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MICRO-DEFORMATION MONITORING OF ACTIVE TECTONIC STRUCTURES IN W SLOVENIA

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ABSTRACT
Monitoring of tectonic movements along three active faults of Dinaric (NW-SE trending) fault system in W Slovenia using TM 71 extensiometers was set up in 2004. After two and a half years of measurements clear trends of displacement were recorded. The average left-lateral displacement along a crack in the inner fault zone of the Idrija fault in Učja valley was reading 0.38 mm/year. Short term (10 months) rates were even greater and reached the value of 0.54 mm/year. Since the Idrija fault is considered generally to be dextral strike-slipping, the observed left-lateral displacement can be explained by variations in principle stress. Raša fault monitoring site at the foot of Vremščica Mt. established an average reverse uplift of hanging wall (SW) block of 0.24 mm/year and left-lateral displacement of 0.16 mm/year. Short term (9 months) vertical displacements reached the value of 0.53 mm/year. The inclined displacement is in agreement with geological and seismological observations. In the Postojna cave system two instruments were installed at the fault which extends parallely to Predjama fault zone. The average vertical displacement rate at Postojna 1 site was 0.01 mm/year. Both devices recorded similar reaction which can be attributed to 12 July, 2004 (Mw=5.2) earthquake with an epicentre 70 km away from the measuring site. Since there were no other stronger earthquakes in the vicinity and time span of monitoring, no other correlations were established with earthquake activity. The observed displacement rates along all three monitored faults of up to 0.5 mm/year are consistent with the regional deformation rate in W Slovenia established from GPS measurements which is of the order of 2 mm/year.

KEYWORDS: tectonic movements, active tectonics, monitoring, Dinaric fault system, Slovenia

1. INTRODUCTION

Slovenia is situated at the NE boundary of the Adriatic microplate, at the junction of three major geotectonic units: the Alps, the Dinarides and the Pannonian basin. Recent geodynamics of the region is controlled by CCW rotation of the Adriatic plate in relation to relatively stable European plate (Vrabec and Fodor, 2006), which results in Slovenia predominant N-S oriented principle stress orientation. On the south lies the undeformed Istrian platform is situated, which gradually evolves into the External Dinarides. For Western Slovenia moderate historical to recent seismicity is characteristic (Poljak et al., 2000).

Within the COST 625 action (Stemberk et al., 2003) we set up deformation monitoring of three active faults in W Slovenia using four TM 71 extensiometers (Šebela et al., 2005). In the first half of 2004 two TM 71 instruments were installed in Postojna cave system on the Dinaric oriented (NW-SE) fault that is situated about 1 km north of Predjama fault. The third and fourth instruments were installed in November 2004 on Raša fault at the SE foot of Vremščica Mt. and on Idrija fault in Učja valley. The fifth instrument TM 71 was set up in 2006 on Kneža fault which is located between Idrija and Ravne fault (Fig. 1).

TM 71 is a mechanical extensiometer designed for installation on narrow cracks (crack gauging) to monitor relative micro-displacements between both walls of the crack. It works on the principle of mechanical interference (Moire effect), and displacements are recorded by interference patterns of two optical grids (Košťák, 1991). The instrument provides three-dimensional results – displacement vector in two perpendicular planes (horizontal and vertical) and angular deviations (rotation). The sensitivity of the system is: 0.05-0.0125 *mm* in all three space co-ordinates, and 3.2 10^{-4} *rad* in angular deviations (Stemberk et al., 2003). The main advantages of this purely mechanical instrument are: it completely avoids the use of electrical transmission means, it furnishes good performances under severe outdoor conditions, and has a long-term stability.

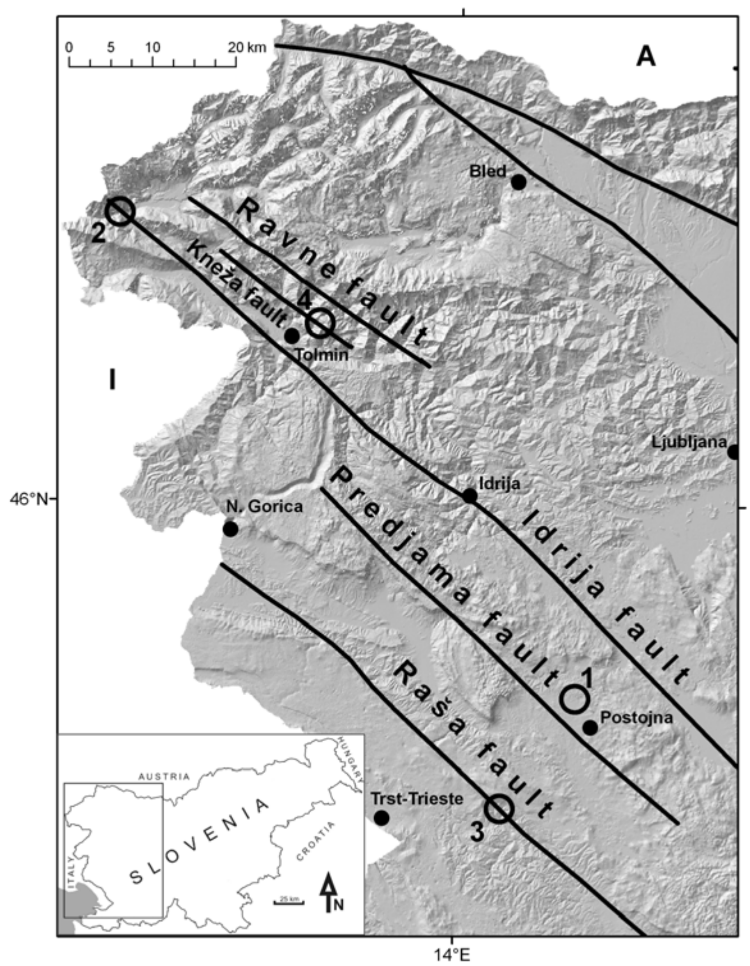


Fig. 1 Major dextral strike-slip faults in W Slovenia with TM 71 monitoring sites: 1-Postojna cave system, 2-Idrija fault, Učja location, 3-Raša fault, Vremščica Mountain, 4-Kneža fault, Zadlaz-Čadrg.

