DIRECT MEASUREMENT OF PRESENT-DAY TECTONIC MOVEMENT AND ASSOCIATED RADON FLUX IN POSTOJNA CAVE, SLOVENIA

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Abstract: Micro-tectonic deformations have been monitored continuously in 3D in Postojna Cave, Slovenia with TM 71 extensometers since 2004. Two instruments, 260 m apart, were installed on the Dinaric oriented (NW-SE) fault zone that is situated about 1,000 m north of the inner zone of the regionally important Predjama Fault. Monitoring on both instruments has shown small tectonic movements (i.e., a general dextral horizontal movement of 0.05 mm in four years [Postojna 1] and extension of 0.03 mm in four years [Postojna 2]). Between the longer or shorter calm periods, eleven extremes have been recorded regarding characteristic changes in displacement. The largest short-term movement was a compression of 0.04 mm in seven days, detected in March 2005, which coincided with the 25 km distant Ilirska Bistrica earthquake (M_L = 3.9). About two months before the earthquake an extension of 0.05 mm occurred and one month before the earthquake the strain changed into a compression of 0.05 mm. The largest permanent peak was detected at the end of 2004. Along the *y*-axis (Postojna 1) there was a dextral horizontal movement of 0.075 mm in one month (November 10 to December 15, 2004). After the sinistral horizontal movement of 0.02 mm (December 15–27, 2004), the *y*-axis retained its permanent position on 0.05 mm, where it remained for more than a year. Regarding the extremes, ten earthquakes were selected that coincided with tectonic micro-displacements. In terms of speleogenesis, the monitored fault zone represents a stable cave environment. Because radon flux is known to change significantly during tectonic and seismic activities, radon air concentrations were monitored in parallel since 2006. During horizontal movements, either dextral or sinistral, radon pathways underground were partly closed, thus hindering radon migration and reducing its concentration in the cave air. Extension movements do not appear to have affected radon transport. Alternatively, the compression process (Postojna 2, February–August 2007) appears to have opened some new routes for radon transport, facilitating radon migration and increasing its concentration in air.

INTRODUCTION

Caves are very special environments where traces of different speleological events can be preserved for over 10^6 years. However, caves are also dynamic environments. Karst waters forming underground passages use preferentially structural geological elements such as bedding planes, especially slipped bedding planes, fissures, faults, folds, etc. (Knez, 1996; Šebela, 1998; Kogovšek and Šebela, 2004; Šebela et al., 2004; Petrič and Šebela, 2004). In most studied cases, geological structures guiding the caves are no longer active. Some examples of active tectonics in karst described from different countries are included in Bini et al., 1992; Gilli and Delange, 2001; Mocchiutti and D'Andrea, 2002; and Plan et al., 2005.

Active tectonic structures in Postojna Cave have been monitored with TM 71 extensometers since 2004 (Šebela, 2005; Šebela et al., 2005; Gosar et al., 2007). Our goal was to detect the size and mechanism of tectonic movements along a well-expressed fault zone in the longest Slovenian cave and to evaluate the coincidence with seismic activity in that karst massif.

Beginning in 2006, we extended our study to include radon (^{222}Rn) as an indicator of tectonic and seismic activity. This radioactive noble gas originates from radioactive decay of ^{226}Ra in the ^{228}U radioactive decay chain in the Earth's crust. Only a fraction of the radon atoms created in a mineral grain emanate into the void space between grains, where they are dissolved either in water or in carrier gases, such as helium or nitrogen, and are thus transported by advection toward the ground surface and the atmosphere (Nero, 1988). This transport is influenced by a number of geophysical and geochemical parameters (Etiope and Martinelli, 2001).

Because in the area of faults the material is crushed, and hence more permeable to radon, the level of radon activity, either in the outdoor air or in soil gas at a fault, is generally

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elevated. Changes in fault activity result in changing radon levels (Virk et al., 1997; Wu et al., 2003). In addition, the phenomena preceding and accompanying an earthquake can significantly change the radon pathways underground and thus govern radon levels appearing at the surface (Etiope and Martinelli, 2001). Thus, if radon is monitored in the outdoor air, soil gas, or thermal water, and a long-term time series of the resulting data is analyzed, in addition to regular fluctuations in radon levels ascribed to the effects of environmental conditions (e.g., temperature, barometric pressure), some anomalous increases or decreases in radon level may be observed and attributed to seismic events (Etiope and Martinelli, 2001).

In this study, radon was monitored continuously in Postojna Cave, together with measurements of micro movements. Micro tectonic movements and radon concentrations in air, observed at two sites at the Dinaric oriented (NW-SE) fault in the Postojna Cave, are examined in relation to seismic activity in the area. This is the first such comparative study between micro tectonic movements and radon air concentration to be investigated in a cave in Slovenia.

GEOLOGY AND SEISMICITY OF THE STUDY AREA

Slovenia is situated in the NE corner of the Adria-Europe collision tectonic zone. The Istria Peninsula (Fig. 1) contains the only outcrop of Adria microplate in the northern Adriatic region. The thrust belts of the Dinarides and Southern Alps form a rim of high topography around Adria. Major Dinaric (NW-SE) strike-slip faults cut and displace fold and thrust structures. Slovenia has considerable seismicity (Vrabec and Fodor, 2006), and this complex and neotectonically active region is of special interest because of the Classical Karst-Kras area (Fig. 2A).

Paleomagnetic data indicate that the motion of the Adriatic microplate has been associated with an approximately 30° counterclockwise rotation (Márton et al., 2003) since the late Miocene or Pliocene. GPS measurements suggest sharp (some mm/year) dextral (transpressive) movements along the Sava Fault and Periadriatic Lineament (Fig. 1), showing that the side intrusion in the northeast Alps is still active (Weber et al., 2004).

The strongest earthquakes that have occurred in Slovenia in recent years were situated along the Ravne Fault (Bajc et al., 2001; Kastelic and Cunningham, 2006). Slovenia is considered to exhibit moderate seismicity, and the External Dinarides (Fig. 1), in particular, are characterized by moderate historic and recent seismicity. Regarding the fault plane solutions, it is evident that the governing stress in the region runs in an approximate N-S direction (Poljak et al., 2000).

According to a geological interpretation based on the analysis of repeated levelling line campaigns data along the Sečovlje-Bled polygon in western Slovenia, the active
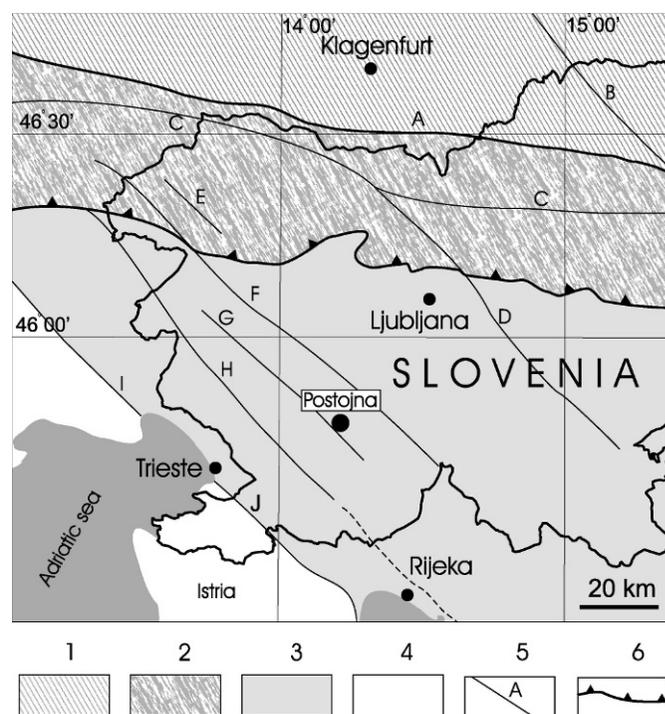
Figure 1. Tectonic situation of W Slovenia. 1-Eastern Alps (Alps), 2-Southern Alps (Dinarides), 3-External and Internal Dinarides, 4-Adriatic foreland, 5-Faults (A-Periadriatic Lineament, B-Labot Fault, C-Sava Fault, D-Stična Fault, E-Ravne Fault, F-Idrija Fault, G-Predjama Fault, H-Raša Fault, I-Palmanova Fault, J-Karst thrust edge), 6-Southalpine thrust front (after Poljak, 2007 and Placer, 1999).

tectonic structures (vertical movement) include at a minimum: a juvenile syncline between Strunjan and Koper, the Kras (Fig. 2A) Imbricate Structure, The Divača Fault, the Raša Fault, the Southalpine Front (Fig. 1), and the Julian Alps thrust (Rižnar et al., 2007). The Ravne Fault was responsible for the 1998 (M_W = 5.6) and 2004 (Krn, M_W = 5.2) earthquakes and appears to be an outstanding example of an actively propagating strike-slip fault cutting through pre-existing mountainous terrain (Kastelic and Cunningham, 2006).

