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Displacements registered around the 13 March 2006 Vrbové earthquake M = 3.2 (Western Carpathians)

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Abstract: Information is given about the micro-displacement monitoring network in the Dobrá Voda epicentral area, where regular monitoring started in May 2004 and an earthquake occurred on 13 March 2006. The measurement is carried out with the use of verified, stable and sensitive 3D crack gauges TM71 produced by GESTRA Sedloňov, Czech Republic. All the gauges installed across significant tectonic structures in this earthquake zone registered displacements pertinent to the said last earthquake. The results obtained within the Dobrá Voda (W Slovakia) monitoring network are analysed in view of the 13 March 2006 earthquake. The measurements indicated remaining sinistral strike-slip displacements in the Dobrá Voda fault zone, as well as active subsidence of the Pannonian Basin. Moreover, the measurements indicated even more detailed data about the fault movement development during the instability process developing before and after the earthquake.

Key words: Dobrá Voda, micro-displacements, earthquake, TM71 crack gauge.

Introduction

The Dobrá Voda epicentral zone was selected to be investigated for displacements on several faults supposed to be active according to geological studies. This area is one of the most earthquake prone zones in Slovakia. The research was initiated within the international project COST 625 "Monitoring of active tectonic structures".

The first gauge was installed in Dobrá Voda village. The area is known for the very significant Plavecké Podhradie–Dobrá Voda fault, and measurements started in May 2004. Three other gauges were installed in October 2005. The sites selected for the second installation are also connected with important tectonic zones: Smolenice fault, Plavecké Podhradie–Dobrá Voda fault zone, and Ludinský (Dobrá Voda) fault zone (Figs. 1, 2, 3). The crack gauge TM71 was applied for this type of monitoring, regarding its long successful use in many countries. Let us name the Rhine Fault (Fecker et al. 1999), the Cordillera Blanca (Stemberk et al. 2003), the region of Gargano and Norcia in Italy (Stemberk et al. 2003), a series of sites in Slovakia (Petro et al. 2005), Simitli Graben in Bulgaria (Dobrev & Košťák 2000; Dobrev et al. 2005), the Gulf of Corinth in Greece, and other places such as the Peter the Great Ridge in Tajikistan (Košťák et al. 1992).

On Monday 13 March 2006, at 8 h 28 min UTC, the vicinity of the town of Vrbové was hit by a weak earthquake (48.6ºN, 17.7ºE). Its local magnitude was established as $M_L = 3.2$ (http://www.seismology.sk); according to the ANSS catalogue, the hypocentre was situated at a depth of 10 km and magnitude established to $M_L = 3.6$ (http://www.ncedc.org/anss). The quake was felt in the surrounding area, and during the event damage to buildings was registered too. This earthquake was the largest one during the latest six years.

Dobrá Voda epicentral area — geological and tectonic setting

The locality belongs to the northern part of the Malé Karpaty Mts. It is a segment of the Inner Western Carpathians. As far as neotectonic setting is concerned, the area is situated in the Western Slovakia neotectonic region (Hók et al. 2000). The whole area is composed of three tectonic structures: Mesozoic Brezová elevation, Mesozoic Dechtice elevation, and Neogene strike-slip Plavecké Podhradie–Dobrá Voda fault zone which forms the northeastern part of the Mur-Münz-Leitha lineament. The Plavecké Podhradie–Dobrá Voda fault zone originated during the Early Miocene (Marko et al. 1991).

Numerous earthquakes are produced here due to the crossing of two fault systems: The Mur-Münz-Leitha ENE–WSW striking lineament, and the Nesvačili-Trnava NW–SE striking lineament. Generally, this region represents the most earthquake-prone region in Slovakia. The strongest registered quake occurred on 9 January 1906, with the intensity $I_o = 8.5$ °MSK-64.

During the last century, 154 earthquakes of $M > 2$ were registered here. The local microseismic network registered 1143 microearthquakes in the period 1999–2005. The penultimate earthquake occurred on 19 September 2003 with magnitude $M_L = 3.1$.

