Micro-displacement monitoring in caves at the Southern Alps–Dinarides–Southwestern Pannonian Basin junction

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Abstract
In situ micro-displacement monitoring in caves at the seismically active junction of the Southern Alps, Dinarides and Southwestern Pannonian Basin revealed active tectonic micro-deformations. The largest total vertical movement of 0.35 mm (2008–2018) occurred at Kostanjeviška Jama (Southwestern Pannonian Basin–Dinarides). Two abrupt displacements observed at that cave location correspond to pre- and post-seismic episodes in 2014 and 2015. At Pološka Jama (Southern Alps), more gradual and continuous displacement on a monitored bedding plane of 0.13 mm down-slip (2008–2018) was observed. This movement is attributed to slope relaxation as well as tectonic activity on the Julian Alps thrust fault and the seismogenic Ravne Fault, which generated earthquakes at $M_w = 5.6$ in 1998 and $M_w = 5.2$ in 2004. At Jama pri Svetih Treh Kraljih in Dinarides, activity on the Ravne Fault was shown as sinistral-horizontal (0.1 mm) and vertical (0.15 mm) movement along an E–W-oriented tectonic structure. This shallowly buried site also experienced cyclic seasonal displacements. At Županova Jama, multiple short-term horizontal dextral and sinistral strike-slip pulses (2016–2018) demonstrated active tectonic micro-deformations within the wider zone of the Dobrepolje and Želimlje faults. At Postojnska Jama, two episodes of vertical movement on a NW–SE-oriented fault are associated with earthquake swarms: the first episode was in 2010 ($M_{LV} = 3.7$) and the second in 2014 ($M_{LV} = 4.3$). In-cave flood events do not coincide with periods of micro-displacement activity in the studied caves, and therefore are not the drivers of the micro-displacement.

Keywords Micro-displacements · TM71 extensometer · Active tectonics · Caves · Slovenia

Introduction

Caves represent natural archives of information beneath the Earth’s surface; they can be more than 100,000 or even more than a million years old and can be treated as “natural boreholes”. Caves and karst areas can preserve evidence of palaeoseismic events (Kagan et al. 2005; Šebela 2008; Becker et al. 2012; Sanz Pérez et al. 2016), and especially caves are also highly suitable locations for studies of neotectonic deformations (Mariani et al. 2007; Šebela et al. 2010a, b; Littva et al. 2017). With regard to such studies, some researchers have suggested the term “cavitonics” (Littva et al. 2015), because a generally accepted term for the study of tectonics in caves is lacking.

To study active tectonics in Slovenian caves by means of micro-displacement monitoring, the first two TM71 extensometers (Košták et al. 2007) were installed in Postojnska Jama in 2004. Another two caves (Kostanjeviška Jama and Pološka Jama) were equipped during 2008, and two more (Jama pri Svetih Treh Kraljih and Županova Jama) in 2011. There is just one gauge in each of the latter four caves, whereas the Postojnska Jama instrumentation has recently been increased to four gauges. Each instrumentation site was chosen to enable capture of data about different types of tectonic structures (faults, fissures, bedding planes) belonging to different geotectonic units: the External Dinarides (Postojnska Jama, Jama Svetih Treh Kraljev, Županova Jama), the
Southern Alps (Pološka Jama) and the Southwestern Pannonian Basin (Kostanjeviška Jama).

Monitoring of micro-displacements using TM71 extensometers is taking place at numerous sites (~300) in Europe and worldwide and is commonly sited in karst caves in significant faults and fissured zones (Briestenský et al. 2007, 2015, 2018; Gosar et al. 2009; Šebela et al. 2010a; Baroň et al. 2016, 2019), along slope deformation structures (Petro et al. 2004; Stemberk et al. 2017; Baroň et al. 2016), on surface outcrops within active tectonic zones (Košťák et al. 2007; Stemberk et al. 2015, 2019a) and in artificial tunnels (Petro et al. 2005, 2011; Stemberk and Košťák 2008).

Active tectonic displacements are observed on the Earth’s surface with geological, seismological, geodetic and satellite observations (Vičič et al. 2019; Grenerczy et al. 2005). There is a lack of such observations beneath the surface even if we have some studies in boreholes and mines. Karst caves as natural openings in carbonate rocks represent valuable sites for micro-displacement monitoring. Caves are generally developed between important regional faults and not directly on the fault zones, because underground karst water preferably uses opened fractured zones forming underground passages (Šebela 1998). This is important for theoretical innovation in understanding micro-displacements in tectonically active regions by organization of the underground micro-displacement monitoring. In this way, we will not get big tectonic movements as are observed on big regional fault zones, but we will get micro-displacements, which are mostly underestimated in regional geodynamic models but hold important information for regional active tectonic situation. Information obtained by micro-displacement monitoring is important also for understanding active processes forming karst caves.

In the current study, selection of the extensometric observatories was based upon the locations of epicentral areas in Slovenia and the recognition of potentially active faults in the caves. Other important factors were monitoring-site accessibility and access to desirable (electrical and data transmission cables). Only the monitoring sites at Pološka Jama and Jama pri Svetih Treh Kraljih, which are not show caves, lack access to electricity.