LiDAR mapping to image seismogenic strike-slip faults in the Julian Alps in Slovenia was performed along the Idrija and Ravne Faults (Cunningham et al., 2006). One site (Kapa) in the Idrija LiDAR survey area may indicate some surface rupturing and other landscape features typically associated with strike-slip faulting. The Tolminka springs basin on the Ravne Fault is an example of a localized and active transtensional basin constructed within an overall transpressional system (Cunningham et al., 2006).

The strongest seismic event in the last 100 years around Postojna was the Cerknica earthquake (1926) (M_m = 5.2) that probably originated on the Idrija Fault (Ribarič, 1982). The epicenter was 10 km east of Postojna. The
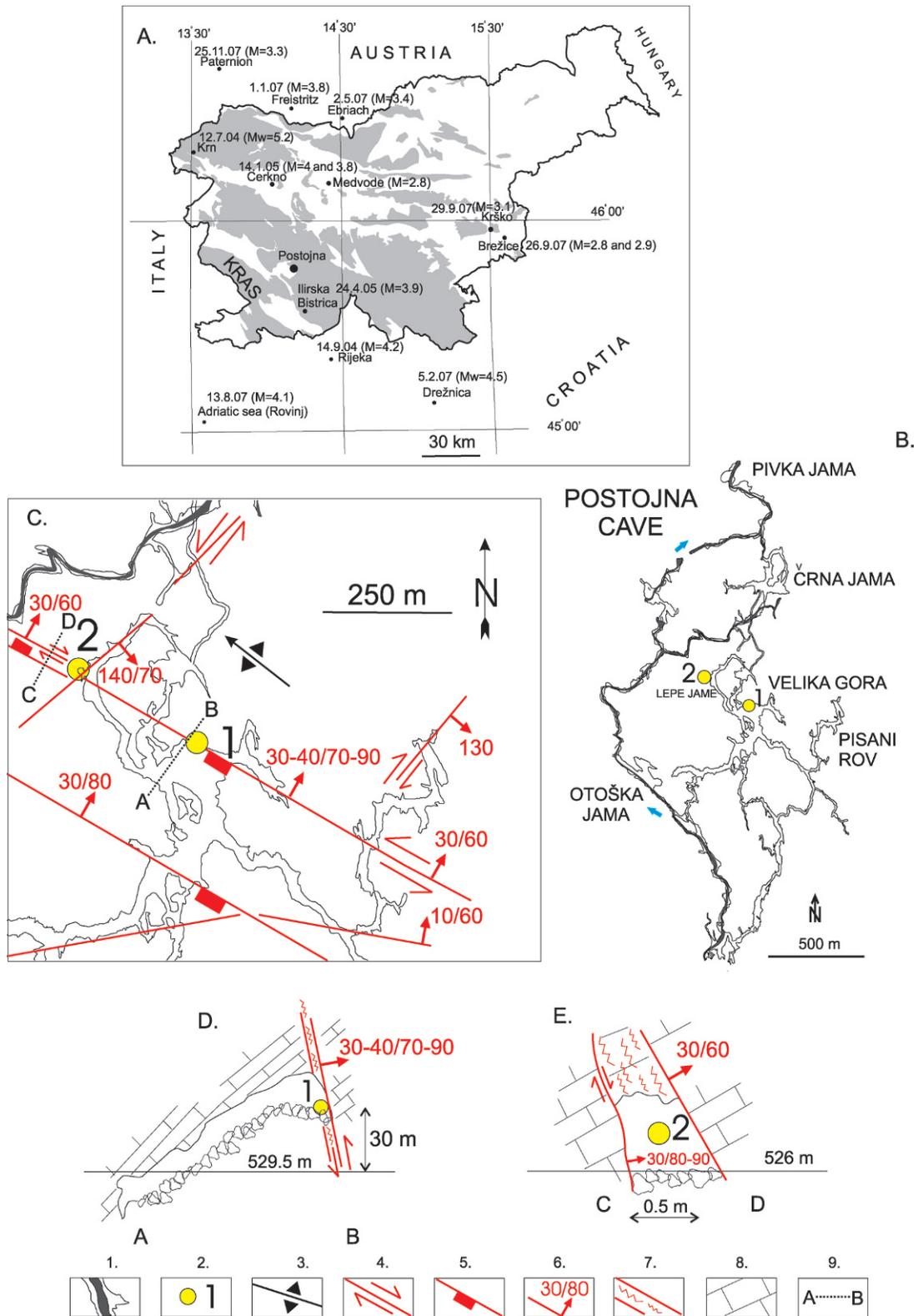
Figure 2. Tectonic structure of Postojna Cave. A.-The position of Postojna and Kras in Slovenia with epicenters of the stronger earthquakes. Grey areas are karst outcrops, B.-The passages of Postojna Cave with monitoring sites (1-Postojna 1, 2-Postojna 2), C.-Structural-geological map of the monitoring sites, D.-AB cross section, E.-CD cross section, 1-Underground river Pivka, 2-Monitoring sites: 1 (Postojna 1) and 2 (Postojna 2), 3-Postojna Anticline, 4-fault with horizontal (dextral) displacement, 5-fault with vertical displacement, 6-strike and dip of fault, 7-fault zone, 8-Upper Cretaceous limestone, 9-cross section.

newspaper *Edinost* (Anonymous, 1926) reported that in Postojna Cave a large stalagmite, one meter in diameter, collapsed due to the earthquake.

Experimental Setting

Site Description

The Postojna Cave (Fig. 2B), with 20 km of galleries, is the longest known cave system in Slovenia. The passages are developed in an approximately 800-m-thick package of Upper Cretaceous bedded limestones (Šebela, 1998).

The cave is situated between two important Dinaric faults, the Idrija Fault on the north and the Predjama Fault on the south (Fig. 1). The tectonic structure of the area between these faults is characteristic of a transition zone between two dextral strike-slip faults. In Postojna Cave, we can distinguish older overthrusting and folding deformations and younger faulting deformations. Overthrusting took place after the deposition of Eocene flysch. During the Miocene and Pliocene, the overthrusting was accompanied by folding. The principal folding deformation in the cave is the Postojna Anticline. Cave passages are developed in both flanks of the anticline (Fig. 2C) and follow the strike and dip of the bedding-planes, especially those with interbedded slips (Čar and Šebela, 1998).

The northern edge of Velika Gora (Fig. 2C and 2D) is developed along the Dinaric oriented (NW-SE) reverse fault zone, with traces of vertical displacement for some meters (Fig. 2C, monitoring site Postojna 1). The same fault zone from Velika Gora can be traced in some parts of the cave, but other parts do not exhibit the same tectonic characteristics. In the SE part of the cave, a horizontal sinistral movement with 60° dip angle for fault zone NW from Velika Gora is observed. The same fault zone exhibits vertical and horizontal displacements (Fig. 2C, monitoring site Postojna 2) and is cut by the cross-Dinaric fault zone (Sasowsky et al., 2003). Different tectonic activities are observed on the same Dinaric-oriented fault zone, sometimes with four individual tectonic phases.

