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Can deep seated gravitational slope deformations be activated by regional tectonic strain: First insights from displacement measurements in caves from the Eastern Alps

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ABSTRACT

Tectonic elastic strain and ground deformations are documented as the most remarkable environmental phenomena occurring prior to local earthquakes in tectonically active areas. The question arises if such strain would be able to trigger mass movements. We discuss a directly observed fault slip and a subsequent minor activation of a deep-seated gravitational slope deformation prior to the M = 3 Bad Fischau earthquake between end of November and early December 2013 in NE Austria. The data originate from two faults in the Emmerberg and Eisenstein Caves in the transition zone between the Eastern Alps and the Vienna Basin, monitored in the framework of the FWF "Speleotect" project. The fault slips have been observed at the micrometer-level by means of an opto-mechanical 3D crack gauge TM-71. The discussed event started with the fault activation in the Emmerberg Cave on 25 November 2013 recorded by measurements of about 2 μm shortening and 1 μm sinistral parallel slip, which was fully in agreement with the macroscopically documented past fault kinematics.
One day later, the mass (micro) movement activated on the opposite side of the mountain ridge in the Eisenstein Cave and it continued on three consecutive days. Further, the fault in the Emmerberg Cave experienced also a subsequent gravitational relaxation on 2/3 December 2013, when the joint opened and the southern block subsided towards the valley, while the original sinistral displacement remained irreversible. The process was followed by the M = 3 earthquake in Bad Fischau on 11 December 2013.
Our data suggest that tectonic strain could play a higher role on the activation of slow mass movements in the area than expected. Although we cannot fully exclude the co-activation of the mass movement in the Eisenstein Cave by water saturation, the presented data bring new insight into recent geodynamics of the Eastern Alps and the Vienna Basin. For better interpretations and conclusions however, we need a much longer period of observations.

1. Introduction

Studies on contemporary regional tectonic strain are essential for a better understanding of recent tectonic processes and earthquake triggering (e.g. Papadimitriou et al., 2006) as it is one of the most remarkable environmental phenomena controlling local earthquakes (e.g. Kawakata et al., 2006; Tronin, 2010; Grant et al., 2011; Whitehead and Ulusoy, 2013; Wu et al., 2013; Zhao, 2010). Ground deformations can be observed at a distance of up to several tens of kilometres from the future epicentre by seismological methods (Bowman and King, 2001) or by means of remote-sensing approaches like radar interferometry (for references see Tronin, 2010). Along single activated faults associated to the main fault systems, the tectonic strain usually shows up as small displacements at micrometre-scale (Stemberk et al., 2008).

The question arises if such regional tectonic strain was able to trigger mass movements. Possible influence of active tectonics on deep-seated gravitational slope deformations (DSGSD) and other landslides is a frequently discussed topic throughout the literature (for the reference review, see e.g. Agliardi et al., 2009). Such influence could be direct or indirect; the indirect control is considered to be especially through the impact of tectonic deformation on the pattern of joints as future detachment planes and zones of weakness (Gupta, 2005), and through the

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major role of tectonic forces in shaping the mountain topography, especially on the spatial orientation of valleys and drainage networks (e.g.: Abrahams and Flint, 1983; Embleton, 1987; Ollier, 1981; Pohn, 1983; Scheidegger, 1980). Direct control is considered to happen by shaking due to differential loading by seismic waves. According to Keefer (1984), all types of landslides can occur due to seismic tremors; at slopes in a marginally stable state even a weak earthquake could activate mass movement, e.g. a rockfall. About 20% of all registered landslides worldwide are supposed to be triggered by earthquakes (Wen et al., 2004) and significant casualties and material losses are associated with landslides triggered by earthquakes. Co-seismic landslides sometimes produce more victims than are due to building damage (García-Mayordomo et al., 2009), which seems to be also the case in the April 25, 2015, magnitude 7.8 Gorkha earthquake in Nepal (Petley, 2015).