2. GEOLOGY AND TECTONICS OF SLOVENIA

Slovenia is situated at the NE part the Adria microplate, whose northern margin (Southern Alps-Dinarides) is highly deformed and backthrusted onto the central, less deformed part of the Adria microplate (Poljak et al., 2000). After the Cretaceous-Palaeogene subduction, the Periadriatic line developed the character of a strike-slip fault with a dextral sense of horizontal displacement (Bemmelen, 1970).

Collision of European and African plates results in predominantly N-S oriented recent principal stress direction in the region of Slovenia. This resulted in a system of conjugate strike-slip faults. In W Slovenia right-lateral NW-SE oriented strike-slip faults prevail and left-lateral NE-SW oriented strike-slip faults in E Slovenia. In addition there are several W-E oriented reverse faults and north verging thrusts. Adria's major aseismic outcrop is the Istria peninsula. In northern Slovenia we observe a significant and sharp (few mm/year) dextral (and transpressive) gradient in GPS velocities along the Sava fault and Periadriatic zone, suggesting that lateral extrusion in the NE Alps is still active being driven by the CCW rotation of Adria (Weber et al., 2006). In External Dinarides GPS observations showed N- to NNE-directed movements in the range from 0.5 to 2 mm/year (Vrabec et al., 2006). The basic structural characteristics of the External Dinarides are a dense pattern of faults in a NW-SE direction, in addition to thrusts with south-westward direction of thrusting. In External Dinarides strike-slip and transpression displacement along NW-SE trending faults is present.

3. SEISMICITY OF W SLOVENIA

The territory of Slovenia can be considered as one of moderate seismicity. No surface rupture related to any earthquake has been detected so far in Slovenia (Poljak et al., 2000). In External Dinarides we find moderate historical and recent seismicity (Fig. 2). Data from the last 20 years show that most earthquakes in SW Slovenia are situated along Raša and Idrija faults, delineated in NW-SE direction (Michelini et al., 1998). Focal mechanisms for the most earthquakes indicate right-lateral or reverse

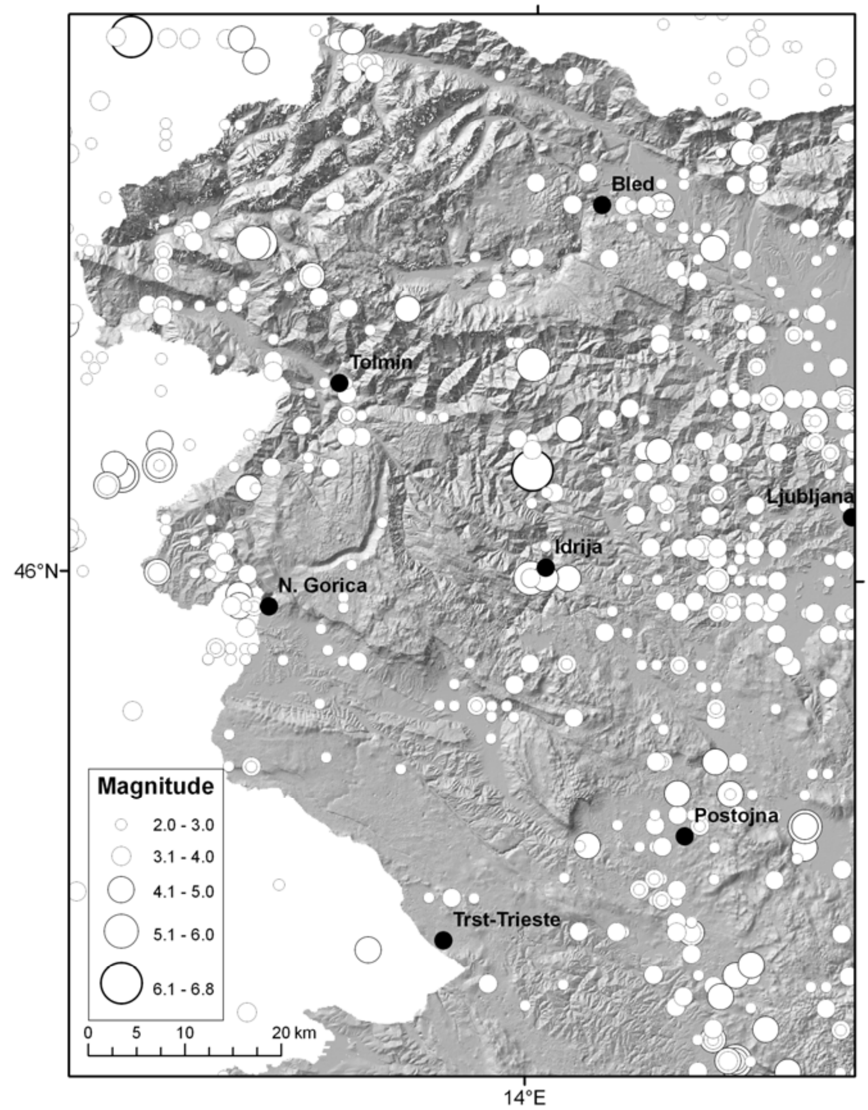


Fig. 2 Seismicity map of W Slovenia (EARS catalogue for the period 567-2004).

faults (Poljak et al., 2000). The strongest earthquake ever recorded in the Alps-Dinarides junction was the 1511 western Slovenia earthquake (M=6.8). The exact location and mechanism of this event are still debated (Fitzko et al., 2005).

Although strike-slip and thrust-type dominate, there are also a few earthquakes with normal-type faulting. From the fault plane solutions it is evident that the governing stress in the region runs approximately in N-S direction (Poljak et al., 2000).

The region of NW Slovenia undergoes a recent increase in seismic activity with two damaging earthquakes in the Upper Soča valley. The 12 April 1998 (Mw=5.6) and 12 July 2004 (Mw=5.2) earthquakes occurred on the NW-SE trending near-vertical Ravne fault in the Krn mountains at 7-9 km depth (Zupančič et al., 2001). The focal mechanisms of both earthquakes show almost pure dextral strike-slip motion (Kastelic et al., 2006).