The locations for installation of the extensometers in Postojna Cave were selected to evaluate if the monitored fault is tectonically active and to determine whether the tectonic activity has any influence on speleogensis. The two devices were installed in the same fault zone but on different fault planes. Postojna 1 was installed at the contact point between a fault plane (dip angle 70–90° to the NE) and a collapse block, partly covered with flowstone (Figs. 2D and 3). The second device (Postojna 2) was installed in a narrow natural passage, which was enlarged artificially 30-years-ago, between two fault planes that are about one half meter apart (Figs. 2E and 4). The northern fault plane dips to the NE at 60° and has horizontal striation, representing dextral movement. The southern one constitutes the normal fault, dipping towards the NE by 80–90° and shows vertical striation. The fault zone being monitored is about 1,000 m north of the inner zone of the

Figure 3. Monitoring site Postojna 1 with TM 71 instrument (photo S. Šebela).

Predjama Fault (Fig. 1). Postojna 1 is 68 m below ground surface and Postojna 2 is 60 m below ground surface and about 1,400 m from the entrance to the cave.

Measurement Techniques

Measurement of Micro Movements

We employed a TM 71 extensometer, developed by Blahoslav Košťák (Košťák, 1969). This is a mechano-optical instrument that measures displacement in three dimensions (*x*, *y* and *z*). It works on the principle of the Moiré optical effect, which changes when two transparent plates move (Košťák, 1977; 1991). Each plate is fixed into the outcrop of a fault plane or fissure. The instrument is very robust and simple, and needs no source of energy. This is good for long-term observations under varying

Figure 4. Monitoring site Postojna 2 with TM 71 instrument (photo S. Šebela).

meteorological conditions (Avramova-Tacheva and Koš-ťák, 1995). The characteristic of the TM 71 is long-term measurement of movements accurate to within 0.01 mm.

Measurements at Postojna 1 began May 26, 2004 and at Postojna 2 on February 26, 2004. The instruments are set permanently at the sites and their readings are taken generally once a month. Because the cave temperature is stable throughout the year (9 °C to 11 °C), any influence of temperature on data records can be disregarded. The measurements have an evaluation accuracy of 0.01 mm in all three displacement co-ordinates, x, y and z.

MEASUREMENT OF RADON

Barasol probes (MC-450, ALGADE, France) were used during the first two years, and then replaced by Radim 5 WP monitors (SMM Company, Prague, Czech Republic). The Barasol probe is designed primarily for radon measurements in soil gas. The probe gives radon concentration, based on alpha spectrometry of radon decay products in the energy range of 1.5 MeV to 6 MeV using an implanted silicon detector. The detector sensitivity is 50 Bq m^{-3} with a sampling frequency of four times an hour. In addition to radon concentration, the probe also records temperature and barometric pressure. The Radim 5 monitor is used mostly for radon measurements of indoor air. It determines radon concentration by measuring gross alpha activity of the decay products ^{218}Po and ^{214}Po, collected electrostatically on the surface of a semiconductor detector. The sensitivity is about 50 Bq m^{-3} and the sampling frequency is twice an hour. Data are stored in the inner memory of both instrument and then transferred to a personal computer for further evaluation, usually once every two months. Instruments are checked regularly, using a portable AlphaGuard radon monitor (Genitron, Germany) as a reference instrument. Radon measurements were collected from the beginning of April through October 2007 at Postojna 1 (Fig. 7) and from October 2006 through October 2007 at Postojna 2 (Figs. 8 and 9).

Hourly average values of the outdoor air temperature at the Postojna meteorological station were obtained from the Office of Meteorology of the Environmental Agency of the Republic of Slovenia. Data on seismic events were obtained from the Office of Seismology of the same Agency. We considered only those earthquakes for which the magnitude M_L was higher than 2 and the distance R between our measurement site and the epicenter was less than 3 times Dobrovolsky's (Dobrovolsky et al., 1979) radius R_D, defined by $R_D = 10^{0.43 \times M_L}$. Origin 6.1 Data Analysis and Graphing Software were used for statistical data evaluation and presentation.

RESULTS AND DISCUSSION

MICRO DISPLACEMENTS

The measurement results include three coordinates, x, y, z, which are principally perpendicular to the observed fault

zone (i.e., $+x$ represents compressive movement of the monitored fault zone, $+y$ represents sinistral-lateral movement, and $+z$ vertical movement) relative shear in the fault: N subsidence or S uplift. Displacements recorded at both sites (Figs. 5 and 6) are generally small, the range of movements being within 0.1 mm ($+0.02$ to -0.075). The plots show a number of sharp peaks. However, the development of such peaks in individual coordinates generally could not be matched between the two monitored sites. Some peaks are thus due to records close to the limits of recording accuracy. A certain similarity, however, can be observed between the two sites regarding the trend of development and periods of unrest. The total length of the displacement vector at each of the two sites developed parallel increasing short-term trends of about 0.1 mm yr^{-1} in the period July 2004–March 2005; later the trend fell to zero.

Detailed analysis of the individual coordinates show evidence of some periods of unrest alternating with more quiet periods. Movements detected in the y- and z-axes for both instruments were simultaneous, which suggests real tectonic movements. In general, unrest was recorded from the start of measurements at the beginning of 2004 until about March 2005, and then again during the period from October 2006 to January 2008.

Extremes (E) of the periods of unrest (Figs. 5 and 6) are indicated at the following periods/sites/coordinates/dates:

(a) E1: Postojna $2/x \rightarrow -0.055$ mm/March–June 2004 (March 11 to June 29, extension; June 29 to July 13, compression; Krn earthquake July 12, 2004);
E2: Postojna $1/z \rightarrow -0.03$ mm/May–June 2004;

(b) E3: Postojna $1/x \rightarrow -0.04$ mm/July 30 to December 15, 2004 (extension); $x \rightarrow -0.02$ mm/December 27, 2004 to January 26, 2005 (extension);
E4: Postojna $1/ y \rightarrow -0,075$ mm/November 10, 2004 to December 15, 2004 (dextral horizontal movement); December 15 to December 27, 2004 (sinistral horizontal movement)-permanent change of 0.05 mm;
E5: Postojna $2/ z \rightarrow -0.03$ mm/September–November 2004;
E6: Postojna $2/z \rightarrow -0.05$ mm/February–March 2005 ($+0.04$ mm in 7 days);
E7: Postojna $2/x \rightarrow -0.04$ mm/January–March 2005; January 14 to March 22, 2005 (extension); March 22 to May 6, 2005 (compression); Ilirska Bistrica earthquake April 24, 2005;
E8: Postojna $2/y \rightarrow -0.04$ mm/January–March 2005; January 14, to February 23, 2005 (dextral horizontal movement); March 29 to May 6, 2005 (sinistral horizontal movement); Cerkno earthquakes January 14, 2005; Ilirska Bistrica earthquake April 24, 2005;
E9: Postojna $1/z \rightarrow -0.02$ mm/January–March 2005; (the value in the error limit);