The aim of the study is to detect in situ long- and short-term micro-displacement trends in karst caves within the zones of influence of the Ravné Fault, Predjama Fault, Želimalje Fault, Žužemberk Fault and Brežice–Koprivnica Fault. Study focused upon detection of tectonic micro-displacements in the context of tectonic activity in the area around the junction of the Southern Alps, the Dinarides and the Southwestern Pannonian Basin.

Slovenia’s tectonic setting

Slovenia is part of a convergent-margin zone between the Adria Microplate and the Eurasian Plate (Castellarin et al. 2006; Burrato et al. 2008). It is characterized by moderate seismicity related to faulting. There are five significant fault zones: (1) the South Alpine thrust zone, (b) the Istria–Friuli thrust zone, (c) the Dinaric strike-slip fault zone, (d) the Periadriatic transpressive fault zone and (e) the Zagreb–Mid-Hungarian shear zone (Atanackov et al. 2016, 2021). The Dinaric area (Fig. 1) is characterized mainly by sub-vertical faults with directions ranging between NW–SE and NNW–SSE, the most important of which are the Idrija line and its auxiliary faults (Placer 1981).

Earthquakes located in western Slovenia, where the Moho is 45–50 km beneath the surface, display higher shear-wave attenuation than do those beneath Italy’s eastern Po plain where the Moho is shallower. The zone of interaction between the Southern Alps and the External Dinarides is characterized by a more diffuse and less intense seismicity (Gentili and Franceschina 2011).

A right-lateral motion of $3.8 \pm 0.7$ mm/year on active faults oriented N317° in the Northern Dinarides was determined by Moulin et al. (2016). According to the authors, the Northern Dinarides absorb most of the Adria–Eurasia motion, thus representing the northeastern boundary of the microplate. They propose an additional shortening component oriented approximately W–E with a magnitude of 1–2 mm/year. The motion of the Adria Microplate imposes far-field stresses that are transferred farther eastwards (Moulin et al. 2016).

The present-day surface kinematic model for the Alpine region during the period 2004–2016, based on a high-level GNSS dataset (Global Navigation Satellite System), is dominated by the counter-clockwise motion of the Adria Microplate, causing compression in the Eastern Alps and dextral shear in the Central Alps (Sánchez et al. 2018). In the Alps–Dinarides–Pannonian Basin junction zone, horizontal velocities in the range 1–4 mm/year relative to the stable part of the Eurasian Plate are present. These large relative velocities are controlled by the north-eastward motion of the Adria Microplate towards the Southern and Central Alps and the Dinarides. The southern part of the Eastern Alps shows a slower vertical uplift rate of about 1–1.5 mm/year. A pronounced N- and NE-oriented movement was found in the Southern and Eastern Alps, as well as in the Apennine Peninsula, the Venetian–Friuli Basin and the Dinarides. Measurements confirmed a fault system in a W–E direction along the boundary between the Southern Alps and the Adriatic region. There is evident shortening of about 2 mm/year across the southern front of the Eastern Alps. In the
Dinarides a shortening of about 3 mm/year across the Adriatic coastline is found. This magnitude decreases toward the Pannonian Basin, reducing to 0.5 mm/year. There is shortening across the south-eastern front of the Alps and the northern part of the Dinarides. At present, the largest shear strain is detected in the south-eastern part of the Alps. The Dinarides show a compressional strain with a right-lateral shear (Sánchez et al. 2018).

Faults in southwestern Slovenia have become progressively more steeply dipping during the evolution of the External Dinarides (Kastelic and Carafa 2012). Currently, they are steep to sub-vertical and are active as strike-slip faults (Kastelic et al. 2008). The calculated long-term horizontal velocity field shows a general SSW–NNE orientation with magnitudes decreasing from the crustal areas of the External Dinarides (Kastelic and Carafa 2012). Active faults in southwestern Slovenia absorb only 0.3–0.4 mm/year of the overall 2 mm/year horizontal velocities, representing 20% of the regional compression. With such low slip rates along these faults, a significant part of the Adria–Eurasia convergence is transmitted inland. The slip rates are most likely underestimated, however, reflecting the absence of data related to active faults in the Southern Alps in the model of Kastelic and Carafa (2012).

In Slovenia, the modest body of morphological evidence of offsets related to active tectonics (Kastelic et al.