4. MONITORING OF ACTIVE FAULTS WITH TM 71 EXTENSIOMETERS

Four locations for TM 71 measurements of active faults in Slovenia were selected (Fig. 1). TM 71 monitoring in Slovenia started in Postojna cave system on February 2004 (Postojna 2; Lepe Jame) - on the Dinaric NW-SE oriented fault zone in the wider zone of Predjama fault. Measurements on the second location in Postojna cave system called Postojna 1 (Velika Gora) started on May 2004. In November 2004 two TM 71 instruments were installed on Idrija fault (Učja) and on the Raša fault (Vremščica). The fifth instrument in Slovenia was installed on Kneža fault in November 2006.

4.1. POSTOJNA CAVE SYSTEM

The Postojna cave with its 20 km of galleries is the longest known cave system in Slovenia. From impermeable flysch of Pivka basin the river Pivka

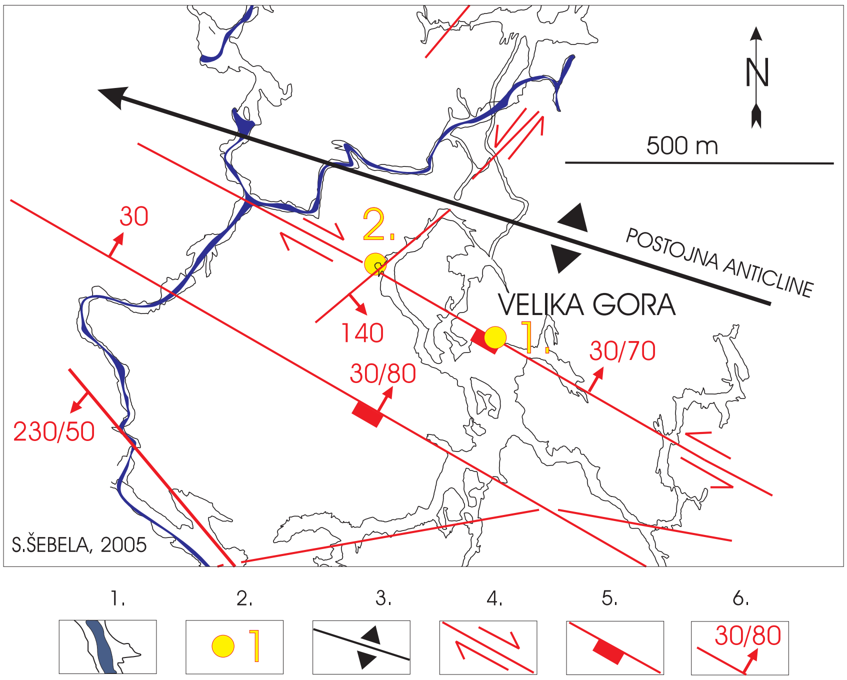


Fig. 3 TM 71 monitoring sites in Postojna cave system and basic structural geological map. 1-groundplan of the cave and underground river Pivka, 2-TM 71 monitoring site (1-Postojna 1, 2-Postojna 2), 3-anticline, 4-fault with horizontal dextral movement, 5-fault with vertical movement, 6-dip direction and dip angle of the fault.

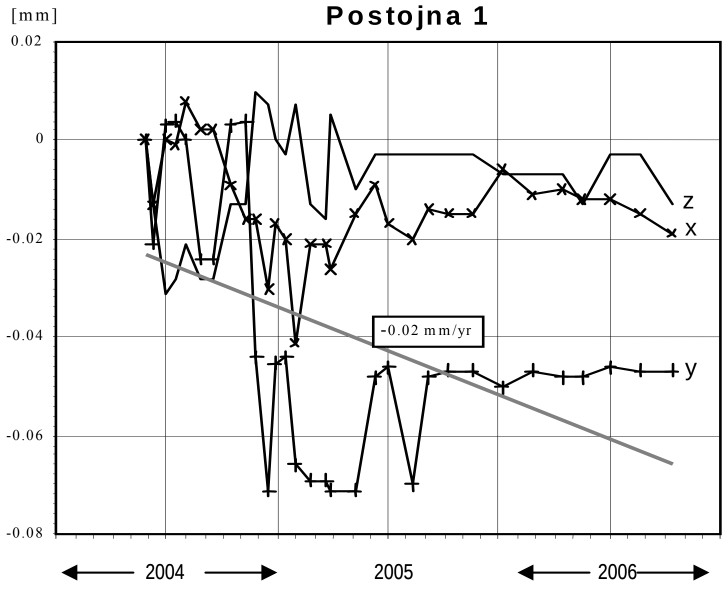
sinks to the cave and comes out as a spring of Unica River in Planina cave.

Postojna cave system is situated between two regional faults, Idrija fault on the north and Predjama fault on the south. Tectonic structure of the area between those two faults has all the characteristics of on inner zone between two strike-slip faults (Šebela, 1998). In the Postojna cave system we 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. Principal folding deformation in Postojna cave system is Postojna anticline (Fig. 3). Cave passages are developed in both flanks of anticline and follow strike and dip of the bedding-planes, especially those with interbedded slips.

The biggest collapse chamber in the cave called Velika Gora (Fig. 3) shows that final breakdown occurred when the room was exposed no more to river floods. The northern edge of Velika Gora collapse chamber is developed inside Dinaric oriented (NW-SE) fault zone with vertical displacement of several meters (TM 71 monitoring site Postojna 1). The reactivation of the tectonic zone through different time periods enlarged the collapse chamber to the actual size. Occasional river floods helped to carry the collapse blocks away. The same fault zone from Velika Gora can be found in the other parts of the cave. But in other parts it doesn't have the same tectonic characteristics. In SE part of the cave we can observe horizontal movements with 60^0 of the dip angle for the fault zone, NW from Velika Gora the same fault zone has vertical and horizontal displacements (TM 71 monitoring site Postojna 2) being cut by relatively younger cross-Dinaric fault zone, which is younger than 780 000 years (Sasowsky et al., 2003). On the same tectonic zone we observe different tectonic effects, sometimes even four different tectonic phases.

The sites for TM 71 installation in Postojna cave system were selected to prove or to deny that the monitored fault is tectonically active. Two devices were installed on the same fault zone. Postojna 1 represents the contact between the fault plane and a collapsed block. TM 71 device Postojna 2 is installed between two fault planes, which are about half a meter apart. The observed fault is situated about 1 km north from the inner zone of Predjama fault.