(c) E10: Postojna $2/y \rightarrow -0.025$ mm/October 2006–January 2007; October 13 to November 16, 2006
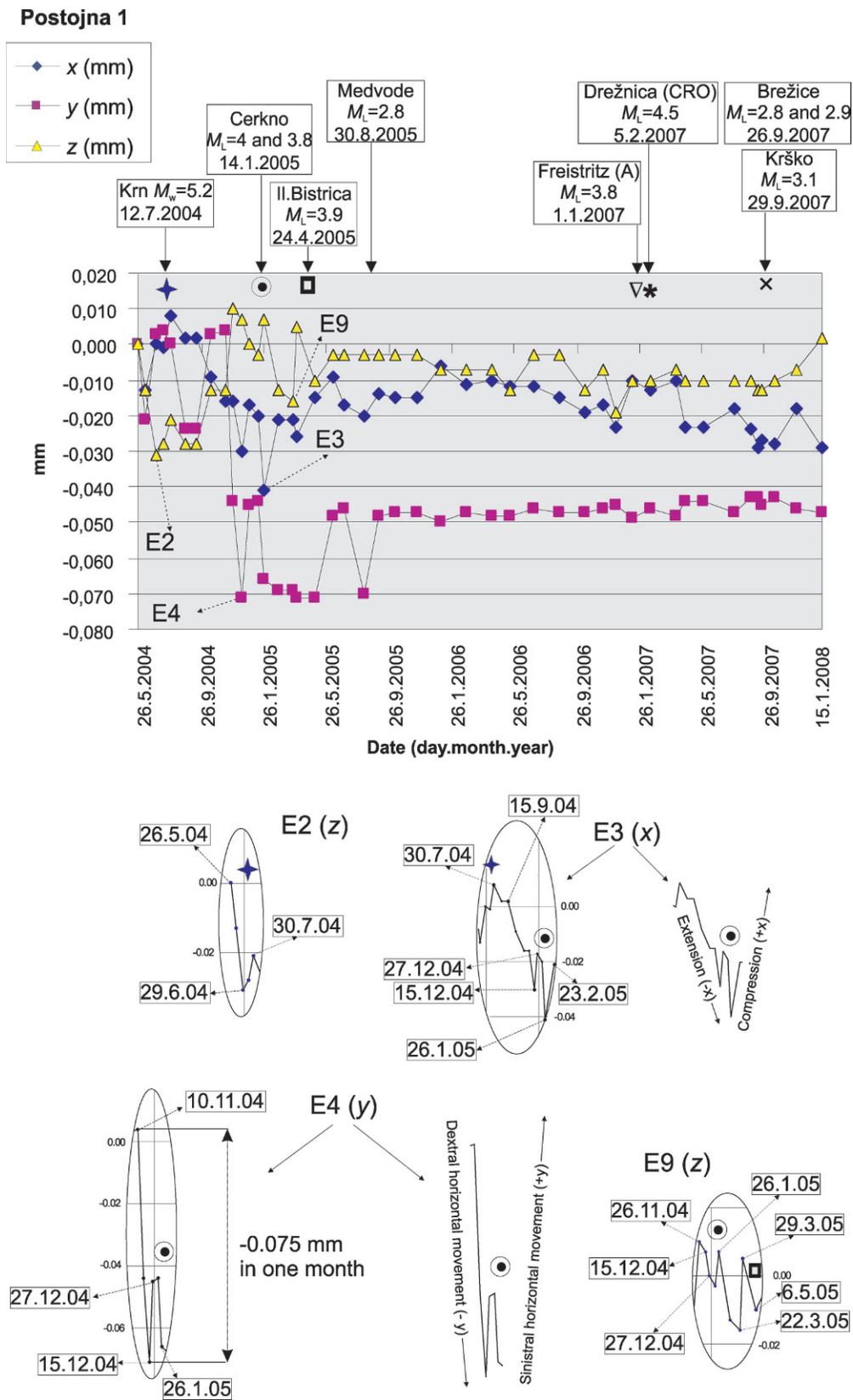
Figure 5. Displacements recorded by TM 71 at Postojna 1 monitoring site.
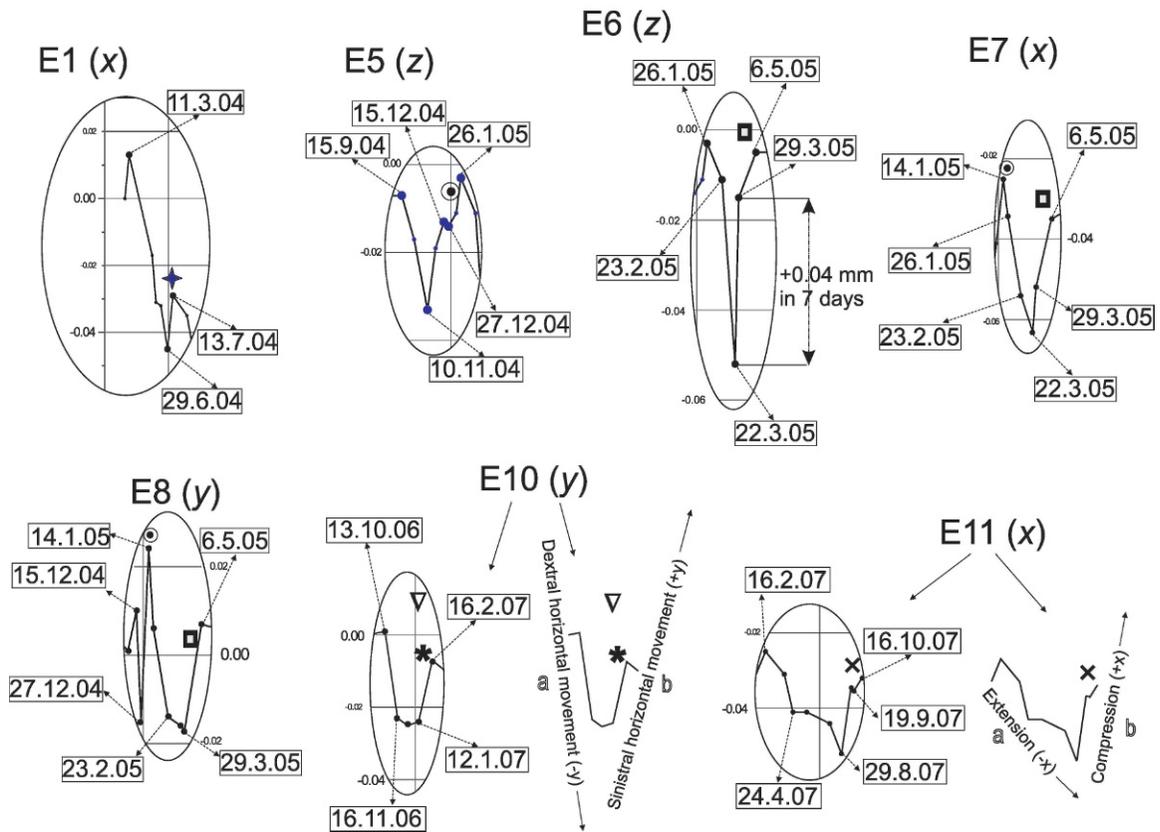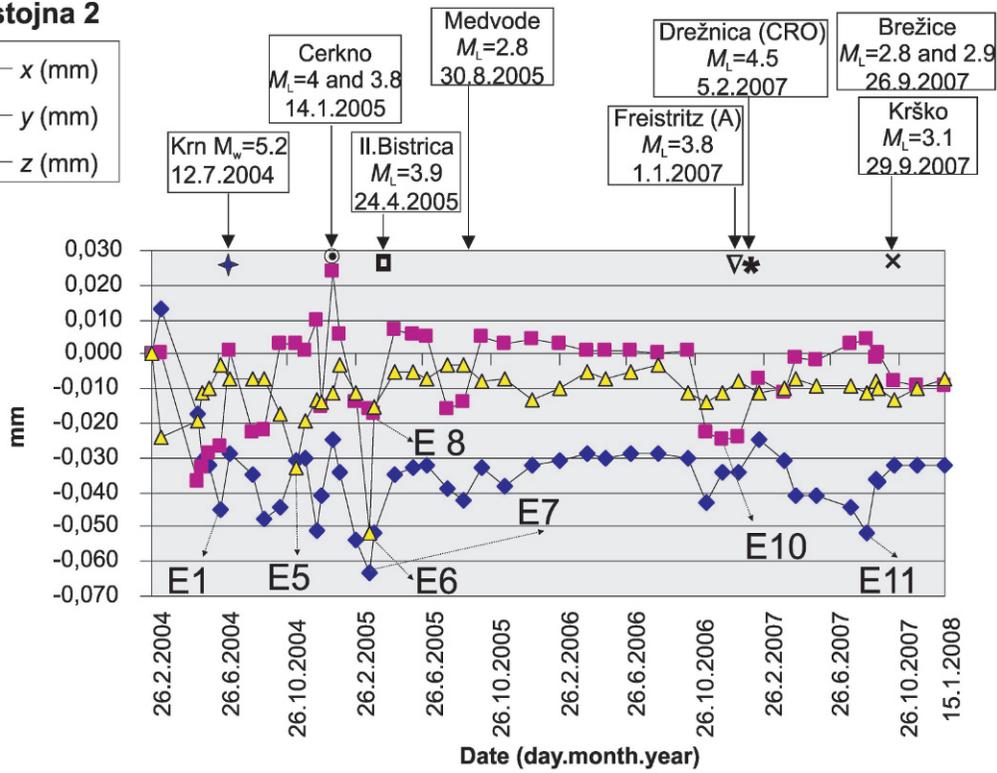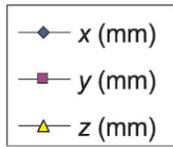
Figure 6. Displacements recorded by TM 71 at Postojna 2 monitoring site.
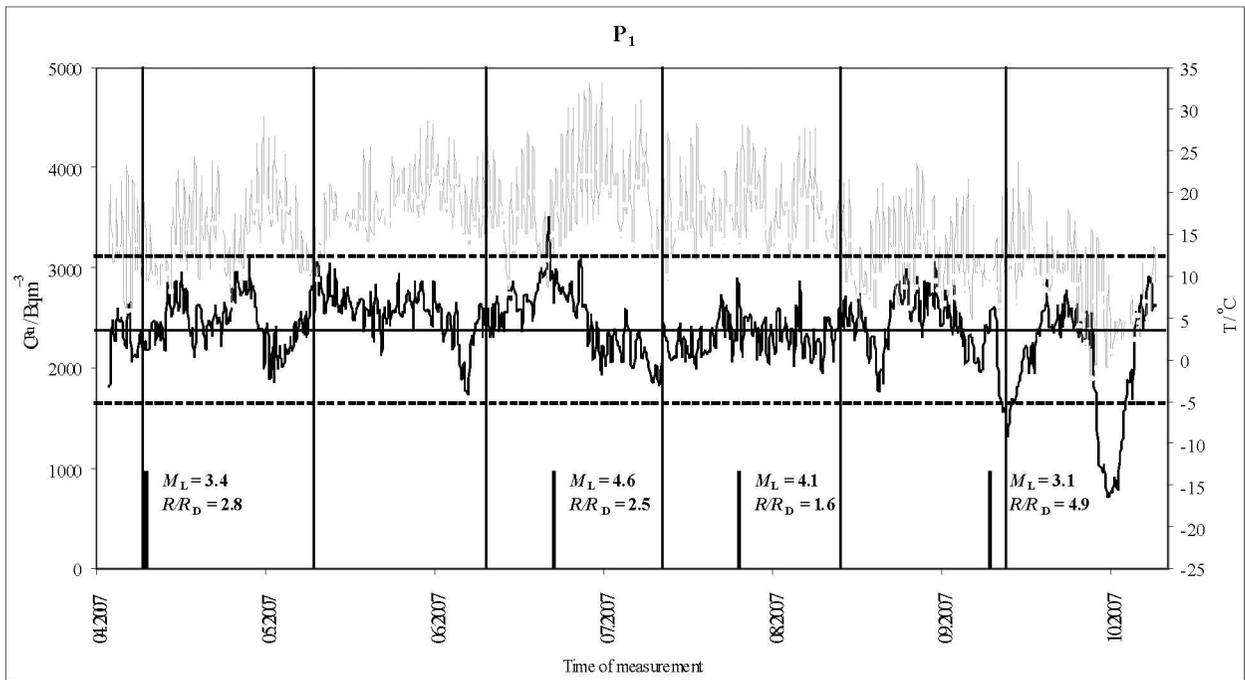
Figure 7. Time series plot of radon concentration in air (black line) at the Postojna 1 site and temperature of the outdoor air (grey line) at the Postojna Meteorological Station (April–October 2007); the relevant earthquakes are inserted, with M_L and R/R_D values indicated, $M_L = 3.4$ (Ebriach, Austria), $M_L = 4.6$ (38 km south from Zadar, Croatia), $M_L = 4.1$ (near Rovinj, Croatia), $M_L = 3.1$ (Krško, Slovenia) (see Table 1).
