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RECENT MICRO-TECTONIC MOVEMENT FROM THREE KARST CAVES, SLOVENIA

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Abstract: Monitoring of micro-tectonic movement in Postojna cave started in 2004 and in Polog and Kostanjevica caves in 2008. In Postojna cave two TM 71 extensometers, 260 m apart, are installed at the same fault zone, which extends about 1 km north from the Dinaric oriented (NW-SE) Predjama Fault. Since 2004 to the present small tectonic movements are detected, dextral horizontal movement of -0.05 mm for Postojna 1 and extension of -0.03 mm for Postojna 2. But the highest peaks can be of 0.08 mm. Preliminary results in Polog cave, where TM 71 is placed in the vicinity of 1998 (Mw=5.6) and 2004 (Mw=5.2) earthquakes on the Ravne Fault, show -0.08 mm of extension between two limestone beds (from October 2008 to March 2009). From March to May 2009 the movement on *x*-axis returned back to -0.02 mm. The highest trend in Kostanjevica cave was detected as vertical movement along *z*-axis for +0.035 mm from June 2008 to May 2009, representing subsidence of the NW block and uplift of SE block. In all three studied caves the data obtained by TM 71 monitoring are related to active tectonic movements of wider fault zones of Predjama (Postojna cave), Ravne (Polog cave) and Brežice Faults (Kostanjevica cave).

Keywords: micro-tectonic movement, TM 71 spatial extensometer, Postojna cave, Polog cave, Kostanjevica cave, Slovenia.

1. Introduction

Monitoring of micro-displacement in tree Slovene karst caves (Postojna, Polog and Kostanjevica caves) is organized with four TM 71 extensometers. The monitoring in Postojna cave started on 26th May 2004 (Postojna 1) and on 26th February 2004 (Postojna 2). Two instruments, being 260 m apart, are installed within Dinaric oriented (NW-SE) fault zone. The studied fault zone is situated about 1 km north from regionally important Dinaric oriented (NW-SE) Predjama Fault and about 5 km south from Idrija Fault (Fig. 1). The last strongest earthquake (10-20 km SE from Postojna cave) with magnitude of 5.6 (Poljak et al. 2000) was Cerknica earthquake in 1926.

In Polog cave an instrument is installed between two tectonically displaced limestone beds, about 50 m inside the cave from its SE entrance. Monitoring has taken place since 19th June 2008. The cave is situated 250-800 m south from Ravne Fault, that was active during 1998 (Mw=5.6) and 2004 (Mw=5.2) earthquakes (Gosar, 2007). The focal mechanism of both earthquakes shows almost pure dextral strike-slip movement (Kastelic et al., 2008).

In Kostanjevica cave TM 71 is placed inside cross-Dinaric (NE-SW) oriented fissured zone. Regular monthly monitoring is going on since 17th June 2008. The cave is situated 13 km south from the Krško nuclear power plant and about 3 km south from the main northern branch of Brežice Fault, which is determined as active fault (Verbič, 2005).

In Slovenia three additional TM 71 extensometers are placed on the surface within Idrija and Raša Faults and near Ravne Fault (Gosar et al., 2007; Gosar et al., 2009). Some temperature corrections are possible on surface outcrops. Karst caves and artificial tunnels are very suitable for TM 71 installation due to the stable temperature conditions.

The TM 71 monitoring in Slovenia started as part of the COST 625 project (3D monitoring of active tectonic structures) and is continuing within Slovenia-Czech bilateral projects.