However, the link between aseismic regional tectonic strain and DSGSDs in Alpine terrains still remains rather unknown. Here we discuss a directly observed fault slip and a subsequent minor mass movement activation prior to an M = 3 earthquake between end of November and early December 2013 in the Southern Vienna Basin (Austria).

2. Methods

The presented data originate from two out of seven sites, where we observe the contemporary displacements along active faults in the Eastern Alps in the framework of the Speleotect monitoring network (Baroň et al., 2014, 2015, Fig. 1). The fault slips are observed at the μm-level in 3D inside caves by means of TM-71, which is an opto-mechanical crack gauge device fixed to respective fault planes (Klimeš et al., 2012). The method gives excellent results in terms of accuracy, resolution and durability of long term monitoring of very slow displacements (Košt'ák, 1991, 2006; Stemberk et al., 2010; Briestenský et al., 2010, 2014).

The measuring principle is based on the mechanical interference between glass indicators with two optical grids causing moiré patterns (Koš'ák and Popp, 1966; Klimeš et al., 2012; Marti et al., 2013). Our glass indicators contain spiral grids with a density of 20 gratings per mm for displacement and the parallel-line grids of 100 lines per mm for rotations. The moiré patterns have to be transformed into the metric system by counting moiré fringes in the displacement and rotation fields of the glass plates, identifying the axis of symmetry and then solving specific mathematical equations (Koš'ák and Popp, 1966). The centre to centre distance between the glass plates is calculated using the number of fringes and the direction of the displacement as indicated by the principal axis of the symmetry pattern (see, for example, Rowberry et al., in print). When only the number of fringes is considered the instrumental resolution is 0.025 mm but this can be improved up to one micron by measuring changes in the principal axis (Rowberry, pers. comm.). The transformation is done manually and recently also automatically using a Matlab (MathWorks®) code (Marti et al., 2013). The most up-to-date comprehensive description of the TM-71 device and its application for active-tectonic purposes was recently presented by Briestenský et al. (2015).

The TM-71 devices were installed permanently and are measuring displacements and rotation of two respective blocks (i.e. both sides of the cave passages that are intersected by the faults) in 3D. Three-dimensional monitoring is important as displacements between joint faces are frequently accompanied by a rotational component (Košt'ák, 1991, 2006). The TM 71 crack gauges are complemented with automatic meteorological stations (registering air temperature, pressure and humidity at the devices) and devices for automatic readings based on web cameras connected to field computers. The measurements have