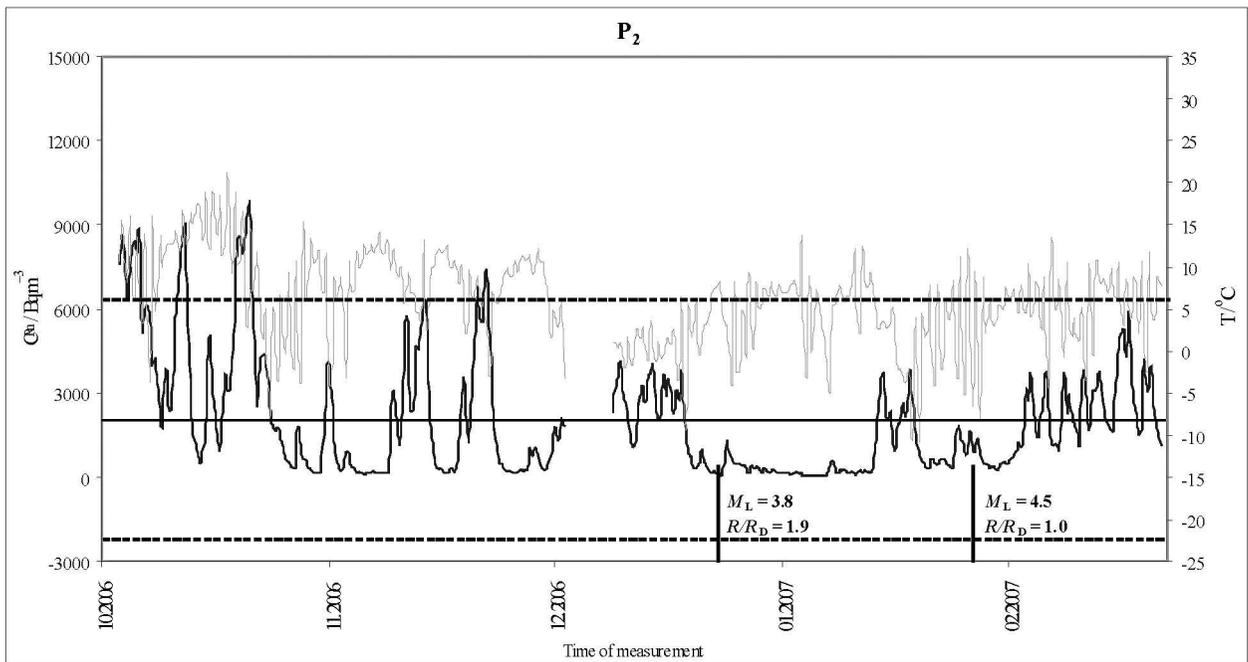
Figure 8. Time series plot of radon concentration in air (black line) at the Postojna 2 site and temperature of the outdoor air (grey line) at the Postojna Meteorological Station (October 2006–March 2007); the relevant earthquakes are inserted, with M_L and R/R_D values indicated, $M_L = 3.8$ (Freistritz, Austria), $M_L = 4.5$ (Drežnica, Croatia) (see Table 1).
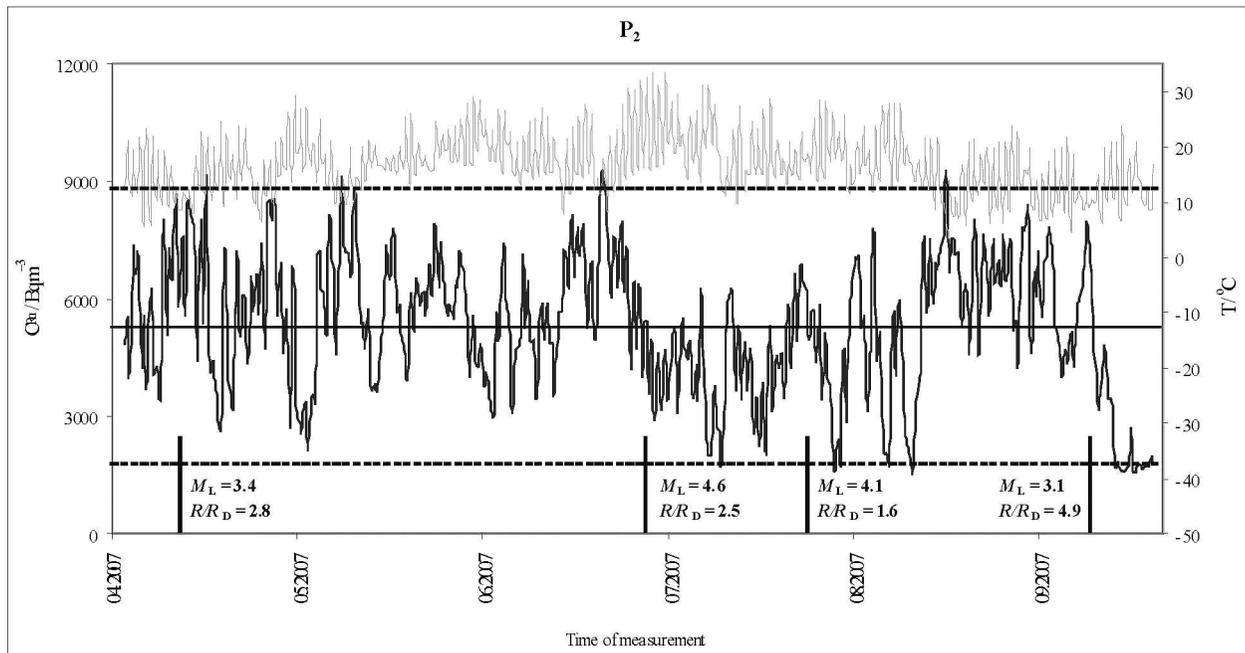
Figure 9. Time series plot of radon concentration in air (black line) at the Postojna 2 site and temperature of the outdoor air (grey line) at the Postojna Meteorological Station (April–October 2007); the relevant earthquakes are inserted, with M_L and R/R_D values indicated, $M_L = 3.4$ (Ebriach, Austria), $M_L = 4.6$ (38 km south from Zadar, Croatia), $M_L = 4.1$ (near Rovinj, Croatia), $M_L = 3.1$ (Krško, Slovenia) (see Table 1).