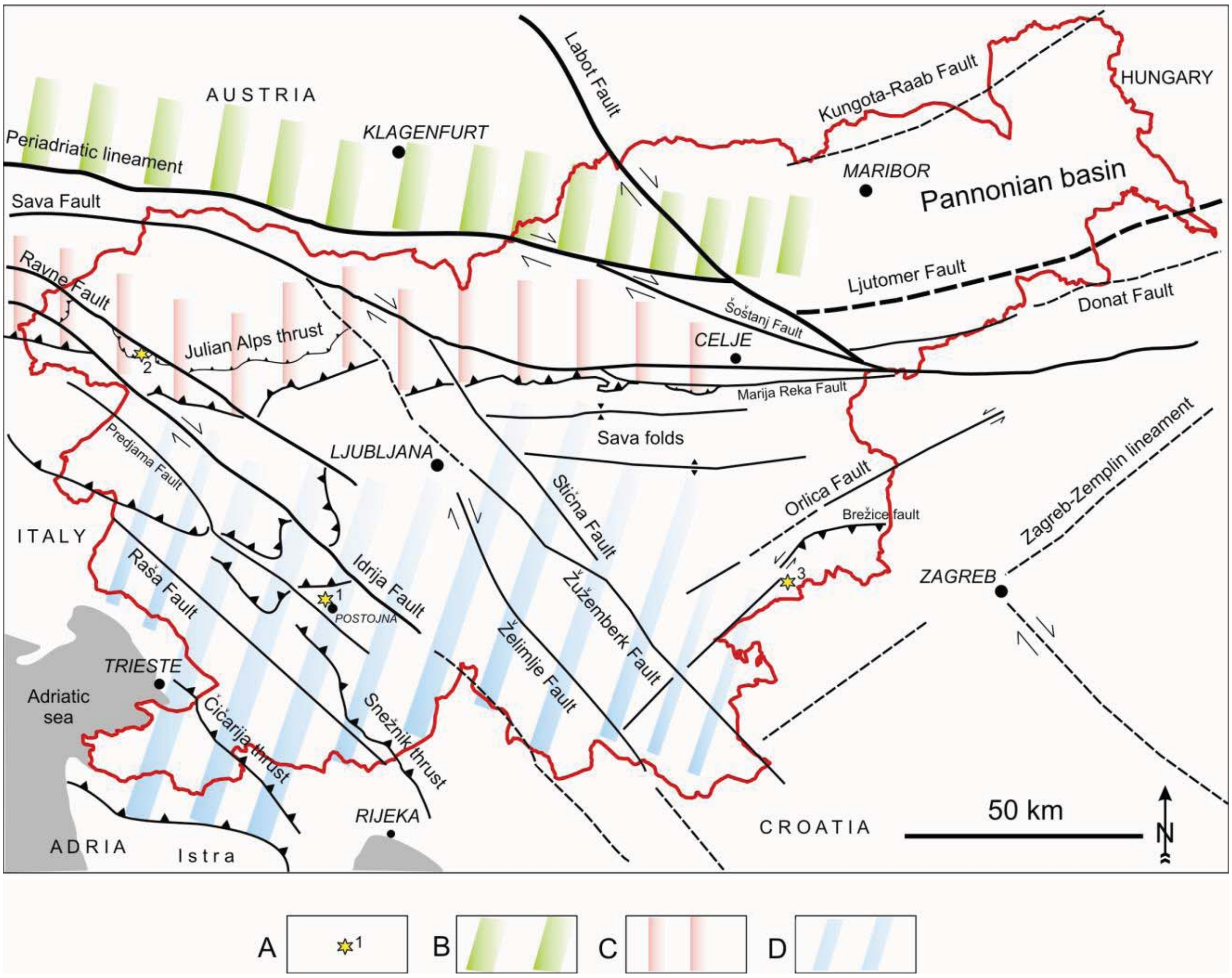


Fig. 1. Structural geology of Slovenia and TM 71 monitoring sites in karst caves. A-monitoring site (1-Postojna cave, 2-Polog cave, 3-Kostanjevica cave), B-Eastern Alps, C-Southern Alps, D-Dinarides. Compiled by S. Šebela after Placer (2008) and Poljak (2000).