According to Marko et al. (Marko et al. 1991) the present compressional stress field in the studied area is ori-

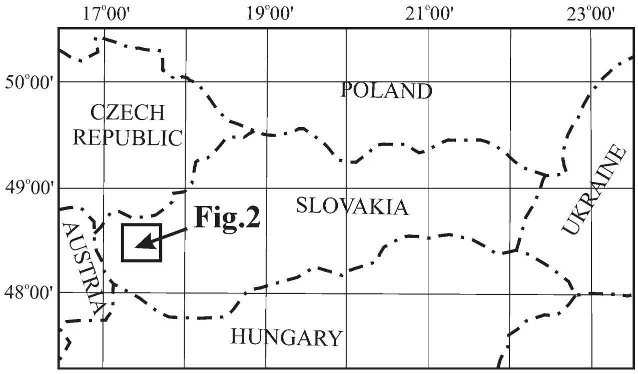

Fig. 1. Position of the studied area.

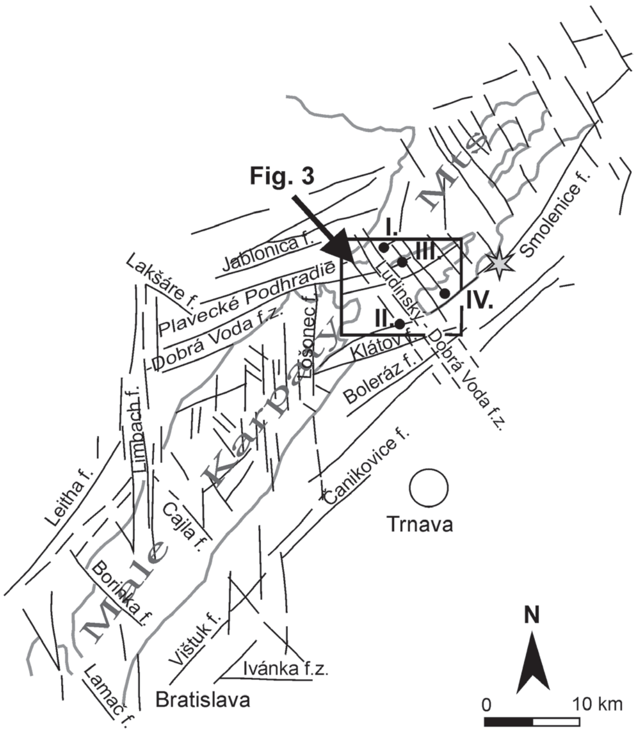

Fig. 2. Significant faults in Malé Karpaty Mts area (modified after: Kováč et al. 1989; Marko et al. 1991; Hók et al. 2000) and sites of the TM71 gauges. Black dots — TM71 sites, grey star — 13th March 2006 earthquake epicentre, TM71 gauges: **I** — Dobrá Voda, **II** — Prekážka quarry, **III** — Slopy Cave, **IV** — Zbojnícka Cave.

ented WNW–ESE. Grünthal & Stromayer (1986) state a different direction: NNE–SSW.

Sites of TM71 devices

Dobrá Voda — Site No. I

Dobrá Voda site is situated at the SE contact of the Mesozoic Brezová elevation with the Dobrá Voda Depression (Fig. 3). The depression is developed along NE–SW striking faults and forms a northeastern section of the Plavecké Podhradie–Dobrá Voda fault zone (Fig. 2). Halouzka et al. (1999) supposed that the fault zone was active from Middle Pleistocene to Holocene. It is typical of dextral strike-slip slickenside (5° → 040°) occurrence. The gauge TM71 was installed across a NE–SW striking fault cutting Eggenburgian conglomerate (Fig. 4). It is located in a disused railway furrow, near a local karst spring, in the village centre.

Prekážka quarry — Site No. II

The gauge was installed across a NE–SW striking failure (75° → 135°) cutting the Carpathian Jablonica conglomerate (Fig. 5). It is a segment of the Smolenice fault (Fig. 2). The fault was exposed in an old local quarry, in its west facing wall. It is possible to find slickensides on a gravel surface of normal fault character. Another system of slickensides (34° → 225°) is not so significant, but has already been discerned by Marko & Kováč (1996) as well. According to these authors, the fault represents a deep Badenian normal fault. The fault forms a segment of the Malé Karpaty Mts marginal fault zone, the fault border between the northern part of the Malé Karpaty Mts and the Pannonian Basin (Fig. 2). Its neotectonic activity was established from the Late Pliocene to Quarternary (Halouzka et al. 1999).