**Fig. 1** Tectonic setting of Slovenia with principal faults, strongest earthquakes and TM71 extensometer locations (modified after Šebela et al. 2010b). Legend: 1 — caves equipped with TM71 extensometer devices (1 — Postojnska Jama; 2 — Pološka Jama; 3 — Kostanjeviška Jama; 4 — Jama pri Svetih Treh Kraljih; 5 — Županova Jama). 2 — earthquake (EQ) epicentres (1 — Idrija EQ 1511 (MW=6.3, Falcucci et al. 2018); 2 — Zagreb EQ 1880 (MW=6.3, Kozák and Čermák 2010)); 3 — Ljubljana EQ 1895 (ML=6.1 after Ribarič 1982) and Mw=6 after Tiberi et al. (2018)); 4 — Brežice EQ 1917 (MW=5.6 after Ribarič 1982) and Mw=5.0 after Nečak and Cecić (2018)); 5 — Cerkljna EQ 1926 (M=5.8, Ribarič 1982)); 6 — Ilirska Bistrica EQ 1956 (M=5.1, Vidrih and Godec 2006)); 7 — Bovec EQs 1998 (Mw=5.6) and 2004 (Mw=5.2) Kastelic et al. 2008). 3 — Eastern Alps; 4 — Southern Alps; 5 — Dinarides; 6 — Pannonian Basin.
The thrusting of the Adria Microplate, along with pushing by the Africa Plate, may be causing the sub-lithospheric elevation of the Pannonian region (Šumanovac and Dudjak 2016). The push exerted by the Africa Plate on the one hand, together with extension in the Pannonian Basin caused by the asthenosphere rising in the opposite direction, have caused the Adria Microplate to be thrust beneath the Pannonian segment of the Eurasian Plate (Šumanovac and Dudjak 2016).

Methodology

Micro-displacements along selected faults, fissures and bedding-planes have been measured by specially designed TM71 extensometers (e.g. Košťák et al. 2007; Marti et al. 2013; Klimeš et al. 2012), which help to measure 3D deformations and block rotations in two planes perpendicular to each other. The gauge represents optical-mechanical crack gauge, using moiré patterns (Košťák 1969). These moiré patterns appear, when two glass plates with specially designed spirals or circles overlap and undergo small displacement. This is the principle of the gauge, which includes two sets of the glass sheets, one in vertical and one in horizontal plane. Afterward, the moiré patterns are transformed into the metric system by counting moiré fringes. The gauge provides an accuracy of ±0.005 mm along three orthogonal axes (x, y and z) (Rowberry et al. 2016). At the same time two rotations are measured in horizontal and vertical planes (xy and xz) with a precision of ±0.00016 gon (Košťák et al. 2007; Stemberk et al. 2015; Briestenský et al. 2007, 2015), where a gon (gradian) is a unit of angular measurement equivalent to π/200 of a radian or 9/10 of a degree. In the last years, higher resolution was computed, which could reach 0.000087 rad (Rowberry et al. 2016).

Micro-displacements are observed in 3 mutually perpendicular directions (Fig. 2) along the x, y and z axes, in Cartesian coordinates, where x is the amount of opening (−x) or closing (+x) between two surfaces, y is dextral (−y) or sinistral (+y) horizontal movement and z is vertical displacement. Sense of the displacements can be sometimes different regarding a way of installation. Two planes of rotation (measured in gons) represent rotation of a vertical plane (xz) and of a horizontal plane (xy).

Data are usually collected manually once a month by taking photographs of two glass plates. Some monitoring sites, with access to electricity, were equipped with cameras to record images (to be interpreted) automatically once per day (Postojna 3 and Postojna 4 in 2016; Županova Jama in 2018).

The areas near the measurement sites were mapped in detail geologically, especially with regard to their structural geological characteristics, including indications of older tectonic displacements. Postojnska Jama, Jama pri Svetih Treh Kraljih and Županova Jama belong to
The tectonic unit of Dinarides (Fig. 1) that are cut by thrusts and Dinaric-oriented (NW–SE) faults as Raša, Predjama, Idrija, Želimlje, Žužemberk and Stična faults (Fig. 1). Pološka Jama is part of Southern Alps tectonic unit (Fig. 1) while Kostanjeviška Jama belongs to the border zone between Dinarides and Pannonian Basin (Fig. 1).

Postojnska Jama

The cave is situated in the southwestern part of Slovenia, within the Dinarides, with tectonically active Dinaric (NW–SE) and cross-Dinaric (NE–SW) faults (Fig. 1). Cave passages lie between the Idrija and Predjama faults and are developed in Upper Cretaceous limestones. There are numerous broken speleothems in the cave, some of which are thought to have been damaged by tectonic activity (Šebela 2008). Detection of active displacements and recognition of the effects of strong prehistoric earthquakes can be achieved only by careful study of the palaeo-environmental records and evidence of events not related to tectonics, such as glaciations, sediment creep, and catastrophic floods (Becker et al. 2012).

The Dinaric-oriented (NW–SE) fault zone that is situated 1.5 km north of the regionally important Predjama Fault and runs through Velika Gora and Lepe Jame in Postojnska Jama (Fig. 3a), has been monitored by two TM71 extensometers since 2004. At Postojna 1, the TM71 is installed across the contact between the fault plane representing the Velika Gora collapse chamber’s northern wall (dip direction/dip angle 30°/80–90°) and a large (2 × 2 × 1 m) collapsed limestone block (Fig. 4). At Postojna 2, about 300 m northwest, the TM71 is installed across two fault planes (Figs. 3 and 4). The northern fault plane (30°/60°) shows horizontal slickensides indicative of dextral movement and the southern one (30°/80–90°) carries vertical slickensides (Fig. 4).