2. Structural geology

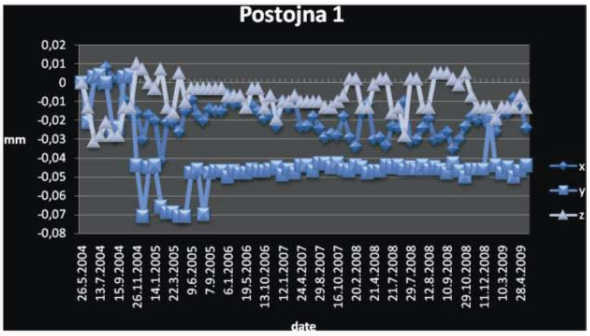
Slovenia is situated at the border between Adria microplate and Eurasia plate and characterized by complex and neotectonically active geological conditions. The studied area including three karst caves is part of Adria microplate south from Periadriatic lineament (Fig. 1). Since the late Miocene to Pliocene paleomagnetic data had indicated about 30° counterclockwise rotation of Adria microplate (Márton et al., 2003).

Regarding geologic structures during Miocene to recent the thrust belts along the Adria margin include Dinaric thrust systems, South-Alpine thrust system and Dinaric faults. Dinaric thrust systems are post-Eocene, representing NW-SE striking fold-and-thrust belt that can be followed from Istra peninsula towards central Slovenia (Vrabec and Fodor, 2006). They belong to External Dinarides that are characterized by moderate historic and recent seismicity.

The S- to SE-verging fold-and-thrust-belt of the Southern Alps formed in the Miocene. Dinaric faults cut and displace both Dinaric and South-Alpine fold-and-thrust structures. Many Dinaric faults, including Idrija Fault, formed as dip-slip normal faults and were only later dextrally reactivated (Vrabec and Fodor 2006).

A large part of regional deformation seems to be still concentrated on Periadriatic lineament as long-lived structural system, whereas the younger structures south of it, such as Dinaric faults, have a comparatively minor role (Vrabec and Fodor, 2006). The GPS-based best-fitting angular velocity vector predicts actual convergence in Dinarides at ≤ 5 mm/year (Weber et al., 2009). Recent seismicity of Raša and Idrija Faults is of the right-lateral strike-slip or reverse type (Poljak et al., 2000). The displacement rates of up to 0.5 mm/year along Idrija and Raša Faults were detected on surface outcrops by TM 71 instruments (Gosar et al., 2009). Predjama Fault is generally not threated as one of important active faults in SW Slovenia. Placer (1999) included Predjama Fault into the outer part of Idrija tectonic zone. Brežice Fault in SE Slovenia was identified as reverse fault on the southern limb of Krško syncline, built up of several reverse faults and backthrusts. The northern branch of Brežice Fault is neotectonic fault with sinistral horizontal movement and vertical reverse movement, uplift of SE block (Verbič, 2005).

Placer (2008) proposed the tectonic subdivision of Slovenia into: Adriatic-Apulian foreland (Istra on figure 1), Dinarides (External and Internal), Southern Alps, Eastern Alps, and Pannonian basin. Postojna TM 71 monitoring sites are located within External Dinarides. Polog cave can be found inside Southern Alps (Fig. 1) and Kostanjevica cave is in transition area between External Dinarides, Internal Dinarides and the Pannonian basin (Placer, 2008).



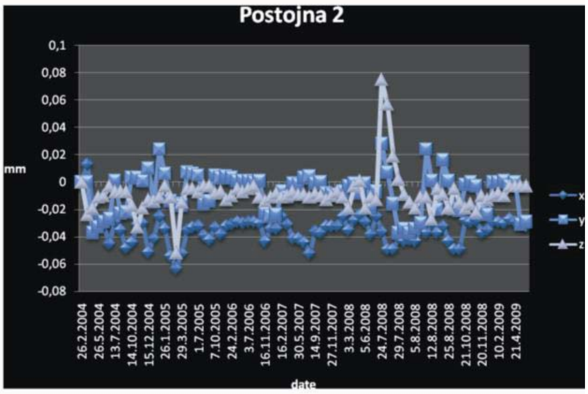


Fig. 2. Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral), +*z* subsidence of northern block (-*z* uplift of northern block)) detected with TM 71 extensometers for Postojna cave (Postojna 1 and Postojna 2 monitoring sites).

