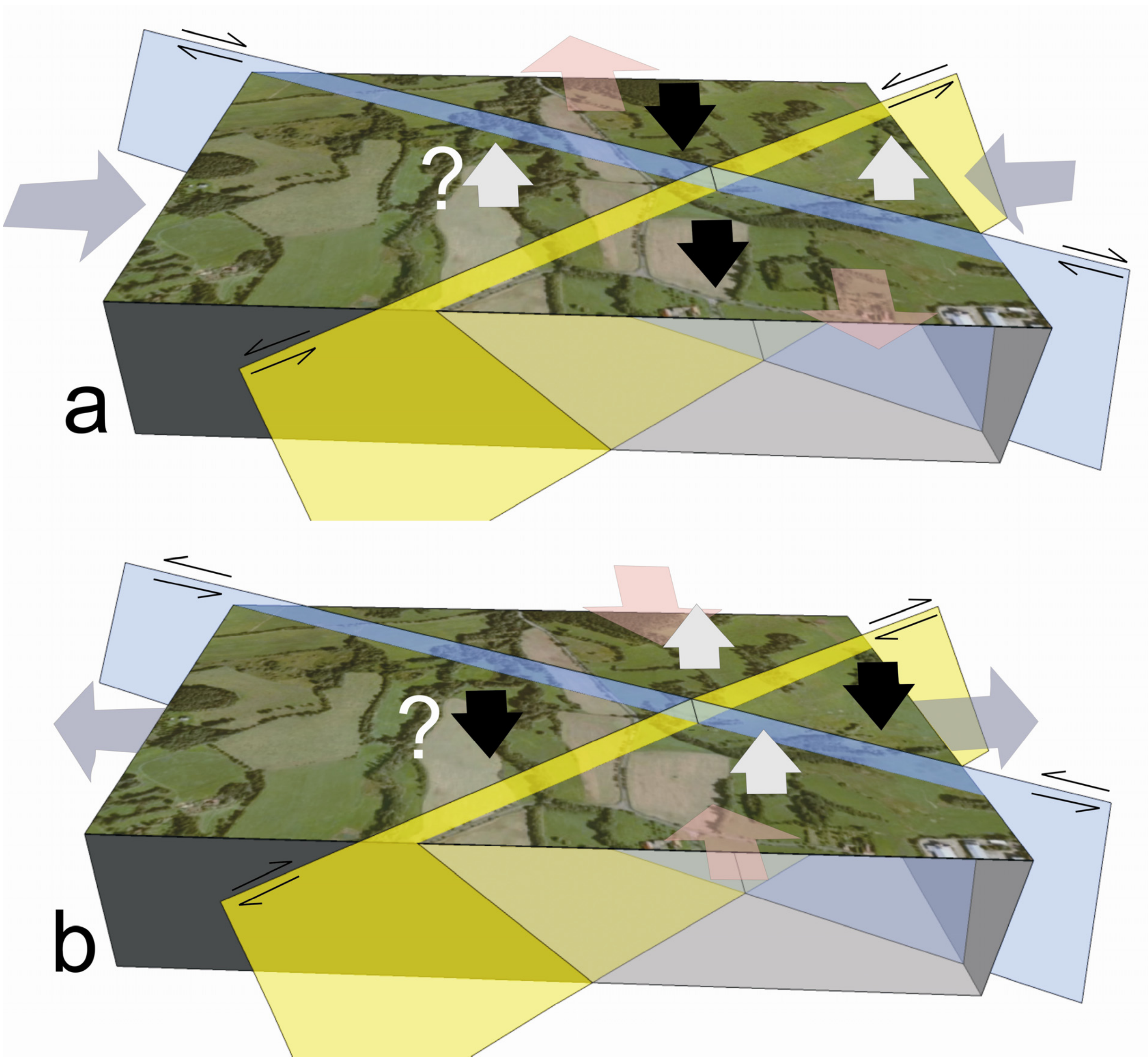

Fig. 7 A) 3D blockdiagram showing the diplacement trends of the blocks monitored in Strašín cave during activation period in summer 2008
B) A 3D blockdiagram showing the diplacement trends of the blocks monitored in Strašín cave during activation period in spring 2009. Light grey arrows indicate uplift, black sinking, light blue compression and pink extension direction. Blue fault plane is observed by device No. 1, yellow by device No. 2.