Results from Postojna cave system monitoring are showing small movements along all the three Cartesian coordinates. On the site Postojna 1 (Fig. 4) the *y*-axis shows about -0.02 mm/year right-lateral movement in average. Short term rate in the first year of observation was even -0.05 mm/year in average, but later the movements stopped. Because the cave temperature is stable (9-11° C) throughout the year, the temperature influence on data record can be excluded. Although the measurements at Postojna 1



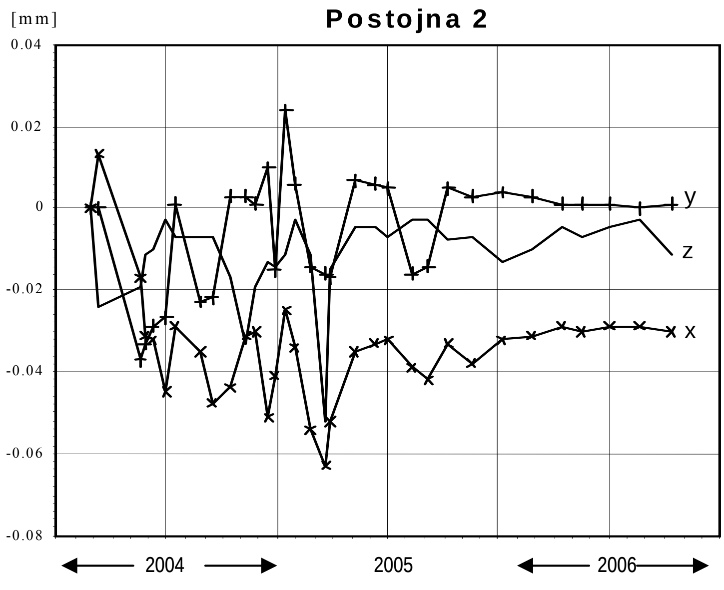


Fig. 4 Displacements recorded with TM 71 at the monitoring sites Postojna 1 and 2.
$+x$ represents closing of crack, $+y$ horizontal left-lateral slip, $+z$ downslope slip of SW block.

Fig. 5 Left: the crack in the inner zone of the Idrija fault in the Učja valley. The arrow shows the location of TM 71 instrument. Right: The exposure of the fault plane 50 m from the crack shown in the left figure with clear striations indicating subhorizontal movements.

device started only on 26 May 2004, it seems that both devices recorded similar reaction to 12 July, 2004 (Mw=5.2) earthquake which had epicentre 70 km away from the measuring site.

Movements that can be detected in y and z-axes for both the instruments (Fig. 4) as simultaneous, show that we are dealing with real tectonic movements. Such movements on Postojna 1 were interrupted clearly in the y-axis by the end of 2004 and then in the beginning of 2005, when the original value of 0.03 mm doubled. In spring of 2004 the values of x-axis (Postojna 1) were again interrupted. The fact is that shifts on Postojna 2 were not so extraordinary although both devices are situated on the same fault zone. Nevertheless, extremes occurred simultaneously. Besides, the map in Fig. 3 shows that Dinaric oriented fault monitored by TM 71 instruments is cut by a cross-Dinaric fault, which might represent the cause for the differences on both the devices. In the period of measurements no trend in angular deviation was recorded at either of the sites.

In Postojna cave system it is also necessary to consider tectonic activity effects of other factors that may interfere with TM 71 monitoring. It is water percolation from the surface and effects manifested by radon emanation. Therefore, in July 2005 we started to monitor radon concentration in the cave near the TM 71 monitoring sites.

4.2. IDRIJA FAULT

The best morphologically expressed fault in the region of W Slovenia is the Idrija fault (Fig. 1), which is clearly visible in topography and in aerial or satellite images. It extends from the Italian border near Bovec to the Croatia in Gorski Kotar (N of Rijeka), having a total length of more than 120 km. The strongest historical earthquake in the region, the »Idrija« earthquake of 1511 with estimated magnitude of 6.8 (max. intensity X) is usually related to this fault (Ribarič, 1979), but its exact location and relation to the faults in the region is still not clear (Fitzko et al., 2005). The second strongest known event with magnitude 5.6 occurred in 1926 at the SE end of the Idrija fault. However, recent seismicity in the vicinity of this fault is rather low (Poljak et al., 2000).

In November 2004 we installed the TM 71 device in the NW part of Idrija fault, where good exposure of the main fault zone was found in the Učja valley near Bovec. The whole fault zone is here more than 1 km wide and was divided in outer and inner fault zones by Čar and Pišljar (1993). The TM-71 instrument is installed on a prominent crack in the central part of the inner fault zone (Figs. 5 and 6), which cuts 50 m high wall of the canyon.

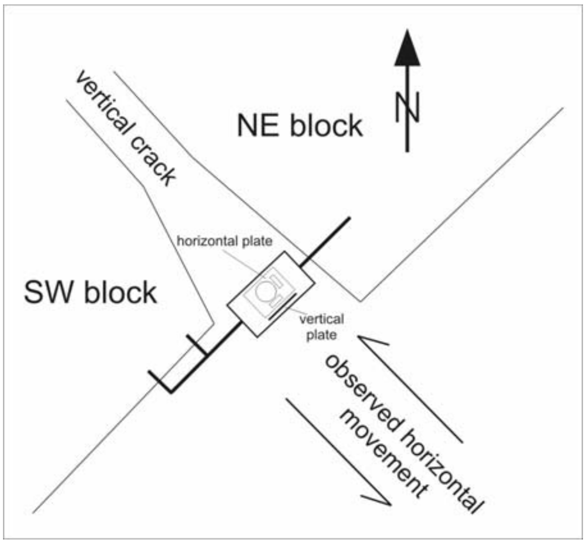


Fig. 6 The sketch of TM 71 installation on the crack in the Idrija fault zone with indication of observed displacement.