3. Methodolgy

TM 71 is a mechanical, optical and spatial extensometer designed for installation on narrow cracks to monitor relative micro-displacements between both walls of the crack. Instrument can be situated on the surface or in the underground. It can be used for measurement of tectonic deformations, slow landslide movements, stability of mine walls etc. The sensitivity of the instrument is 0.05-0.0125 mm in three dimensions *x*, *y* and *z* (Stemberk et al. 2003). Presented in figures 2 and 3, the value of +*x* represents compression of the observed fault (-*x* extension), +*y* represents sinistral horizontal movement (-*y* dextral) and *z* vertical movement.

Monitoring with TM 71 extensometers has been practiced all over the World for more than 30 years (Koš'ták, 1969; Koš'ták, 1991; Koš'ták, 1998; Koš'ták, 2002; Koš'ták et al., 2007; Stemberk et al., 2008a).

In Postojna and Kostanjevica caves data are generally taken once a month or even more frequent. In Polog cave data are taken about 10 times per year due to the difficult uphill access across 1998 coseismic rock falls. To get representative results at least one-year long monitoring is requested.

4. Results and discussion

4.1. Postojna cave

In the longest Slovene karst cave - Postojna cave, the Dinaric-oriented (NW-SE) fault zone has been monitored for micro-deformations with two TM 71 instruments since 2004. The cave (20570 m long and 115 m deep) is developed in Upper Cretaceous limestones. At Postojna 1 monitoring site TM 71 is installed in the contact between fault plane, representing the Velika Gora collapse chamber's northern wall, and a 2x2x1 m collapse block of limestone. Postojna 2 site is an artificially enlarged narrow (1-1.5 m wide) natural cave passage.

The movements obtained from two, 260 m distant, monitoring sites in Postojna cave are small (Fig. 2), but there are some interesting peaks (maximum for 0.08 mm on both monitoring sites) and very stable periods with almost no movements (Postojna 1 and 2 *y*-axis from the end of 2005 to 2008) what supports our hypothesis of monitoring the real tectonic micro-displacements, excluding other causes as influence of karst water oscillation or karst collapses.

Responses to Earth's stress changes regarding *x*, *y* and z-axes are not the same on two monitoring sites in the cave, even though monitoring the same fault zone. Generally we detect dextral horizontal movement of -0.05 mm from 2004 to the middle of 2009 for Postojna 1 and extension of -0.03 mm from 2004 to the middle of 2009 for Postojna 2 (Fig. 2).

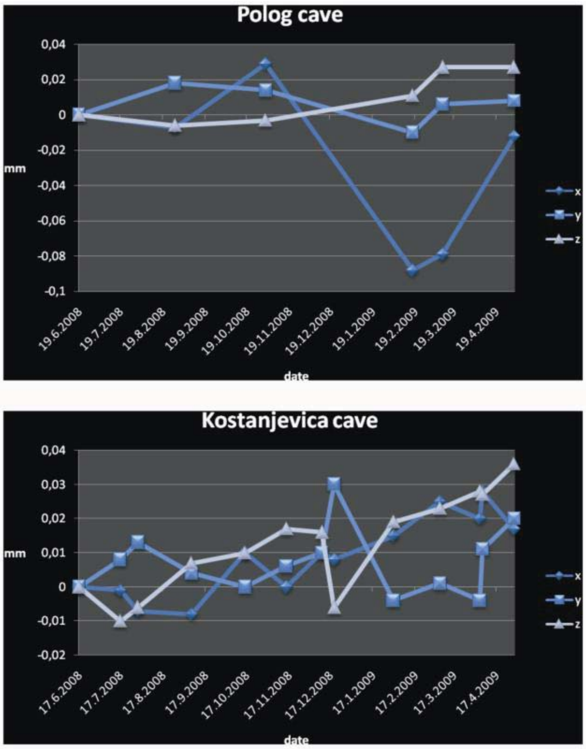


Fig. 3. Relative displacements detected with TM 71 extensometer for Polog cave (+x compression (-x extension), +y sinistral horizontal movement (-y dextral), +z uplift of NW block (-z subsidence of SE block)) and for Kostanjevica cave (+x compression (-x extension), +y sinistral horizontal movement (-y dextral), +z uplift of SE block (-z subsidence of NW block)).