During October 2016, two additional instruments were installed on the Dinaric-oriented (NW–SE) fault zone that lies about 300 m south of Velika Gora. Postojna 3 is located on the limestone wall (220°/80°) at the northern edge of...
the Koncertna Dvorana collapse chamber, which coincides with the fault zone (Figs. 3 and 4). Postojna 4 is in a lateral chimney passage, fitted across a fault plane with the opposite dip direction (30°/60°; Figs. 3 and 4).

All four TM71 instruments in Postojnska Jama are in dry passages, away from flooded underground channels (Fig. 3), to eliminate potential effects of water-level oscillations on micro-displacements.

**Pološka Jama**

The cave monitoring site, where monitoring commenced on 19 June 2008, is in the Julian Alps, about 300 m south of the Ravne Fault (Fig. 1). It is developed in Dachstein (Upper Triassic: T₃²+3) bedded limestone (Buser 1986). There is an upper entrance at 1249 m above mean sea level and two lower entrances at 720 and 730 m (Fig. 5) on the eastern slope of Krn Mountain (2244 m). The cave, which is 10,800 m long and 704 m deep, lies between 250 and 800 m south of the Ravne Fault. The extensometer is installed about 50 m inside the cave, between two slipped bedding planes (Fig. 6a, b) that dip 40° towards the southeast. The Julian Alps Thrust (SE-verging and parallel to the monitored bedding plane), a major active regional structure within the Southern Alps geotectonic unit (Poljak 2000), passes about 200 m beneath the monitoring site. According to Poljak (2000), the contact with the Southern Alps geotectonic unit over-riding the Internal Dinarides is about 4.5 km south of the monitoring site (Fig. 1).

According to Rižnar et al. (2007) the South Alpine Thrust (Southern Alps on Fig. 1; according to Poljak 2000) is the...
most active structure in western Slovenia in the sense of vertical movement. A maximum of 7 mm/year of relative vertical movement has been observed along the Sečovlje–Bled (Adriatic Sea–Julian Alps) levelling profile. The activity of the Julian Alps Thrust is also obvious, but it is minor compared to that of the South Alpine Front (Rižnar et al. 2007).

Fig. 4 Four locations of TM71 extensometer monitoring installations in Postojnska Jama. Postojna 1 — Velika Gora; Postojna 2 — Lepe Jame; Postojna 3 — Koncertna Dvorana; Postojna 4 — chimney

Fig. 5 Location of the TM71 extensometer in Pološka Jama, and simplified block model (on the right) showing results of micro-deformation monitoring. Legend: 1 — slipped bedding plane with dip direction and dip angle in degrees; 2 — bedding-plane with dip direction and dip angle in degrees; 3 — fault with dip direction and dip angle in degrees; 4 — position of the TM71 extensometer, 5 — site where a large limestone block (1 × 0.5 × 0.5 m) collapsed after the 1998 Bovec earthquake (Mw = 5.6). The cave’s upper entrance is to the northwest
According to Milanič et al. (2009), recent tectonic activity was determined for the Julian Alps Thrust and also, though less clearly, for the South Alpine Front.

Pološka Jama is a typical Alpine cave, only suitable for safe access and study by trained speleologists. This was the main reason that only the southeastern part of the cave underwent tectonic mapping (Fig. 5). The presence of Dinaric-oriented faults and fissures in this area indicates that the cave is within the wider Ravne Fault zone. As well as Dinaric-oriented tectonic structures, slipped bedding planes that dip toward the southeast are particularly common in this zone.

Moreover, Pološka Jama was selected because of its proximity to the 12 April 1998 ($M_w = 5.6$) earthquake activity on the Ravne Fault. According to personal communications from speleologists, following this earthquake some freshly fallen blocks were noticed in the cave (Fig. 5). The hypocentre of another earthquake in 2004 ($M_w = 5.4$) was also close to Pološka Jama.

The Ravne Fault is an active NW–SE-trending dextral strike-slip fault. In the current north-directed maximum horizontal stress regime, this segmented fault is lengthening through active growth at its northwestern end. In the upper parts of the crust the activity is distributed over a wide deformation zone that includes reactivated brittle thrust faults (Kastelic et al. 2008). The Ravne Fault cuts through the Southern Alps Thrust along its northwestern and central segments (Kastelic et al. 2008).

Willingshofer and Cloetingh (2003) detected uplift of the central zone of the Eastern Alps and the Southern Alps, and eastward motion of fault-bounded blocks. According to the authors, such a deformation pattern is best explained as reflecting lateral extrusion superimposed upon north–south compression.

Displacement of bedding-planes is visible in the walls of some cave passages. Translations of up to 5 cm (Fig. 6b) have been noted, in the same directional sense as the ongoing motion determined by the TM71 monitoring.