A gauge was installed in a trench, one meter below surface.

Slopy Cave — Site No. III

The gauge was installed eight meters below the surface in a karst — joint cave at Slopy Hill. The cave developed in Wetterstein Limestones (Salaj et al. 1987), along a NE–SW striking thrust fault (Figs. 3, 6). Development of cave spaces was predestined by fault planes of 70° dip, downward changing to 55° dip. According to Mitter (1983), the cave is 75 m long and 30 m deep. Our analysis proved 36 m depth, fresh damages of cave sintres, and tectonic breccia. During winter seasons, warm vapour arising on the surface has been observed.

Zbojnícka Cave — Site No. IV

The cave developed in Stainmal limestone (Salaj et al. 1987) of the Brezová elevation (Fig. 3) along an E–W failure. According to Mitter (1983) it is fluvio-karst type, 250 m long. A central gallery is cut by N–S striking faults, and slickensides of normal fault character were found. The gauge was installed at a depth of 11 m, across 65° → 245° failure (Fig. 7) with dextral strike-slip horizontal component. The component is documented by relative displacement of blocks, and freshly crashed sinters as well (Fig. 8).

Methodology of monitoring

Long-term field measurement requires special equipment, stable under hard outdoor conditions. Such a suitable instrument has been found in crack gauge TM71

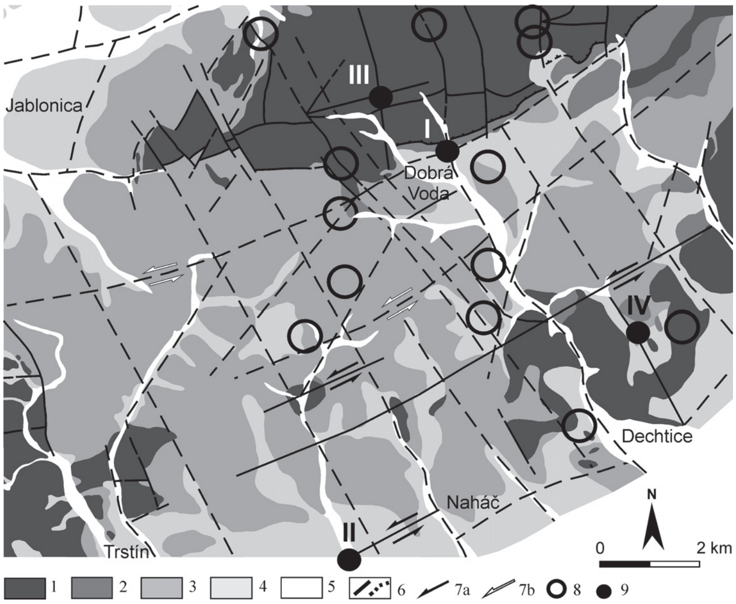

Fig. 3. Tectonic sketch of the Dobrá Voda epicentral area and sites of the TM71 gauges (modified after: Salaj et al. 1987; Marko et al. 1991). **1** — Pre-Senonian lithostratigraphical units of the Inner Carpathians, **2** — Senonian and Paleogene of Myjavská pahorkatina Upland, **3** — Miocene, **4** — Quaternary deluvial sediments, **5** — Quatenary fluvial sediments, **6** — faults, **7a** — movements estimated on the basis of structural analysis and monitoring, **7b** — movements supposed by Marko et al. (1991), **8** — macroearthquake epicentres (1904–2003), **9** — TM71 gauges: **I** — Dobrá Voda, **II** — Prekážka quarry, **III** — Slopy Cave, **IV** — Zbojnícka Cave.