(dextral horizontal movement); January 12 to February 16, 2007 (sinistral horizontal movement); Freistritz earthquake (Austria) January 1, 2007; Drežnica earthquake (Croatia) February 5, 2007; E11: Postojna $2/x \rightarrow -0.035$ mm/February–August 2007; February 16 to August 29, 2007 (extension); August 29 to October 16, 2007 (compression).

When looking for earthquakes that might coincide with the registered displacements we found 10 events (Table 1, Figs. 5 and 6). The first was the Krn earthquake of July 12, 2004 ($M_w = 5.2$), which had an epicenter 70 km NW from the measuring sites. The earthquake occurred during the period of E1 and E2 when some fault opening along the x-axis at Postojna 2 (Fig. 6) and vertical movements along z-axis at Postojna 1 (Fig. 5) were recorded. Lateral movements observed at Postojna 1 and 2 during the (a) period were of special interest and were first reported by Šebela et al. (2005). Before the earthquake, the displacement along the y-axis corresponded to dextral lateral movement, and just before or during the earthquake, the movement changed to sinistral, with a step of about 0.03 mm (Šebela et al., 2005).

The second event, comprising two earthquakes (Cerkno, $M_L = 4.0$ and 3.8 on January 14, 2005), appeared in the (b) period, just after the extreme E4 in the y-axis (Fig. 5) that represents a dextral lateral slip of -0.075 mm. The most significant change in our observations appeared between November 10 and December 15, 2004. Between December 15, 2004 and Decemebr 27, 2004 movement on the y-axis was +0.03 mm (horizontal sinistral lateral slip). After the event, the step on the y-axis remained at about -0.05 mm, where it remains today. On December 26, 2006, the large Sumatra earthquake ($M_W = 9.2$) occurred. Can long-distant changes in stress and strain in the Earth's crust be an alternative cause of the big step or we registered just a coincidence? The slip registered on the y-axis at Postojna 2 was not as large as that registered at Postojna 1, even if we are observing the same fault zone, but not the same fault line. The movement on the y-axis (Postojna 2, first peak on E8) was -0.02 mm (dextral lateral slip from December 15 to December 27, 2004) and +0.04 mm (sinistral lateral slip from December 27, 2004 to January 14, 2005). During the Cerkno earthquakes, the TM 71 instrument registered significant movements on the z-axis (E5) at the Postojna 2 site (Fig. 6).

The extreme E6 on the z-axis (Fig. 6) appeared before the Ilirska Bistrica earthquake (April 24, 2005, $M_L = 3.9$) that was situated 25 km SE from Postojna. From March 22 until March 29, 2005, +0.04 mm was registered in seven days on the z-axis, the largest displacement recorded in one week. The Cerkno earthquakes and the Ilirska Bistrica earthquake occurred during three extremes (E6, E7 and E8; Postojna 2, Fig. 6). At Postojna 1, during the period of the Cerkno-Ilirska Bistrica earthquakes, we detected small displacements along the z (E9) and y-axes (-0.02 mm) (Fig. 5).

Table 1. Stronger earthquakes in Slovenia and neighbouring countries during the period of monitoring (sources: Ministry for Environment and Spatial Planning, Environmental Agency of the Republic of Slovenia, 2008, Seismology: http://www.arso.gov.si/potresi/ [accessed January 9, 2008] and European-Mediterranean Seismological Center, 2008, Database of Local Seismological Bulletins from European-Mediterranean Networks: http://www.emsc-csem.org/index.php?page=data&sub=base [accessed January 9, 2008]).