In first 10 months of measurements a clear trend of horizontal displacements y = +0.54 mm/year developed (Fig. 7). It was followed by a significant reversible displacement that occurred at the beginning of 2006. Later the earlier trend continued. The average displacement rate for the first two years of measurements is +0.38 mm/year. In the same period no clear trend in angular deviation was observed in both planes. Relative movement between blocks shows left-lateral horizontal displacement. This is an unexpected result, because Idrija fault is considered to be a dextral strike slip fault (Čar and Pišljar, 1993). There are clear geological evidences of dextral displacement for the geological history, but for recent times no direct proofs are available. Therefore, the dextral strike slip movement was mainly inferred from the orientation of principal stress axis, which is oriented in N-S direction and from fault plane solutions of two stronger earthquakes that occurred on parallel Ravne fault. Observed left-lateral displacement should be therefore possibly explained by local variation of stress direction inside the very complex fault zone (Kavčič, 2006). The amplitude of the observed slip rate of 0.4-0.5 mm/year is in agreement with regional GPS displacement rates in W Slovenia, which are up to 2 mm/year. However, GPS points were too sparse in this study (Vrabec et al., 2006) to establish sense of displacement along individual faults. Only regional rates were determined.

In any case, longer observations and detailed tectonic mapping of complex Idrija fault cross-section in the Učja valley would be necessary to understand better the relations between different cracks observed in outer and inner parts of the fault zone. As for x-axis (opening or closing the crack), this shows clear seasonal effects, which are in good correlation with recorded temperature variations. On the other hand no trend has been established yet on the vertical axis z.

4.3. RAŠA FAULT

The second important fault located approximately 25 km SW from the Idrija fault is the Raša fault, which can be clearly traced in a length of 50 km from N of Nova Gorica to the Snežnik thrust at Ilirska Bistrica (Fig. 1). Most impressive features related to this fault are: almost straight valley of the Raša River and its clear expression in topography around Vremščica Mountain. The fault has a multiplase kinematic development, which is typical for most regional faults of External Dinarides (Jurkovšek et al., 1996). A cross-section of this fault is well exposed near Senožeče where a highway crosses the fault trace. Otherwise there are only few good exposures of the fault. The seismicity in the vicinity of the Raša fault is concentrated mainly in the Mt.Snežnik area at its SE termination. Hypocenters of the earthquakes in this area define a steeply NE dipping fault plane (Michelini et al., 1998).

We explored the whole trace of the Raša fault to find a suitable location for installation of TM 71 extensiometer. In spite of its clear expression in the topography we recognized that there are very few good exposures. The best location was found at the foot of Mt.Vremščica, on its SE side, near Košana. There are two abandoned quarries in the Upper Cretaceous limestone, situated exactly at the fault trace. There is a plan to put the upper quarry again into operation, but the lower one is abandoned for more than 15 years and will remain closed. Therefore, it provides a suitable place for crack gauge measurements. The contact between Upper Cretaceous limestone to the NE and Palaeocene Kozina limestone to the SE (Buser et al., 1967) is exposed in this quarry, separated by the main fault zone, which is approximately 10 m wide. Therefore, it was not possible to install the instrument in the main fault plane, but we selected a parallel crack in the exposed wall of the quarry built of Cretaceous limestone (Figs. and 9). The measurements started in November 2004.

In two years of observations the average reverse uplift of hanging wall (SW) block of -0.24 mm/years and left-lateral displacement of +0.16 mm/year were established. (Fig. 10) Short-term vertical displacements reached the value of -0.53 mm/year.