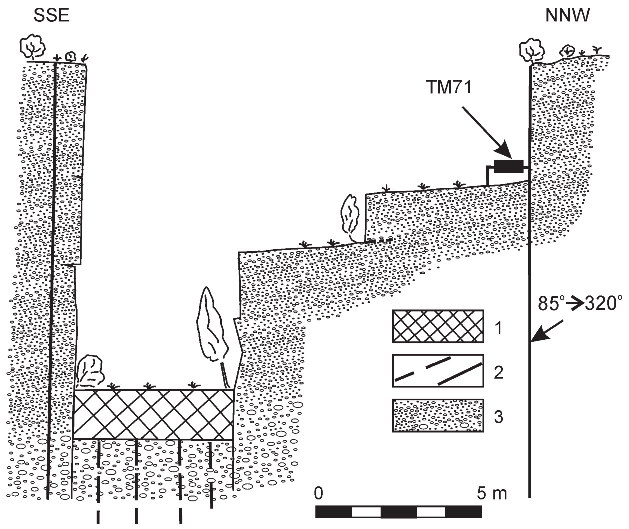

Fig. 4. Situation of Dobrá Voda site with TM71 gauge. **1** — anthropogene sediment, **2** — faults, **3** — Eggenburgian conglomerate.

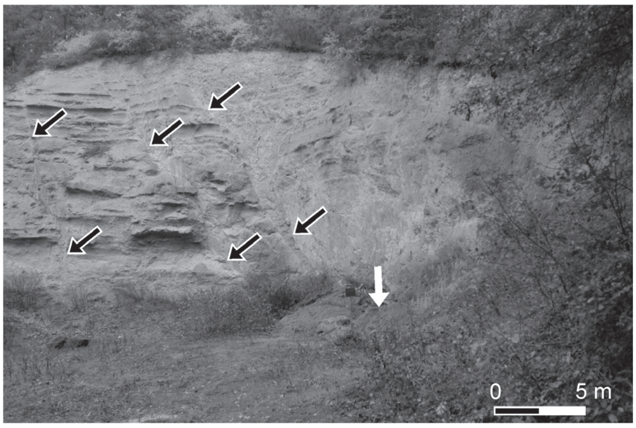

Fig. 5. Prekážka qaurry site with significant faults (black arrows). White arrow shows location of TM71 gauge.

(Fig. 7), produced by GESTRA, Sedloňov, a device tested to suit such special demands (Košťák 1991). This instrument works on the mechanical optical principle (moiré), with results showing any electrical transmission effect. Due to its sturdy body and anticorrosion indicator elements, the equipment becomes very stable in nature, and can survive under harsh long-term outdoor conditions, almost without any maintenance (Košťák 2006). This gauge proved able to survive current moderate seismic events, while showing residual and permanent displacements. It measures spatial displacement between two blocks or discontinuity faces.

The gauge system TM71 represents a combined moiré 3D displacement indicator equipped with 20 to 70 lines/mm circular grids for displacement indication and 100 lines/mm linear grids to indicate angular deviation in two planes (Košťák 1991). In the case of minimum interference of exogene processes, the instrument is able to demonstrate relative spatial movements between two fault faces or two blocks, as low as 0.01 mm/year, and relative angular deviations of up to 0.00032 rad. The gauge TM71 bears Czechoslovak Patents Nos. 131631 and 246454.

In the case of the Dobrá Voda area, the measurements of displacements are taken once per month.

Analyses and discussion of recorded displacements

An interesting fault mechanism in terms of block rotation between boundary strike-slip faults was published by Ron et al. (1984). Later Marko (1991) applied it to interpret Middle Miocene deformations studied in the Brezovské Karpaty Mts. Our observations at Dobrá Voda together with other monitoring points reported here, come to certain details in deformation trends that agree generally with such a mechanism but show a more complex development connected with earthquake preparation period