Date	Depth, km	M_L	Location	Air distance from Postojna
July 12, 2004	13	$M_w = 5.2$	Krn	70 km NW
September14, 2004	8,9 (?)	4.2	Fužine-Rijeka (Croatia)	50 km south
September 22, 2004	16	3.5	Zgornji Prekar	70 km NE
November 24, 2004	25	5.2	Manerba del Garda (Italia)	290 km W
November 25, 2004	15	5.2	Jabuka (Croatia)	310 km S
January 14, 2005	20	4	Cerkno	45 km NW
January 14, 2004	20	3.8	Cerkno	45 km NW
April 24, 2005	17	3.9	Ilirska Bistrica	25 km SE
August 30, 2005	18	2.8	Medvode	45 km NE
November 24, 2005	16	2.5	Postojna	5–10 km W
December 12, 2005	19	2.9	Žiri	30 km NW
January 30, 2006	12	2.1	Prestranek	10–15 km south
June 21, 2006	16	2.8	Gorski Kotar (Croatia)	70 km SE
August 30, 2006	22	2.4	Škofja Loka	45 km north
September 3, 2006	13	2	Podnanos	22 km W
September 24, 2006	15	2.2	Podnanos	22 km W
January 1, 2007	16	3.8	Freistritz/Bistrica v Rožu (Austria)	80 km north
February 5, 2007	10	$M_w = 4.5$	Drežnica (Croatia)	90 km south
May 2, 2007	16	3.4	Ebriach/Obirsko (Austria)	80 km NE
July 18, 2007	?	4.6	38 km south from Zadar (Croatia)	240 km SE
August 13, 2007	27	4.1	Adriatic sea, near Rovinj (Croatia)	95 km SW
September 26, 2007	3	2.8	Brežice	115 km E
September 26, 2007	5	2.9	Brežice	115 km E
September 29, 2007	10	3.1	Krško (Raka)	105 km E
November 25, 2007	12	3.3	Paternion (Austria)	107 km NW

M_L = local magnitude
M_w = moment magnitude

Between May 6, 2005 and October 13, 2006, the Postojna 2 monitoring site was very stable on all three axes. The only reliable disruption (Fig. 6) was from July 1 to October 7, 2005 during the Medvode earthquake (August 30, 2005, $M_L = 2.8$), being about 0.02 mm along y-axis. A displacement peak of about 0.02 mm was also recorded along the y-axis at Postojna 1 (Fig. 5), from July 1 to September 7, 2005.

The Postojna 1 site was very stable from June 9, 2005 until the beginning of 2007. Even during the earthquakes in 2007, significant movements were not detected, the y-axis in particular being very stable. During the third time (c) period (the year 2007), some movements on Postojna 2 (E10 and E11) were recorded. During the earthquakes in Austria (Freistritz, January 1, 2007, $M_L = 3.8$) and in Croatia (Drežnica, February 5, 2007, $M_L = 4.5$) we detected movement along the y-axis by −0.025 mm (E10). The Brežice (September 26, 2007, $M_L = 2.8$ and 2.9) and Krško earthquakes (September 29, 2007, $M_L = 3.1$) in Eastern Slovenia coincided with an extension along the x-axis of −0.035 mm from February 16 until August

29, 2007 and with a compression of +0.025 mm between August 29, 2007 and October 16, 2007. The fact that movements were recorded both before and after the earthquakes is important. Preceding movements, based on observation of micro-movements, have also been reported on several other occasions in Europe (Košťák et al., 2007; Stemberk and Košťák, 2007).

Monitoring results show small movements along all three axes. At Postojna 1 (Fig. 5), −0.05 mm dextral lateral movement (y-axis) was recorded over four years, and at Postojna 2 (Fig. 6), an extension of −0.03 mm over four years was recorded. The short-term rate of change averaged −0.05 mm yr^{-1} at Postojna 1 in the first year of monitoring (2004). The measurements for the y-axis in the year 2006 were very stable for both devices and show no movement at all.

The micro displacements determined in Postojna Cave were very small and frequently within the limits of error (0.01 mm). However, on the basis of some obvious extremes that generally coincided with seismic activity and of silent periods with almost no movement (Figs. 5 and

6), we believe that slow tectonic processes are being monitored within the aseismic fault zone.

In 2004 and the first part of 2005, some significant peaks, the largest being 0.075 mm in one month on the y-axis, were registered at Postojna 1 (Fig. 5, E4). From September 2005 till January 2008 (Fig. 5), the Postojna 1 monitoring site was very stable, especially along the y-axis. Because the extensometer is fixed between the collapse block and the fault wall of the collapse chamber (Fig. 3), we would expect some non-tectonic movements due to the instability of the collapse blocks, especially on the z-axis. The only two marked extremes along the z-axis (Fig. 5, E2 and E9) are very small, 0.020–0.025 mm, and coincided with the Krn, Cerkno and Ilirska Bistrica earthquakes. The stability of the largest collapse chamber in the cave, Velika Gora, is in this sense, very high.

The Postojna 2 site (Fig. 4) is in an artificially enlarged small natural passage, where the extensometer is fixed between two striated fault planes. The curves show some well-expressed peaks (Fig. 6), some of which coincide with earthquake activity. The highest extremes (E1 and E6, Fig. 6) do not exceed 0.05 mm. The calm period starting in September 2005 was interrupted at the end of September 2006. In 2007, two extremes (Fig. 6, E10 and E11) were concurrent with the Freistritz, Drežnica, Brežice and Krško earthquakes.

Even though we are observing the same Dinaric-oriented fault zone, the same response is not, in general, observed at the two monitoring sites that are separated 260-m-horizontally and 33.5-m-vertically (Fig. 2). One of the causes can be that the Dinaric-oriented fault is cut by a relatively younger cross-Dinaric fault (Sasowsky et al., 2003). Another fact is that the same fault zone is not necessarily tectonically active to the same degree along its length. Along the monitored fault zone we have found traces of at least four different old movements, but recent, very slow tectonic movements, that are showing a general horizontal dextral-lateral movement (Postojna 1) and extension (Postojna 2), are in agreement with the active tectonic situation on Dinaric faults in SW Slovenia. The earthquakes (Table 1) with lower magnitudes, even those close (5–22 km) to the monitoring sites, do not coincide with the micro-tectonic movements.

RADON LEVELS

Time series of radon activity concentrations (C_{Rn} in Bq m^{-3}) were measured at Postojna 1 and Postojna 2 (Figs. 7, 8 and 9) and recorded in parallel with the outdoor air temperature. C_{Rn} at Postojna 1 (Fig. 7) showed regular diurnal fluctuations, as previously observed at other locations in the cave (Vaupotič et al., 2001). The arithmetic mean of C_{Rn} over the whole period of monitoring is 2380 ± 376 Bq m^{-3}. During this time, no unrest was recorded at Postojna 1 and no effect of the unrest at Postojna 2 on radon level at Postojna 1 can be seen (extension until August 29 and compression from August 29 to October 16,

2007; Fig. 6). None of the earthquakes on May 2, 2007 (M_L = 3.4, R/R_D = 2.8), July 18, 2007 (M_L = 4.6, R/R_D = 2.5) or August 13, 2007 (M_L = 4.1, R/R_D = 1.6) appear to have had any connection, although their magnitudes were relatively high for the region and their R/R_D values quite low (Zmazek et al., 2003). The decrease in C_{Rn} after September 26, 2007 (Fig 7) cannot be paralleled with earthquakes that occurred in the period September 26, 2007 to September 29, 2007 because their epicenters were too far away (R/R_D between 4.8 and 7.1) although their magnitudes were not so low for the region (M_L from 2.1 to 3.1). This decrease in C_{Rn} was most probably caused by decreases in outdoor air temperature. It is well known that radon level in the Postojna Cave is governed mainly by the so called chimney effect (Vaupotič et al., 2001; Vaupotič, 2008). The cave system behaves as a huge fireplace: when the outdoor air temperature falls below the temperature of the cave, the air current from the warmer cave carries radon-rich air towards the outdoor air, causing fresh outdoor air with low radon levels to enter the cave and reducing the C_{Rn} in the cave. This occurred at Postojna 1 towards the end of September 2007 (Fig. 7) when the outdoor air temperature, which was below 0 °C for several days, fell far below the cave temperature. The arithmetic mean of C_{Rn} without the contribution after September 26, 2007 is 2445 ± 275 Bq m^{-3} and may be considered as the summer radon level at Postojna 1.

During radon monitoring at Postojna 2, two tectonic unrest periods were observed, E10(y) and E11(x) (Fig. 6). These may be further subdivided: E10(y) into (1) E10a(y): dextral horizontal movement starting on October 13, 2006 (before radon measurement had started) and ending on November 16, 2006, and (2) E10b(y) sinistral horizontal movement from January 12 to February 16, 2007); and E11(x) into (1) E11a(x) extension from February 16 to August 29, 2007, and (2) E11b(x) compression from August 29 to October 16, 2007. The diurnal variations in C_{Rn} are different from those observed at Postojna 1, thus presumably indicating the effect of micro movements on the transport of radon and its entry into the cave air.