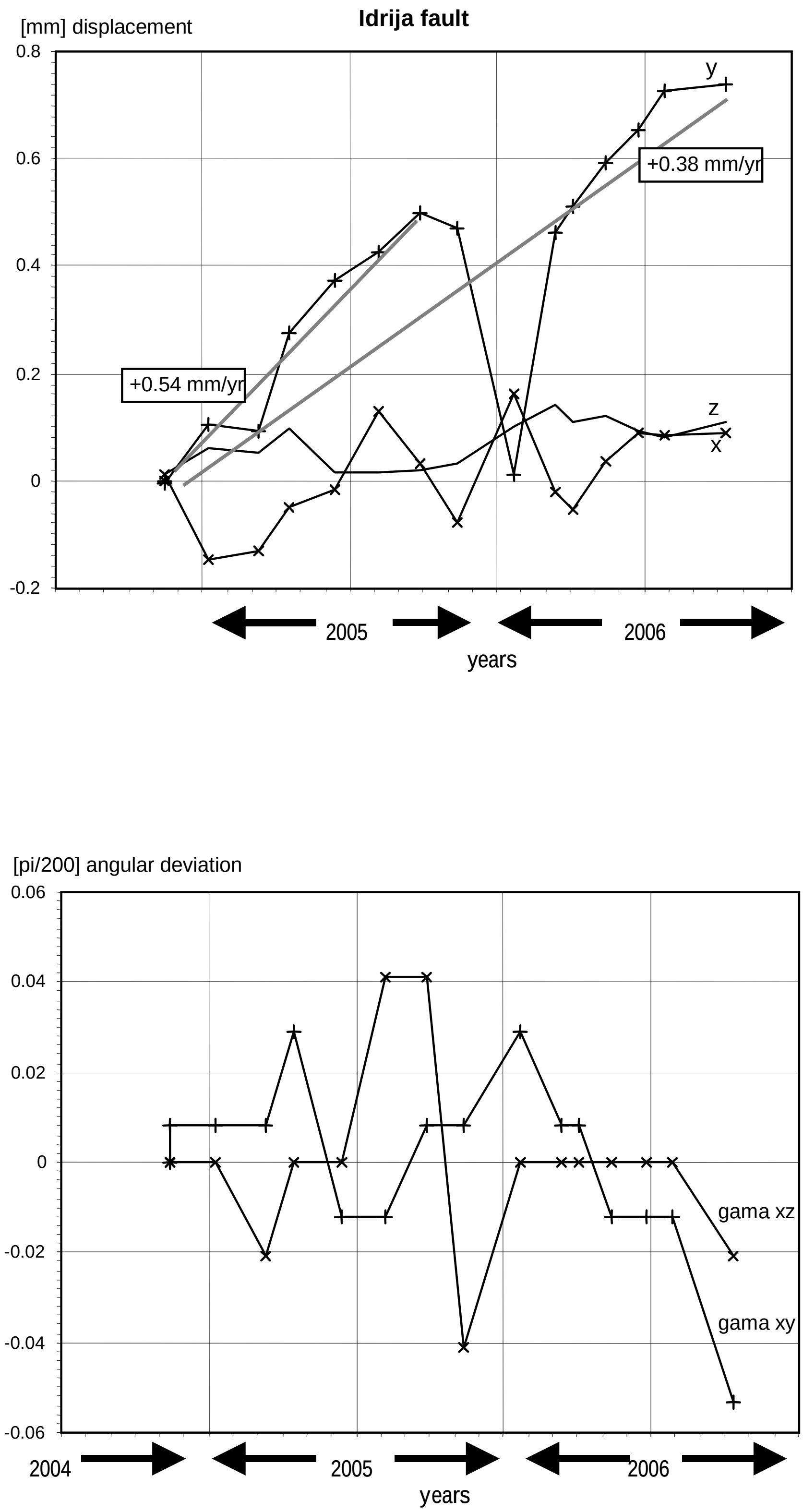


Fig. 7 Displacements and angular deviations recorded with TM 71 at the monitoring site Učja on the Idrija fault. $+x$ represents closing of crack, $+y$ horizontal left-lateral slip, $+z$ downslope slip of SW block.

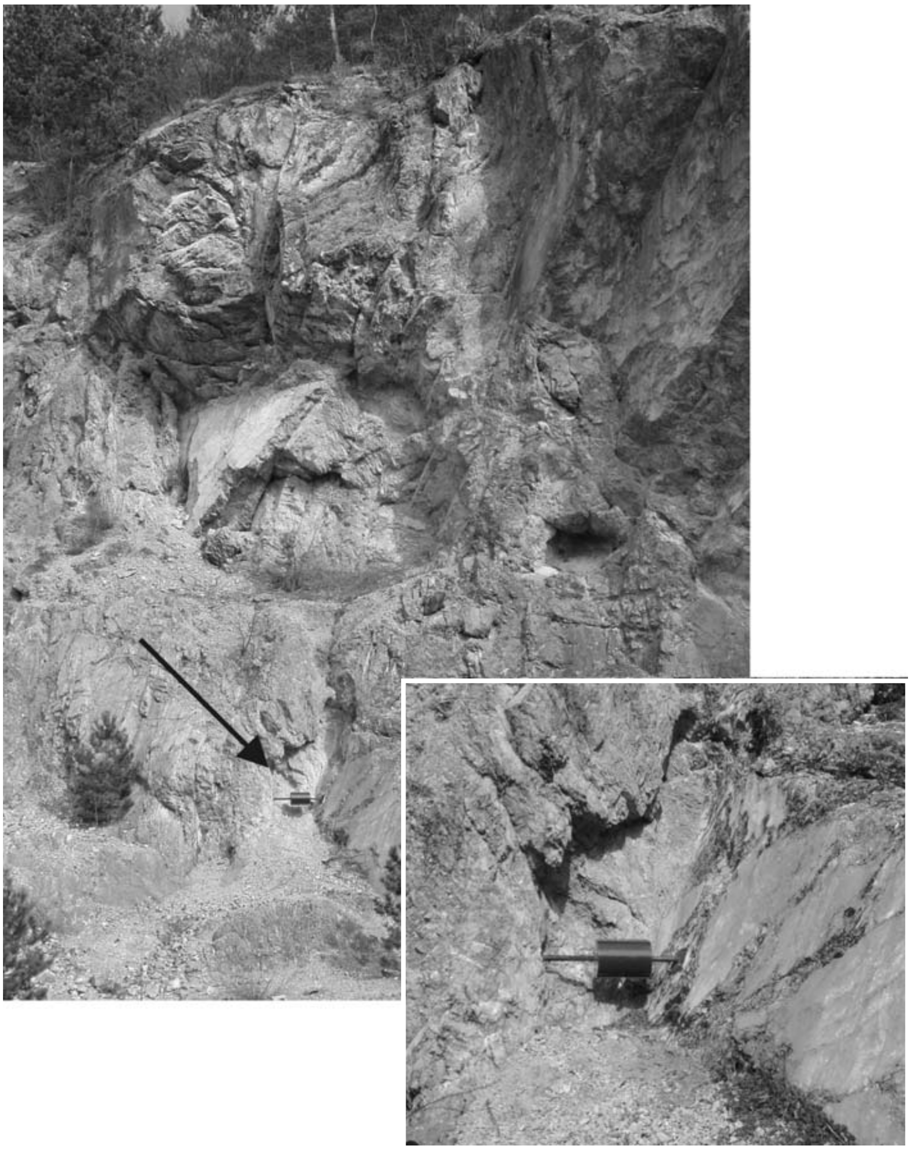


Fig. 8 The quarry at the foot of Vremščica Mt. near Košana on Raša fault zone with location of TM 71 instrument (see arrow). Right - the.measurement point in detail.