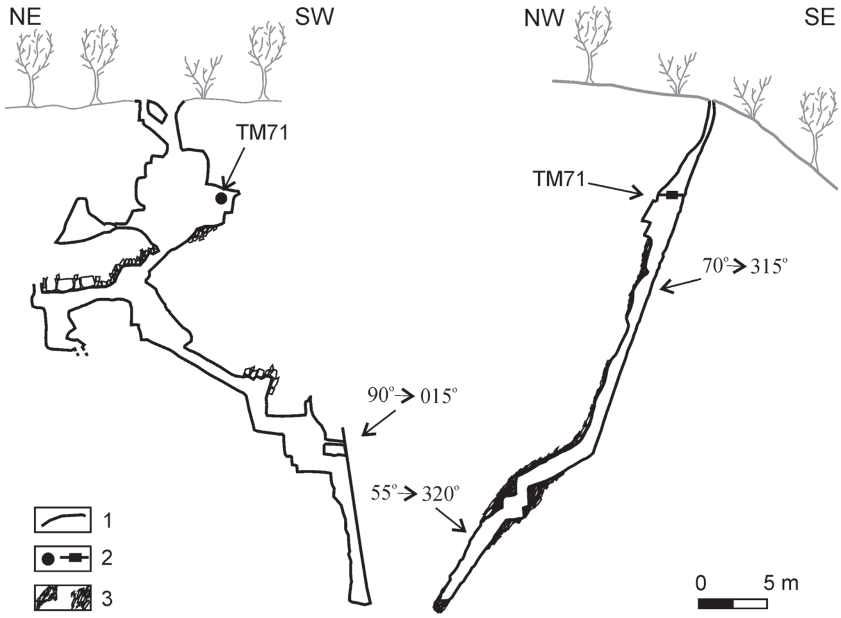

Fig. 6. Vertical profiles of the cave Slopy (documented: Briestenský et al. 2006). **1** — cave spaces, **2** — TM71 gauge, **3** — tectonic breccia.

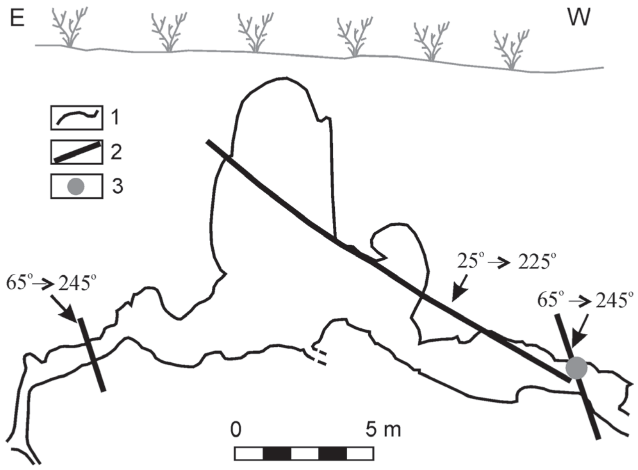

Fig. 7. Vertical profile of the Zbojnícka Cave (documented: Briestenský et al. 2006). **1** — cave walls, **2** — faults, **3** — TM71 gauge.

and post-earthquake return to a relative stabilization. In the following the observation will be demonstrated by key graphs representing the results and will be interpreted with regard to the specific observations that modify the above theory.

Dobrá Voda — Site No. I

From the beginning of monitoring, during two years, measurements were showing low dextral strike-slip displacement trend (0.02 mm/year) along the fault combined with sinistral block rotational trend (0.05 grad/year). Regarding such displacement observation as a phenomenon preceding the quake event of 13 March 2006, the trend may be considered as induced by sinistral strike-slip shear, along the main fault of the Plavecké Podhradie–Dobrá Voda fault zone (see Fig. 13A) that also produce sinistral angular deviations at the fault contact. It corresponds to Marko et al. (1991), which assume that this type of movement should be one of the reasons for blocks rotation, active during the Middle Miocene.

That clear trend sharply changed at the time of the 13 March 2006 earthquake. This change is expressed as fast relative counter micro-rotation of blocks and as a relaxation effect along the fault (see Fig. 9).

Registered angular deviations may prove sinistral strike-slip displacements along the main fault structures, which exert the microblock system to sinistral rotation with dextral strike-slip component at their edges (Fig. 13A). After the earthquake, microblocks are then allowed to make opposite movements — dextral rotation with a sinistral strike-slip component at their edges (Fig. 13B).

Prekážka quarry — Site No. II

Generally, a linear trend of displacement was recorded along the horizontal axis from the start of monitoring. The value of displacement, corresponds to sinistral strike slip movement, and reaches about 0.2 mm during about 1 year of monitoring (y horizontal component). The vertical displacement was calm until the end of January 2006 (z vertical component). Then, a relatively fast acceleration of this displacement was recorded. The value of vertical displacement reached about 0.4 mm during about 1 month. Finally, the vertical displacement z, corresponding to normal faulting, decelerated after 13 March 2006 event (Fig. 10).