**Kostanjeviška Jama**

At 1871 m length and 47 m depth, this is the longest cave yet known in the high-relief Gortjanci Mountains in southeastern Slovenia, where the highest peak is Trdinov Vrh–Sveta Gera (1178 m). The cave entrance is at elevation 170 m, and there is about 70 m of limestone overlying the monitoring site. The cave is occasionally still active upper outflow of the Studena stream, which flows northwards to the Krka River. Kostanjeviška Jama’s entrance passages (Fig. 7) are developed in bedded Lower Cretaceous limestones (Šikić and Pleničar 1975). The TM71 instrument is installed in a cross-Dinaric-oriented fracture zone (140°/80°) at the southwestern end of Kapniška Dvorana chamber. The site lies about 1 km south of the main northern branch of the Brežice–Koprivnica Fault. In the study area, this is a neotectonic fault with sinistral horizontal movement and reverse vertical movement, with uplift of the southeastern block (Verbič 2005). The structure was identified as a reverse fault on the southern limb of the Krško Syncline, as a build-up of several reverse faults and backthrusts, with NNW–SSE maximum horizontal compressive stress. The main northern branch of the Brežice Fault is the main seismic source structure on the southern limb of the Krško Syncline (Verbič 2005). Monitoring of micro-displacements in Kostanjeviška Jama began on 17 June 2008.

**Županova Jama**

This cave is situated near the Želimlje, Dobrepolje and Žužemberk faults (Fig. 9a), which are possible seismogenic sources for the 1895 Ljubljana earthquake ($M_w = 6$; Tiberi et al. 2018).

Županova Jama is situated within the External Dinarides (Poljak 2000; Placer 2008). In terms of its geology (Buser 1974), the area consists of Western Dolomjska Mesozoic rocks, which are cut by Dinaric (NW–SE) faults. According to Poljak (2000), the Žužemberk Fault is well expressed morphologically, and can be followed south-eastwards from Ljubljana and along the valley of the River.
Fig. 7 Kostanjeviška Jama. a Structural geology. 1 — fault or fissure with left-horizontal movement; 2 — fault with dip direction and dip angle in degrees; 3 — TM71 location. b Simplified block model showing results of micro-displacement monitoring
Krka. This fault is deduced to be active with dextral horizontal strike-slip movement, as is typical for other Dinaric faults in this part of Slovenia (Fig. 1).

The southwestern block of the Dobrepolje Fault comprises Triassic rocks and is uplifted, and the northeastern block consists of Jurassic rocks that are relatively down-faulted (Buser 1968). Dextral horizontal movements are also detected along this fault. According to Placer et al. (2010), the vast area between the Southern Alps, the Velebit Mountains and the Želimlje Fault is recently tectonically active due to the rotation and underthrusting of the Istria Peninsula northeastwards beneath the External Dinarides.

Županova Jama is developed within Jurassic limestones, with its current entrance at 410 m above sea level. The cave was formed by a predecessor of the Podlomščica creek, which nowadays runs at lower altitudes nearby (at ~340 m).

According to Gospodarič (1987), rocks that form Tabor hill (492 m) near the cave are folded to form the Tabor Syncline, which separates areas with different lithological units — dolomites in the east and limestones in the west. Županova Jama lies on the northeastern limb of the syncline.

According to Gospodarič (1987) faults in the vicinity of the Tabor Syncline are sub-vertical, mostly with horizontal NW–SE slickensides. The author also describes N–S displacements between bedding planes and faults.

Left-horizontal movements as well as vertical movement with uplift of the northwestern block were detected along some of the cross-Dinaric (NE–SW) sub-vertical faults and fissures. On 08 October 2011, a TM71 extensometer was installed in the southern part of Matjaževa Dvorana, between two sub-vertical fissures (110°/90° and 115°/90°) that are 1 m apart (Fig. 6c, d). The 115°/90° fissure shows vertical movement (uplift of the northwestern block relative to the southeastern block (Fig. 9b).

Results and discussions

Micro-displacements detected by the extensometers

Postojnska Jama

The Postojna 1 and 2 sites showed small micro-displacements, <0.08, mm during the period 2004–2018 (Fig. 10). Overall displacements recorded at Postojna 1 during the 2004–2018 period are 0.07 mm dextral strike-slip, 0.03 mm subsidence of the northern block, and 0.053 mm fault extension. Overall displacements recorded at Postojna 2 during the same 2004–2018 period are 0.06 mm dextral strike-slip, 0.03 mm subsidence of the northern block and 0.038 mm fault extension. Deformation at the Postojna 1 and 2 sites manifests dominantly as dextral strike-slip movement (Fig. 10). Karst caves are very stable environments regarding the air temperature and humidity. In Postojna Cave, air temperature fluctuation during the 1-year long period, in the area where TM71 extensometers are located, is <0.8 °C and relative humidity is 95–100% (Šebela and Turk 2011). Micro-tectonic displacements detected with TM71 extensometers cannot be related to such small differences in air temperature and humidity.