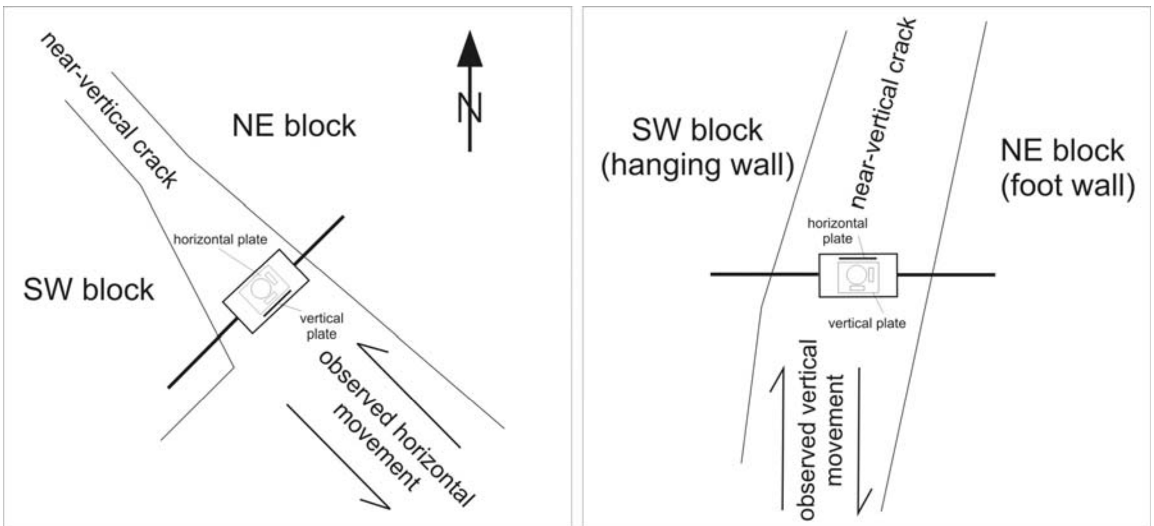
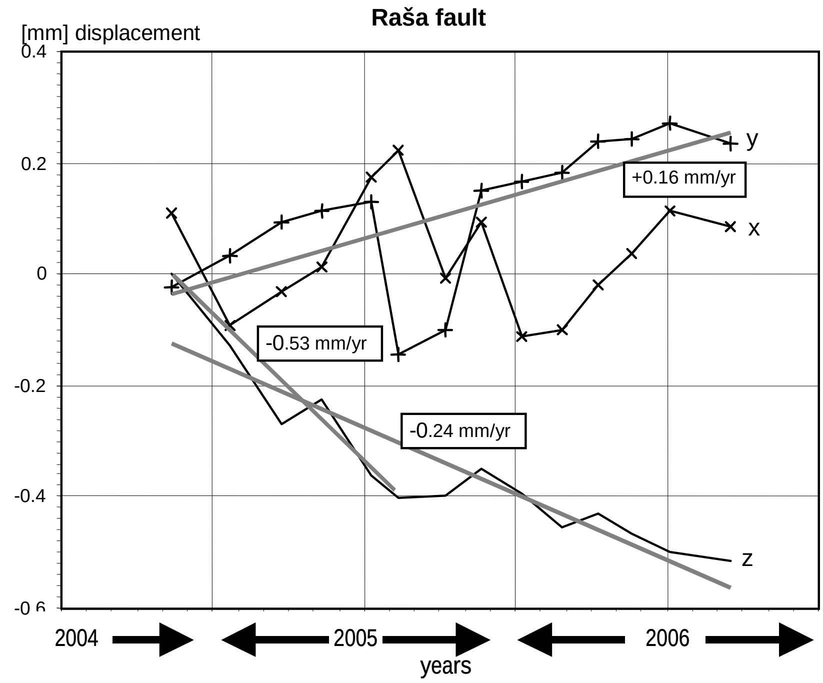


Fig. 9 The sketch of TM 71 installation on the crack in the Raša fault zone with indication of observed displacement. Horizontal plane view (left) and vertical plane view (right).



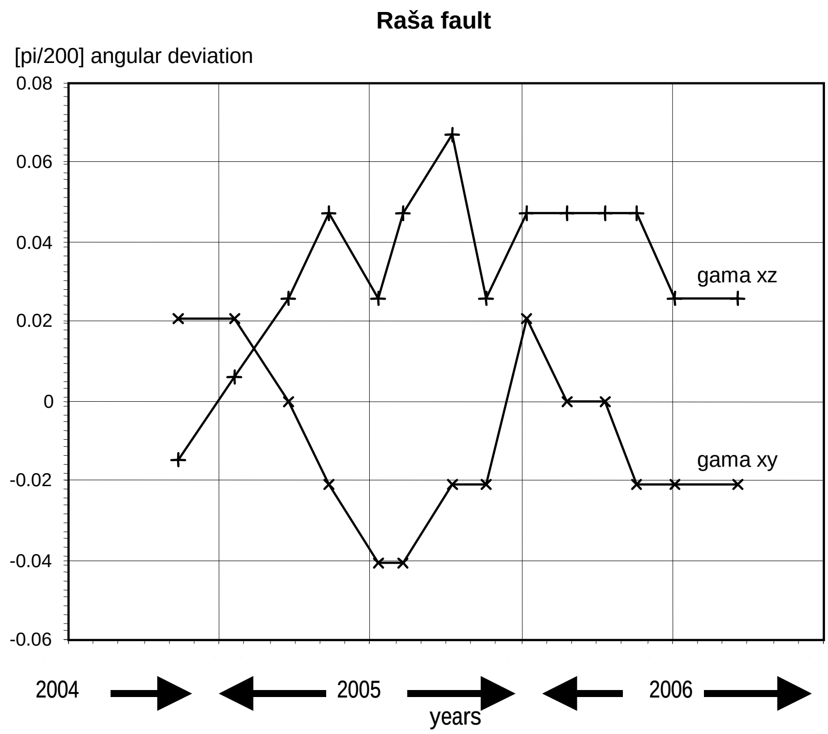


Fig. 10 Displacements and angular deviations recorded with TM 71 at the monitoring site Vremščica on the Raša fault. +*x* represents closing of crack, +*y* horizontal left-lateral slip, +*z* downslope slip of SW block.

Opening or closing the crack as found on *x*-axis shows clear seasonal effects, which are in good correlation with recorded temperatures. No trend in angular deviation was developed in both planes so far. The oblique sense of displacement is only partly in agreement with geological and seismological observations. Regarding possible comparison of our measurements with other data, one must consider that the TM 71 instrument was not installed on the main fault plane, but on one of near parallel cracks. Local variations in stress orientation can therefore explain observed differences. Focal mechanisms of some stronger earthquakes in the active zone of Snežnik Mt., SE of the monitoring site, indicate also strike slip and reverse character (Poljak et al., 2000). On the other hand, Jurkovšek et al. (1996) claim that the fault has undergone multiphase development from reverse over gravitational to the final strike-slip character. No terrestic geodetic or GPS data are available about the sense of the movement along this fault.

5. CONCLUSIONS

The observed displacement rates of up to 0.5 mm/year along three monitored active faults are consistent with the regional deformation rate in W Slovenia established from GPS measurements, which is of the order of 2 mm/year.