The overall arithmetic mean C_{Rn}(tot) for Postojna 2 (Figs. 8 and 9) during the entire period of monitoring (October 2006–October 2007) is 3853 ± 2527 Bq m^{-3}, being about 60% higher than at Postojna 1. The standard deviation is high because of larger fluctuations than at Postojna 1 (Fig. 7). The winter arithmetic mean radon concentration C_{Rn}(w) = 1492 ± 1334 Bq m^{-3} was calculated from the beginning of December 2006 to the end of February 2007, and the summer mean C_{Rn}(s) = 4857 ± 1681 Bq m^{-3} from the beginning of July to the end of August 2007. The ratio C_{Rn}(w)/C_{Rn}(tot) = 0.39 is much lower than, and C_{Rn}(s)/C_{Rn}(tot) = 1.26 similar to other parts of the cave (Vaupotič, 2008). This low C_{Rn}(w)/C_{Rn}(tot) value could have been caused by micro movements, as well as the chimney effect. At the beginning of the plot in Figure 8 C_{Rn}, values are high, start to decrease as

E10a(y) approaches its end, and are very low at the end of this period, although the outdoor temperature was above 10 °C and, hence, the chimney effect could not be operative. Soon after that, two C_{Rn} peaks appear at the temperature minima, which is contrary to expectations based on the chimney effect. C_{Rn} then remains constantly low till almost the end of the E10b(y) unrest. There are periods of elevated C_{Rn} in the second halves of November and December 2006 and January 2007, and the beginning of February 2007, again at the temperature minima as before. Because no unrest was recorded during these times, these elevated Rn levels, except for those in the second half of November 2006, may be assumed as anomalies, possibly coinciding with earthquakes on January 1, 2007 ($M_L = 3.8$, $R/R_D = 1.9$) and February 5, 2007 ($M_W = 4.5$, $R/R_D = 1.1$), respectively. The November 2006 anomaly could not have been paralleled with the January 1, 2007 earthquake because the anomaly precedes the earthquake. The arithmetic means of C_{Rn} for the periods from October 13 to November 16, 2006 (E10a(y) unrest) and from January 12 to February 16, 2007 (E10b(y) unrest) are C_{Rn}(E10a) = 3267 ± 2925 Bq m^{-3} and C_{Rn}(E10b) = 1105 ± 1040 Bq m^{-3}. If the first average is compared with the summer average and the second with the winter average, the following ratios are obtained: C_{Rn}(E10a)/C_{Rn}(s) = 0.67 and C_{Rn}(E10b)/C_{Rn}(w) = 0.74. This suggests that horizontal movement (Fig. 6, E10), either dextral or sinistral, significantly reduced radon levels on the observed fault.

With the appearance of the E11a(x) unrest (from February 16 to August 29, 2007; Fig. 6), C_{Rn} starts to increase (Figs. 8 and 9), resulting in an arithmetic mean of the entire unrest of C_{Rn}(E11a) = 4314 ± 2273 Bq m^{-3}. This value is not significantly higher than C_{Rn}(tot), the ratio C_{Rn}(E11a)/C_{Rn}(tot) being 1.12, and it may therefore be concluded that extension did not influence radon transport. No radon anomalies have been observed during the earthquakes occurring on May 2, 2007 ($M_L = 3.4$, $R/R_D = 2.8$), July 18, 2007 ($M_L = 4.6$, $R/R_D = 2.5$) or August 13, 2007 ($M_L = 4.1$, $R/R_D = 1.6$), although their magnitudes were relatively high for the region and R/R_D values quite low (Zmazek et al., 2003).

On August 29, 2007, the E11(x) unrest continued but changed from extension to compression (E11b(x) from August 29 to October 16, 2007; Fig. 6). C_{Rn} started to increase, giving an arithmetic mean for this period C_{Rn}(E11b) = 5184 ± 2163 Bq m^{-3}. When on September 19, 2007 the compression process slowed down (Fig. 6), C_{Rn} started to decrease and reached very low values towards the end of E11b(x). As for Postojna 1, it is not believed that this decrease coincided with earthquakes that occurred in the period September 26, 2007 to September 29, 2007 because their epicenters were too far away (R/R_D between 4.8 and 7.1), although their magnitudes were not so low for the region (M_L from 2.1 to 3.1) (Zmazek et al., 2003). Because C_{Rn}(E11b) is significantly higher than C_{Rn}(tot), with C_{Rn}(E11b)/C_{Rn}(tot) = 1.35, it can be

concluded that compression significantly facilitates radon transport, thus increasing its activity in air. If only the fast compression period (from August 29 to September 19, 2007; Fig. 6) is taken into account, the related C_{Rn} arithmetic mean is 6150 ± 1739 Bq m^{-3} and the effect of compression on radon transport is even more pronounced.

CONCLUSIONS

Recent studies of active tectonics in Slovenia (Cunningham et al., 2006; Poljak, 2007; Rižnar et al, 2007; Verbič, 2005; Vrabec and Fodor, 2006) suggest that some caves should preserve and generate traces of active tectonics. In this context, two TM 71 extensometers were installed in 2004 in Postojna Cave on the Dinaric-oriented fault zone, situated about 1,000 m to the north of the Predjama Fault (Fig. 1)

The measurements of tectonic micro-displacements showed small tectonic movements on both instruments, a general dextral horizontal movement of 0.05 mm in four years (Postojna 1, Figure 5) and an extension of 0.03 mm in four years (Postojna 2, Figure 6). Eleven extremes of characteristic changes in displacement were determined between variable calm periods. Contemporaneous with some stronger earthquakes (for example Krn earthquake, July 12, 2004, $M_W = 5.2$), unrest was detected. For example, movements of 0.03–0.075 mm were detected in the period of one month along the fault zone. However, after the earthquake, the rock generally returns to the same position as before the earthquake. Similar behavior was described in Slovakia (Briestenský et al., 2007) and other countries (Košťák et al., 2007) where we were monitoring a seismic fault zone and detecting the micro-tectonic changes in Earth's crust before, during and after the earthquakes.

The greatest short-term movement was a compression of 0.04 mm in seven days, detected in March 2005 and coincided with the 25 km distant Ilirska Bistrica earthquake ($M_L = 3.9$). About two months before the earthquake, an extension of 0.05 mm occurred, and one month before the earthquake the stress changed into a compression of 0.05 mm. The largest permanent shift was detected at the end of 2004. Along the y-axis (at Postojna 1), a dextral horizontal movement of 0.075 mm was observed in one month. After the sinistral horizontal movement of 0.02 mm (December 15, 2004 to December 27, 2004), the y-axis retained its position on 0.05 mm, where it is still today. Regarding the extremes, ten earthquakes that coincide with tectonic micro-displacements were selected. In the time frame of speleogenesis, the monitored fault zone today represents a stable cave environment.

During horizontal movement, either dextral or sinistral, radon pathways underground were partly closed, thus hindering radon migration and reducing its concentration in the cave air. Extension does not appear to have affected radon transport. Alternatively, the compression process

(Postojna 2, February–August 2007) appears to have opened some new routes for radon transport, thus facilitating radon migration and increasing its concentration in air. In the present state of knowledge, a more solid explanation of these findings is not possible.

The comparative study is ongoing. The observed fault zone transmits only very small tectonic movements, but long-term monitoring of different parameters could sufficiently explain the relations in Earth's karst massif related to changes in stress and strain before, during, and after the stronger earthquakes. Finally, we will continue our comparative research with other monitoring sites where we have results and ongoing data collection (Stemberk et al., 2003; Košťák et al., 2007; Stemberk and Košťák, 2007; Briestenský et al., 2007).

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