Recorded sinistral strike-slip faulting in this area is in full agreement with geological and geophysical studies (Procházková et al. 1986; Marko et al. 1991; Kováč et al. 2001). The sinistral strike-slip regime accompanied by recent earthquake activity and fault-controlled subsidence is documented at the southwestern edge of this fault zone in the Vienna Basin (Hinsch & Decker 2003; Hinsch et al. 2005; Strauss et al. 2006). Strike-slip values monitored at the Prekážka quarry site agree with the computed average values of movement (0.01–0.1 mm/year) along the main fault zones in the close vicinity during the Pliocene–Quaternary period (Kováč et al. 2001) as well. It proves that the movements continue today.

As for the acceleration of vertical displacement recorded about one and half month before the earthquake, this behaviour is discussed in medium-time earthquake prediction theory, using the gauge TM71, and published by Shanov (1993).

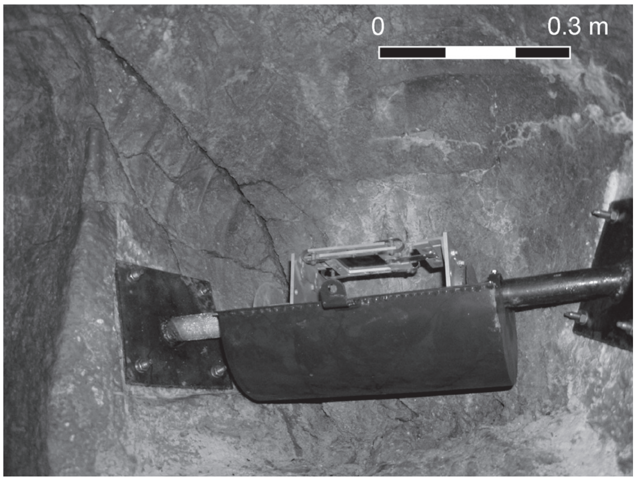

Fig. 8. TM71 gauge installed across 65°→245° failure in the Zbojnícka Cave. Fresh cracks brake sinters in the vicinity of the gauge.

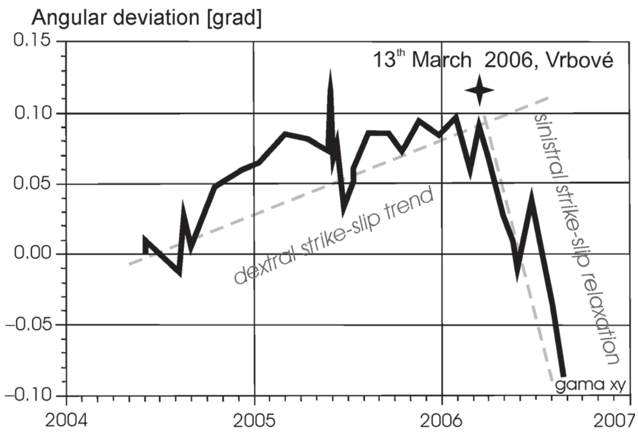

Fig. 9. Block rotation at Dobrá Voda site. **+gama xy** — horizontal fault opening in SW direction (dextral strike-slip movement), **–gama xy** — horizontal fault opening in NE direction (sinistral strike-slip movement).

Slopy Cave — Site No. III

Before the 13 March 2006 earthquake, during the initial period, displacement measurements provided a dextral strike-slip trend (0.1 mm/year) and the fault proved thrusting movement in a SE direction. However, after the quake event strain relaxation allowed for relative backward displacement — relative normal faulting.

Such a development can be well demonstrated by the development observed in angular deviation. Obviously, the record (Fig. 11) displays an abrupt change from a positive to a negative trend.

Yet, later, there appears a peculiar peak in the graph. The peak found in August 2006 (Fig. 11) may raise questions as to what may have happened during that time. It was just during the time of this peak that a swarm of ten microearthquakes with $M_{max}=2.2$ occurred (according to preliminary personal information from J. Sekereš — PROGSEIS f.). The observation of the swarm passed during 5–8 August 2006 and the swarm was located in the close vicinity of the village of Trstín.