Eight notable events were observed simultaneously at the Postojna 1 and Postojna 2 sites (Fig. 10(A–H)). They all display strikingly similar patterns, generally with relative subsidence of the northern block and uplift of the southern block,
together with sinistral strike-slip. This initial phase, which can be defined as a stage of compression, was followed by a relaxation stage, typified by an opposite faulting mechanism.

Two well-expressed short-term vertical displacements (D and F, Fig. 10) were recorded at the Postojna 1 site. The first (D) reached 0.07 mm normal fault movement (between readings on 20 August 2009 and 27 January 2010) and the second (F) showed 0.044 mm normal fault movement (23 March–03 July 2014). The sense of motion is subsidence of the cave wall and uplift of the cave floor (Fig. 3b). Those two periods of accelerated normal displacements were followed by reverse displacements, which are ascribed to relaxation. Rotation on the $xz$ (vertical) plane was 0.04 gon during Episode D. An earthquake swarm beneath the Pivka Valley, 15–20 km south of the Postojna 1 site, observed by Vičič et al. (2017, 2019), fits the (D) episode. The strongest earthquake during that time in the vicinity of Postojna ($M_{LV}=3.7$) occurred on 15 January 2010. It showed seismic activity on an almost-vertical fault plane in two possible directions, the first being N165°E with dextral-horizontal movement and the second being SSW–NNE with sinistral-horizontal movement (Živčić et al. 2011).
Such movement (Fig. 3b) and earthquake swarm during the same period supports the view that real tectonic micro-displacements were being observed; the displacements are not logically attributable to other loads such as forces related to karst water oscillation or karst collapses (destabilization of the cave floor).

At the Postojna 2 site during the D episode (02 October 2009 to 12 August 2010), sinistral-horizontal (0.05 mm) and dextral-horizontal (0.05 mm) movements were detected. During episode H, the Postojna 2 site showed a significant dextral-horizontal displacement of 0.039 mm (10 August–04 October 2017) and...
vertical displacement (normal fault, subsidence of the northeastern block) of 0.033 mm (01 June–10 August 2017). Rotation of the $xz$ plane was 0.08 gon. The only earthquake recorded in the area with $M < 2.0$ occurred in January 2017 at a distance of 15 km from Postojna. No corresponding anomaly was observed at Postojna 1 during this period. Therefore, we consider this displacement to be occurring aseismically.

The records for the Postojna 3 and Postojna 4 sites (Fig. 10) contain only 2 years of measurements. They show no displacements, during the 2017–2018 period. Notice that the Postojna 1 site was also quiet during this period.

The micro-displacements detected by the TM71 extensometers in Postojnska Jama confirm that the area between the Idrija and Predjama faults is active tectonically. These two faults are essentially parallel to each other (Fig. 1) and might merge at depth (Moulin et al. 2016). At the Avče site, about 40 km northwest of Postojna, the horizontal slip rate on the Predjama Fault is $1.6 \pm 0.5$ mm/year (Moulin et al. 2016). When averaged over the last 255 ka, mean slip rates of $1.15 \pm 0.15$, $1.45 \pm 0.25$ and $1.3 \pm 0.2$ mm/year are yielded along the Idrija, Predjama and Raša faults respectively (Moulin et al. 2016). According to Moulin et al. (2016) activation of the Predjama and Raša faults during the Late Pleistocene–Holocene and the onset of vertical deformation (folding and vertical movement on faults) were coeval.

Pološka Jama

Long-term displacement of 0.13 mm (2008–2018; Fig. 11) in Pološka Jama manifests as down-slip along the dipping bedding planes and can mostly be related to slope-relaxation deformations. However, some of the deformations could be associated with tectonic activity along the Julian Alps Thrust (Fig. 1), about 200 m beneath the cave. Short-term episodes of thrusting (displacements in the opposite sense to the long-term trend) were observed during November 2009–April 2010 and June 2011–November 2011. During the second pulse, a horizontal extension between two bedding-planes of up to 0.24 mm was detected. The fact that this extension was preceded by a 0.09-mm compression affirms the tectonic origin of the pulse. These reverse-displacement pulses illustrate the fact that the Julian Alps Thrust is still tectonically active.

According to Buser (1986), marly limestones and marls are present about 1 km beneath the extensometer site. The relatively weak constitution of these lithologies could be an additional cause for slope instability at the monitoring site. The slope deformations detected in Pološka Jama are probably related to the Julian Alps Thrust (SE-verging and parallel to the monitored bedding-plane) within the Southern Alps geotectonic unit (Poljak 2000) and to active displacements connected with the southwestern block of the Ravne Fault (long-term relaxation).

Kostanjeviška Jama

Among all of the TM71 monitoring sites, the largest displacement, with a vertical movement of 0.35 mm between 2008–2018, and subsidence of the southeastern block (Fig. 12), is registered along a NE–SW-oriented fault zone in Kostanjeviška Jama. Much of this vertical displacement occurred in two tectonic pulses, the first of 0.2 mm (April–June 2014) and the second of 0.15 mm (May–June 2017). Such short-term steps would not be related to underground karst water oscillations, but rather to pre and post seismic earth movements. Moreover, dextral horizontal movement of 0.1 mm was observed during the same period, also accelerated during the two cited pulse events. Rotation in the $xy$ plane reached 0.12 gon in February 2019.