Within the y-axis on Postojna 1 the biggest movement of –0.08 mm (dextral horizontal movement) from 10th November 2004 to 15th December 2004 was registered. The movements generally relatively return back to the previous position. The only well expressed permanent step (dextral horizontal movement) remained on Postojna 1 y-axis after August 2005. The results at Postojna 1 show that the collapse blocks cemented by flowstone in Velika Gora chamber are tectonically very stable.

Postojna 2 site showed the highest movements between July and September 2008, horizontal movement of 0.06 mm maximum, changing from sinistral to dextral and relatively returning back to null position, and the best expressed peak on z-axis of +0.08 mm (24-25th July 2008, uplift of southern block).

Due to some different behavior between Postojna 1 and 2 monitoring sites we assume that monitoring shows some local deformations as well. This is in accordance with Kontny et al. (2005) who described probable movement of a particular rock-block at monitoring sites in Polish Sudeten. But on the other hand at least one axis, although different, is comparable between two monitoring sites in Postojna cave (Šebela et al., 2009). Additionally we envisage the detection of general displacements due to changes in regional stress regime, as was described by Stemberk et al. (2008b) in Upper Rhein graben during longer period.

Differences in displacements between two monitoring sites of Postojna cave can be explained by complex geological structure of the cave, representing principal Dinaric (NW-SE) and cross-Dinaric (NE-SW) oriented Fault zones with wider fissured to broken zones among them (Šebela, 1998). Between both monitoring sites the studied Dinaric Fault zone is cut by cross-Dinaric Fault zone (NE-SW) that might transmit some deformations causing differences between Postojna 1 and 2 sites (Gosar et al., 2007).

4.2. Polog cave

The cave is developed in Upper Triassic bedded Dachstein limestone T_3^{2+3} (Buser, 1986). Its upper entrance is situated at 1249 m and lower entrances at 730 m above sea on the eastern slope of Krn Mountains (2244 m). Cave's passages, being 10800 m long and 704 m deep, are situated 250-800 m south from Ravne Fault. The TM 71 is placed between two tectonically displaced limestone beds dipping towards SE for 40°, about 300 m south from Ravne Fault and about 50 m inside the cave from the eastern of the lower entrances. The important regional structure of Julian Alps thrust (SE-verging and parallel to monitored bedding-plane) within Southern Alps geotectonic unit (Poljak, 2000) can be found about 200 m below the monitoring site. According to Poljak (2000) the contact between geotectonic units of Southern Alps over the Internal Dinarides is situated about 4.5 km south from our monitoring site. In the sense of Milanič et al. (2009) and Rižnar et al. (2007) recent tectonic activity was determined for Julian Alps thrust and for Southern Alps thrust unit.

Results of displacements for Polog cave are preliminary. The highest displacement was detected in

x-axis, being of -0.08 mm (Fig. 3) and representing horizontal opening between two limestone beds in the period from October 2008 to March 2009. From March to May 2009 the movement on x-axis relatively returned back to -0.02 mm. Taking into account that cave temperature at the monitoring site varies (2nd November 2008 = 6 °C and 17th February 2009 = 1 °C), the observed displacement can be connected with temperature changes, as well. But on the other side the activity of bedding-plane is well visible in the cave passage that is displaced for about 5 cm. According to the position of Polog cave being south from Ravne Fault and above the Julian Alps Thrust, the results of detected movements with TM 71 represent active deformations of the transition zone between both tectonically active zones.