Zbojnícka Cave — Site No. IV

Initially, before the earthquake of 13 March 2006, we observed a thrusting trend in a NE direction (Fig. 12), which coresponds to sinistral strike-slip movements in the Dobrá Voda–Plavecké Podhradie wide strike-slip fault zone, as supposed by Strauss et al. (2006). This movement trend stopped about one month before the event.

On the other hand the sinistral strike-slip displacements began about one month before the event (Fig. 12). Both observed displacement effects started before the earthquake and continue until now — September 2006.

The registered sinistral strike-slip displacements agree generally with the results of Strauss et al. (2006) who documented active subsidence in the nearby Pannonian

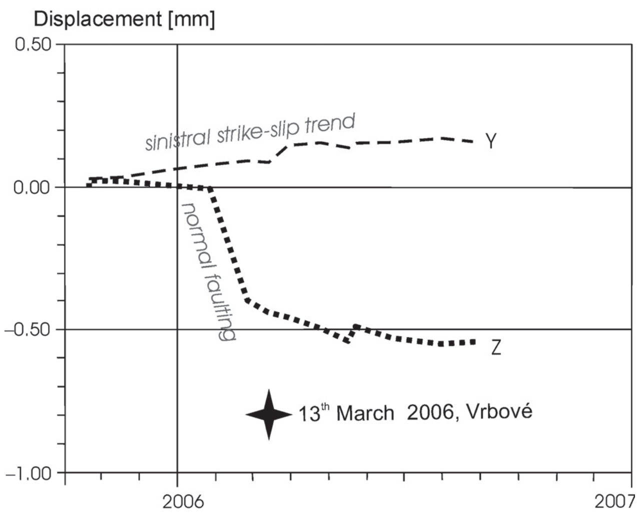

Fig. 10. Displacements observed at Prekážka quarry site. **Y** — strike-slip displacements, **Z** — vertical displacements (subsidence of a SE block).

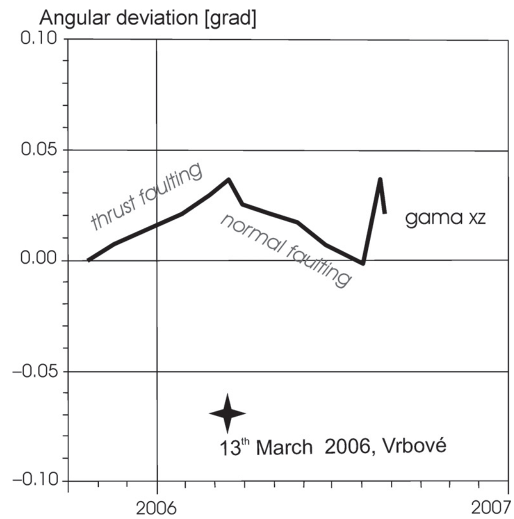

Fig. 11. Block rotation in Slopy Cave. **+gama xz** — vertical fault opening in downward direction (thrust faulting), **–gama xz** — vertical fault opening in upward direction (normal faulting).

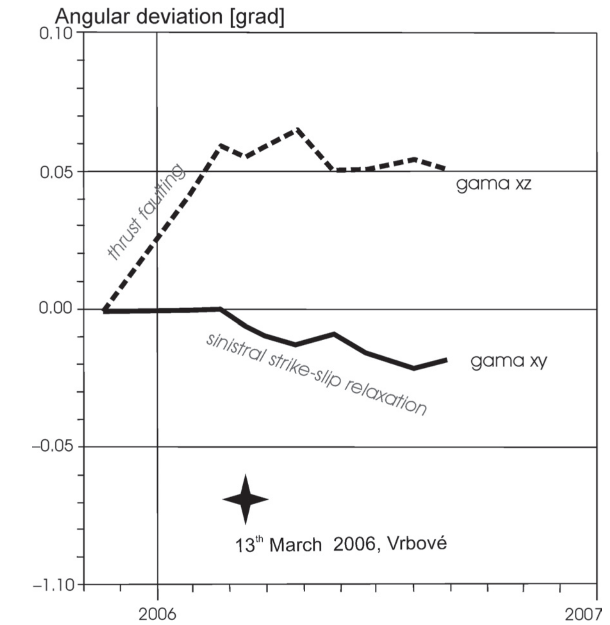

Fig. 12. Block rotations in Zbojnícka Cave. **–gama xy** — horizontal fault opening in E direction (sinistral strike-slip movements), **+gama xz** — upward fault opening (thrust faulting).