Results of the monitoring of displacements in Kostanjeviška Jama are interesting. They are valuable in helping to understand the active tectonic conditions in the Krško Valley, particularly relevant to the stability of the Krško nuclear power plant, which is situated 13 km north of the TM71 monitoring site. Results to date demonstrate the ongoing subsidence of the Krško Valley.

Jama pri Svetih Treh Kraljih

This site displayed a sinistral strike-slip micro-displacement of 0.1 mm along a W–E-oriented fault in the first half of 2012 (Fig. 11). The motion was accompanied by compression (closing of the fault) of a similar magnitude and a 0.28-mm uplift of the southern block. The fault also exhibits seasonal dilation and relaxation, due to the close proximity to surface climate conditions. Vertical displacement was also seasonally cyclic, but it also showed overall 0.15 mm (2011–2018) downs lip of the northern block. Shortly after the 0.28-mm uplift of the southern block in 2012, it subsided 0.2 mm. This displacement, which could be described as accelerated subsidence of the northern block, was followed by uplift of the block at the end of 2012. The evidence from this site demonstrates ongoing tectonic activity within the wider zone of the Ravne Fault, which lies some 800 m north of the cave and about 30 km southeast of the epicentres of the 1998 and 2004 earthquakes (Fig. 1). It supports the idea that W–E-oriented Triassic faults (Čar 2010) are still active.
Unlike the sites discussed above, this locality shows no significant long-term trends in displacements, but reflects changes in the stress-field of the surrounding massif. The only potential overall trend relates to vertical rotation, but this was interrupted by a significant disturbance during the 2015–2018 period. Ten pulses (Fig. 11) display the same pattern: sinistral strike-slip, fault closing, and uplift of the eastern block. The largest pulse was observed during July–September 2017, with 0.15 mm of sinistral strike-slip. All the micro-displacements here can be considered as reversible; they point to tectonic micro-deformations in the wider zone of the Tabor Syncline and the Dobrepolje Fault.

**Micro-displacement pulses and seismic events**

Bursts of seismicity along fault systems in SW Slovenia were detected during 2009–2010 at seismogenic depths...
and correlated with clear changes within the pattern of deformation as exhibited by continuous records from the TM71 extensometers in Postojnska Jama (Vičič et al. 2019).

Normal fault movement of 0.044 mm at the Postojna 1 site (23 March–03 July 2014) can be linked with the earthquake near Pivka on 22 April 2014 (\( M_{LV} = 4.3 \)) and to the earthquake-swarm period (April to December 2014) near Pivka, which registered 400 earthquakes with \( M_{LV} = 0.3–2.5 \) (Živčić et al. 2016). For the \( M_{LV} = 4.3 \) earthquake, analysis of fault plane data showed almost vertical sinistral-movement of strike-slip faults with a cross-Dinaric orientation (N070°E) (Ložar Stopar and Živčić 2016).

In Kostanjeviška Jama (Fig. 12), the most active vertical micro-displacement period (06 April–26 June 2014) follows by some months the \( M_{LV} = 3.6 \) (16 June 2013) and \( M_{LV} = 3.7 \) (13 March 2014) earthquakes, situated 40 km west of the cave and 10 km E of Ribnica (Suha Krajina) (Čarman et al. 2016). An earthquake swarm (\( N = 2947 \)) persisted from June 2013 to December 2014 (with some additional earthquakes in 2015, the strongest on 11 December 2015 \( M_{LV} = 2.4 \)) (Čarman et al. 2016). The best-expressed micro-displacement activity episode in Kostanjeviška Jama, during 2014, can be attributed to post-seismic deformations (related mainly to the \( M_{LV} = 3.7 \) event on 13 March 2014) and pre-seismic deformations (related to the \( M_{LV} = 4.2 \) event on 01 November 2015, Gorjanci Mountains) (Čarman et al. 2015).

The second well-expressed episode of micro-displacement (06 May–22 June 2017) in Kostanjeviška Jama coincides with more recorded local seismic events (Fig. 12) in the period June 2016 to February 2018.

Short-term episodes of micro-displacement activity in Županova Jama between 2017 and 2018 did not coincide with known earthquakes in the immediate vicinity, and must also be regarded as aseismic deformations.

The changing pattern of micro-displacements in caves at the seismically active junction of the Southern Alps, Dinarides and Southwestern Pannonian Basin is related to slope instability and tectonic activity on the Julian Alps thrust fault and the seismogenic Ravne Fault in Pološka Jama. The largest vertical movements that occurred at Kostanjeviška Jama (Southwestern Pannonian Basin–Dinarides) correspond to pre- and post-seismic episodes in 2014 and 2015 in the vicinity of the cave. Micro-displacements at Jama pri Svetih Treh Kraljih are connected with the tectonic activity of Ravne Fault. Tectonic micro-deformations within the wider zone of the Dobrpolje and Želimlje faults (Figs. 1 and 9) are reflected at Županova Jama site. Two periods of earthquake swarms in 2010 and 2014 impacted micro-displacements at Postojnska Jama monitoring site.