Regional Dinaric faults in W Slovenia have dextral strike-slip character according to long- term geological data. There were no terrestic geodetic measurements performed along these faults to establish recent movements, whereas the points used in some GPS projects were too sparse to determine the sense of movement along individual faults. It was possible to derive only the regional deformation rate from them. Fault plane solutions are available and also show dextral strike-slip motion for recent earthquakes on Ravne fault. This fault is not equipped for monitoring with TM 71 instruments, because we have not found yet any suitable location in high mountains for its instalation. Solutions are available also for the SE part of the Raša fault where they show reverse, and strike-slip character. Therefore, direct comparison of micro-deformation monitoring on individual cracks together with other data inside the fault zones can be done to very limited extent. Left-lateral displacement on Idrija fault can be explained by structural anisotropy and local permutation of principle stress axis inside the complex zone of the fault. Oblique displacement with left-lateral component on the Raša fault is partly in agreement with fault plane solutions, although right-lateral movements are expected according to regional geological data.

It would be more important than correlation of micro-deformation monitoring with regional geological and earthquake data if correlation with detail terrestic geodetic or very dense GPS measurements were made. This will only allow for assessment of the sense and rate of movement along individual faults. Unfortunately, no such data are available in the area till now. Performed micro-deformation monitoring with TM 71 instruments provide therefore the first direct proof of recent active tectonic deformations along these faults, especially along Idrija and Raša faults where displacement rates of up to 0.5 mm/year are already significant for seismic hazard studies.

Both devices in Postojna cave system seem to record similar reaction by the end of 2004. One suggestion is to explain such a reaction as a late response to 12 July, 2004 (Mw=5.2) earthquake with epicentre 70 km away from the measuring site. Since there were no other stronger earthquakes in the vicinity and time span of monitoring, no other correlations were established with local earthquake activity.

Mocchiutti and D'Andrea (2002) studied the recent tectonic movements in NE Italy. In the area of Udine (NE Italy) some mechanical measuring instruments (extensometers, fissure meters and pendulum) have been positioned. The monitoring with one of these extensometers in a karst cave has shown a movement of 0.12 mm from 1999 to 2002, which represents the similar order of movement as found in Postojna cave system.

In addition to described four monitoring sites in W Slovenia a fifth one was set up in November 2006 at Kneža fault near Tolmin (Zadlaz-Čadrg).

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REFERENCES

Bemmelen, R. W.: 1970, Tectonische Probleme – der Östlichen südalpen. Geologija, 13, 133-158.

Buser, S., Grad, K. and Pleničar, M.: 1967, Basic geologic map of Yugoslavia. scale 1: 100.000, sheet Postojna, Geological Survey, Ljubljana.

Čar, J. and Pišljar, M.: 1993, Cross section of the Idrija fault and the course of the Učja valley regarding the fault structures. Rudarsko-metalurški zbornik, 40/1-2, 79-91.

EARS 2004: Earthquake catalogue for the years 567-2004. Environmental Agency of the Republic of Slovenia. Seismology and geology office.

Fitzko, F., Suhadolc, P., Aoudia, A. and Panza, G.F.: 2005, Constraints on the location and mechanism of the 1511 Western-Slovenia earthquake from active tectonics and modeling of macroseismic data. Tectonophysics, 404, 77-90.

Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M. and Šribar, L.: 1996, Geological map of the southern part of the Trieste-Komen plateau. Geological Survey of Slovenia, 143.

Kastelic, V., Živčić, M., Pahor, J. and Gosar, A.: 2006, Seismotectonic characteristics of the 2004 earthquake in Krn mountains. Potresi v letu 2004, EARS, 78-87.

Kavčič, M.: 2006, Displacement measurements along some faults in W Slovenia by extensiometers. Graduation thesis. University of Ljubljana, 118.

Košťák, B.: 1991, Combined indicator using Moire technique. Proc. 3rd int. symp. on field measurements in geomechanics, Oslo, 53-60.

Michelini, A., Živčič, M. and Suhadolc, P.: 1998, Simultaneous inversion for velocity structure and hypocenters in Slovenia. J. Seismol., 2, 257-265.

Mocchiutti, A. and D'Andrea, A.: 2002, Morphologic evidence of recent and modern tectonic movements in some caves of the Friuli Prealps (northeastern Italy). Mem. Soc. Geol. It., 57, 487-491.

Poljak, M., Živčić, M. and Zupančič, P.: 2000, The seismotectonic charateristics of Slovenia. Pure and Applied Geophysics, 157, 37-55.

Ribarič, V.: 1979, The Idrija earthquake of March 26, 1511 – a reconstruction of some seismological parameters.Tectonophysics 53, 315-324.

Sasowsky, I.D., Šebela, S. and Harbert, W.: 2003, Concurrent tectonism and aquifer evolution >100,000 years recorded in cave sediments, Dinaric karst, Slovenia, Environmental Geology, 44, 8-13.

Šebela, S.: 1998, Tectonic structure of Postojnska jama cave system. ZRC, 112, Ljubljana.

Šebela, S., Gosar, A., Košťák, B. and Stemberk, J.: 2005, Active tectonic structures in the W part of Slovenia - setting of micro-deformation monitoring net. Acta Geodyn. Geomat., 2/1(137), 45-57.

Stemberk, J., Košťák, B. and Vilimek, V.: 2003, 3D monitoring of active tectonic structures. J. of Geodynamics, 103-112.

Vrabec, M. and Fodor, L.: 2006, Late Cenozoic tectonics of Slovenia: structural styles at the Northeastern corner of the Adriatic microplate. In: Pinter, N. et al. (eds.): The Adria Microplate: GPS Geodesy, Tectonics, and Hazards, 151-168, Springer.

Vrabec, M., Pavlovčič Prešeren, P. and Stopar, B.: 2006, GPS study (1996-2002) of active deformation along the Periadriatic fault system in northeastern Slovenia - tectonic model. Geol. Carpath., 57/1, 57-65.

Weber, J., Vrabec, M., Stopar, B., Pavlovčič Prešeren, P. and Dixon, T.: 2006, The PIVO-2003 experiment: a GPS study of Istria peninsula and Adria microplate motion, and active tectonics in Slovenia. In: Pinter, N. et al. (eds.): The Adria Microplate: GPS Geodesy, Tectonics, and Hazards, 305-320, Springer.

Zupančič, P., Cecić, I, Gosar, A., Placer, L., Poljak, M, and Živčić, M.: 2001, The earthquake of 12 April 1998 in the Krn Mountains (Upper Soča valley, Slovenia) and its seismotectonic characteristics. Geologija 44/1, 169-192.