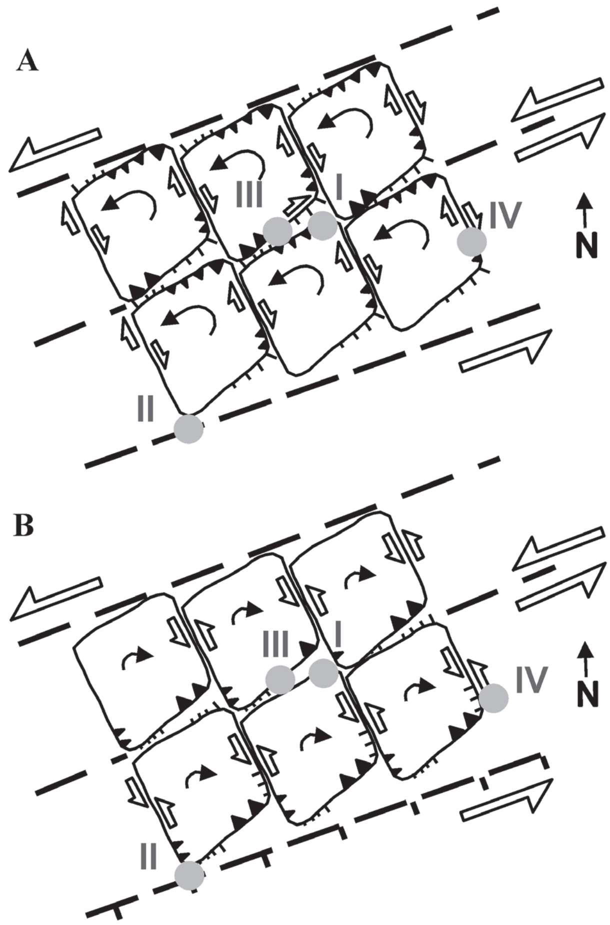

Fig. 13. Model of actuotectonic regime in the Dobrá Voda area. **A** — long-term regime, **B** — short before- and after-quake regime, **I** — Dobrá Voda, **II** — Prekážka quarry, **III** — Slopy Cave, **IV** — Zbojnícka Cave.

Basin, an effect accompanied by rare earthquakes. Thin-skinned thrust types of deformations have been presupposed by Decker et al. (2005) along the Vienna Basin Transform Fault (Mur-Münz-Leitha lineament) terminated in the Carpathians.

Conclusions

Recorded data about displacements and rotations around the 13 March 2006 Vrbové earthquake in the Dobrá Voda epicentral area lead to following conclusions:

— displacements of the order of tenths of mm, as well as angular deviations of up to 0.1 grad were registered in all the gauges installed in the epicentral area during a broader time period when the event occurred;

— specific displacements and angular deviations were recorded not only after the 13 March 2006 quake event but also before it;

— no displacements or angular deviations were observed actually during the event as an immediate effect;

— displacements connected with the earthquake do not need to appear generally at all observation points. The observations concern relative movements between structure walls. Therefore, some points may not be affected because both the opposite walls of the structure under observation will move almost together and the local reaction will be reduced;

— the 13 March 2006 earthquake seems to be a clear breaking point of the behaviour registered in all the monitored sites. That may be explained by strain release or a relaxation process after the earthquake in the epicentral area (see Fig. 13);

— recorded trends of displacements and angular deviations correspond generally to the geological findings reported about the mechanism of recent tectonic movements in the fault zones crossing the studied area;

— in spite of the positive reactions found in the records the authors are aware of the fact that the monitoring period before the event was a little short to confirm the effects and correlations with geological findings unambiguously. Nevertheless, the fact that all the monitoring sites show confirmative reactions, increase their weight.

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