### Extensometric monitoring over the European plate

The Slovene TM 71 localities were developed as part of the European monitoring network TecNet (EU TecNet 2021) set up in the framework of the COST 625 project “3-D monitoring of active tectonic structures” (Borre et al. 2003; Stemberk et al. 2003; Tondi et al. 2005). TM71 extensometers are installed as part of the network with the aim to detect displacements along selected fault structures and stress-field regime changes in significant tectonic and seismic regions Worldwide. Recent results showed e.g. transient periods of displacement acceleration in the Central Apennines (Stemberk et al. 2019a), regarding L’Aquila 2009 and Norcia 2016 earthquakes; displacements in advance to distinct local earthquakes in the Eastern Alps (Baroň et al. 2019); movements during significant earthquake in Malé Karpaty Mts. in 2006 (Briestenský et al. 2007); pressure pulse during 2003 in Bohemian Massif (Košták et al. 2011); remarkable slip event that lasted from September 2011 to May 2012 in Hornusund in Spitsbergen (Stemberk et al. 2015); periods of acceleration with switching between two compressional stress/strain states in Rychlebské Hory Mts. (Stemberk et al. 2019b). Additionally, more studies described: significant tectonic pulse at the end of 2012 and the beginning of 2013 in distant areas of the European plate (Briestenský et al. 2015); evidence of a simultaneous micro-displacement anomaly in the second half of 2014 to the beginning of 2015, which were interpreted as occurrence of a tectonic pressure pulse (Briestenský et al. 2018). A significant period of increased tectonic activity was monitored between 2013 and 2015 on the eastern margin of the Bohemian Massif that revealed an NNW–SSE striking compressional component of the stress field (Briestenský et al. 2021). Moreover, previous studies using TM71 devices proved that anomalous displacements can occur due to deformation propagating through great distances in the heterogeneous block medium of the West European part of the Eurasian plate (Košták et al. 2007), related to strong earthquakes in Iran (1997) and in the North Anatolian fault zone in Turkey (1999).

In general view, the Slovene TM71 cave sites do not show as high micro-displacements as some other European cave sites (Briestenský et al. 2015, 2021). But comparison of micro-displacements in caves from the area of Western Carpathians, External Dinarides in Slovenia and Tian Shan showed simultaneous displacement anomalies as propagation of a tectonic pressure pulse towards the end of 2012 (Briestenský et al. 2015). On the other hand, some Slovene TM71 cave sites show clear dependence of micro-tectonic movements on local seismic events as was the case in 2010 and 2014 at Postojnska Jama. As in other European TM71 sites also in Slovenia more years-long calm periods without movements traverse to tectonically very active periods or opposite.
High floods and micro-displacements in caves

Two high-flood events took place during micro-displacement monitoring in Postojnska Jama, the first between 18 and 19 September 2010 (Šebela 2012) and the second between 05 and 20 November 2014. Both flood events succeeded periods of micro-displacement activity and therefore cannot have been their cause.

High floods on 13 September 2014 destroyed a large part of Kostanjeviška Jama (Fig. 12) but did not flood the TM71 instrumentation site, which was situated in a remote cave room above the reach of high waters. Here also the high waters succeeded a period of micro-displacement activity earlier in 2014 and so cannot have been its cause.

Conclusions

Micro-displacement monitoring using eight TM71 extensometers has been under way since 2004 in five Slovene karst caves at the seismically-active junction of the Southern Alps, the Dinarides and the southwestern Pannonian Basin. All the instruments were installed near or across active faults: the Predjama Fault (Postojnska Jama), the Ravne Fault (Pološka Jama and Jama pri Svetih Treh Kraljih), the Dobrepolje and Želimlje faults (Županova Jama), and the Brežice-Koprivnica Fault (Kostanjeviška Jama). Results indicate the following:

- Areas near active faults can undergo both long-term micro-displacements and brief pulses of significant micro-displacement activity.
- Micro-displacements are sporadic. At some sites, years-long calm periods were observed, interrupted by significant displacement episodes occurring over short periods (months or less).
- In the case of the high-Alpine cave Pološka Jama, in situ micro-displacement monitoring demonstrates not only tectonic effects but also down-slope deformation.
- Periods of micro-displacement activity (tectonic pulses) can be related to nearby seismic activity, to pre- and post-seismic deformations, and also to aseismic deformations.
- All of the TM71 monitoring sites were located in stable cave passages that are no longer used by active karst streams or currently affected by active karst subsidence. Flood events in the caves studied did not coincide with periods of micro-displacement activity and therefore were not found to be the cause of micro-displacements.
- Karst caves can provide valuable components of a micro-deformation monitoring network.

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