4.3. Kostanjevica cave

Kostanjevica cave is the longest cave (1871 m long and 47 m deep) on northern slope of morphologically well expressed Gorjanci Mountains with the highest peak of 1178 m. Cave entrance is at 170 m a.s.l. and above monitoring site there is 70 m of the limestone roof. The cave entrance represents the upper occasionally still active outflow of Studena stream that flows towards north to Krka River. Entrance parts of Kostanjevica cave are developed in Lower Cretaceous bedded limestones (Pleničar et al., 1975). TM 71 instrument is installed 125 m inside the cave in cross-Dinaric (NE-SW) oriented fractured zone that is dipping towards NW for 80°. The monitored tectonic zone is situated about 3 km south from main northern branch of Brežice Fault, which is determined as neotectonic fault with sinistral horizontal movement and vertical reverse movement, uplift of SE block (Verbič, 2005).

Preliminary results of micro-displacements for Kostanjevica cave include data since 17th June 2008 to the middle of 2009. There are movements along all three axes with the highest trend for vertical movement along z-axis for +0.035 mm, representing subsidence of the NW block and/or uplift of SE block (Fig. 3) what is in accordance with Verbič (2005). Some horizontal movement (y-axis) and general extension (x-axis) are presented as well.

5. Conclusions

In three Slovene karst caves (Postojna, Polog and Kostanjevica caves) moderate active tectonic micro-displacements are detected with four TM 71 extensometers. Both Postojna cave monitoring sites (Fig. 2) are very stable with small tectonic movements, being general dextral horizontal movement of -0.05 mm from 2004 to 2009 (Postojna 1) and extension of -0.03 mm for Postojna 2, with two significant peaks of 0.08 mm (Postojna 1-y and Postojna 2-z). Results of Polog cave and Kostanjevica cave (Fig. 3) are preliminary. The highest displacement in Polog cave represents extension (x-axis) between two limestone beds of -0.08 mm in the period of half a year (from October 2008 to March 2009). From March to May 2009 the movement on x-axis relatively returned back to -0.02 mm. The highest trend in Kostanjevica cave was detected as vertical movement along z-axis for +0.035 mm from June 2008 to May 2009, representing subsidence of the NW block and/or uplift of SE block (Fig. 3).

Taking into account numerous TM 71 monitoring studies in other countries (Koš'ták et al., 2007, Kontny et al., 2005) and regarding the data obtained from surface TM 71 monitoring in Slovenia (Gosar et al., 2009), we determined that also in Postojna, Polog and Kostanjevica caves the data of TM 71 monitoring represent active micro-tectonic movements induced by changes in regional stress field.

Paralleling well-expressed micro-movements detected by TM 71 with earthquakes have been described by several authors (Košťák et al., 2007; Stemberk et al., 2008a; Briestenský et al., 2007; Kontny et al., 2005, Shanov, 1993, Gosar et al., 2009). According to the Košťák's hypothesis a strong earthquake would respond to temporary changes in the Earth's crust stress field detectable in the readings of sensitive extensometer instruments (Košťák, 1998; Košťák, 2002).

Although Postojna cave is not situated on a seismically very active area so far, it is close to Snežnik Mountain area, which is one of the most active zones in Slovenia. At the end of July 2008 the highest peak of +0.08 mm at Postojna 2 z-axis (Fig. 2) was detected and about 2.5 months later Pivka earthquakes (M=3.1, M=2.3 and M=1.7) occurred only 12 km south from Postojna 2 monitoring site (Gosar et al. 2009).

The TM 71 instrument in Polog cave is placed in the near vicinity of 1998 (Mw=5.6) and 2004 (Mw=5.2) earthquakes (Gosar 2007) on Ravne Fault and is thus important for studies of recent tectonic activity in the wider area of Ravne Fault.

Monitoring of tectonic displacement in Kostanjevica cave is interesting for understanding the active tectonic conditions in Krško valley and for Krško nuclear power plant being 13 km to the north from TM 71 monitoring site in Kostanjevica cave.

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