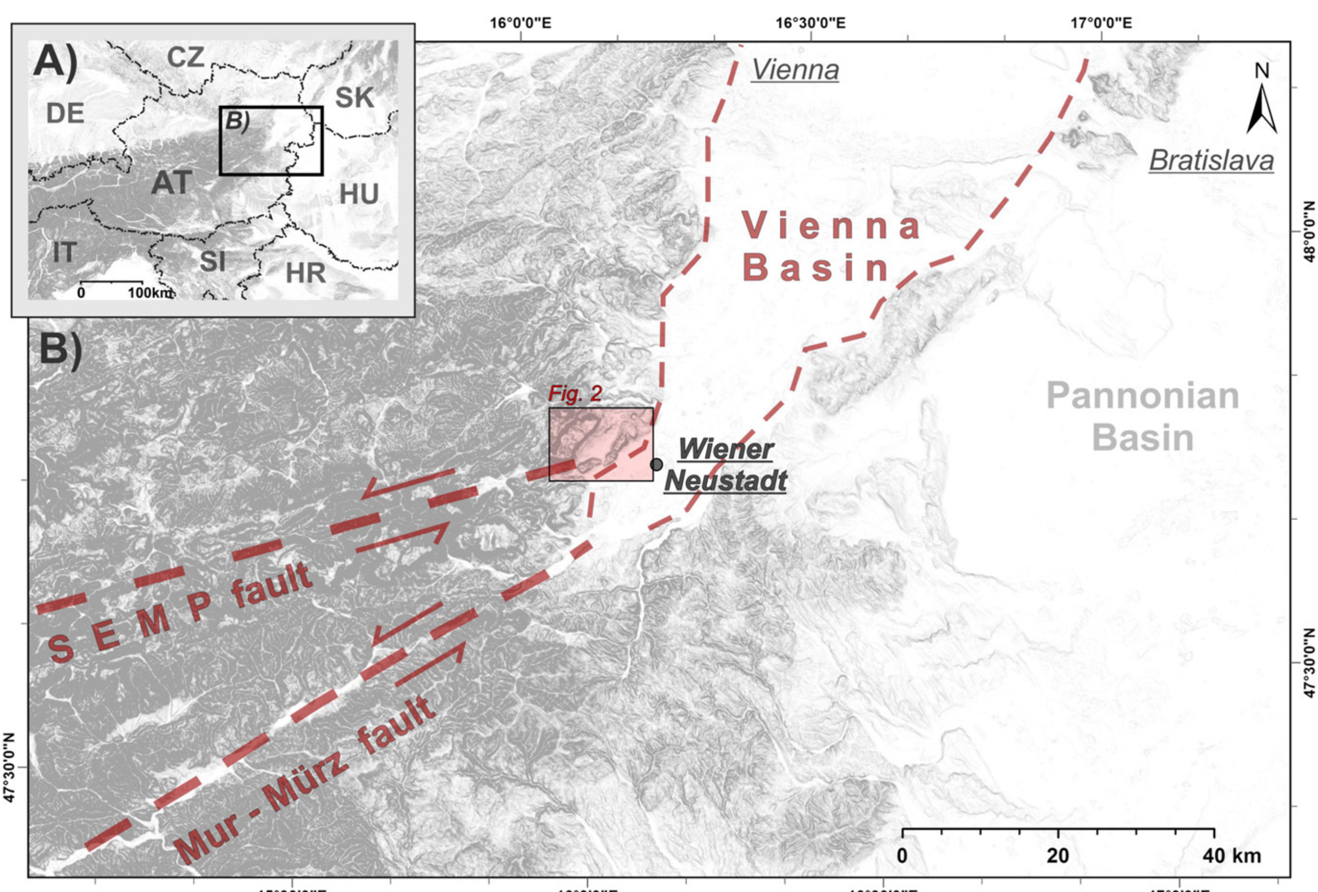

Fig. 1. Location of the study area: A) Position in Central Europe and B) general active-tectonic settings; SEMP – Salzach-Ennstal-Mariazell-Puchberg Fault (slope-gradient map in greyscale with horizontal as white and vertical as black derived from SRTM topographic data by USGS/NASA).

been recorded here on a daily basis at 00:00 a.m. UTC. The caves, where the devices are installed, serve as a perfect environment for such observations, because they are shielded from external factors, especially from thermal fluctuations and there from resulting volumetric changes of rock and of the iron arms that connect the particular glass indicators to the respective fault surfaces.

Data from nearby seismic stations were used to monitor the seismic activity in the area of interest. These stations belong to the national seismic network (Zentralanstalt für Meteorologie und Geodynamik, ZAMG) and the University of Technology in Vienna (TU Wien) in the framework of the project Schools and Quakes (Brückl et al., 2015). The combined analysis of these stations leads to a relatively good location accuracy in the Vienna Basin in the order of 1 km. The closest station is installed in Wiener Neustadt (Fig. 1).

The presented event occurred at two monitored faults in the Eisenstein and Emmerberg Caves at the eastern margin of the Alps in eastern Austria (Figs. 1 and 2). The monitoring devices are located in these caves about 15 and 43 m below the ground surface, respectively.

3. Geological and tectonic setting

Both caves are situated in the transition zone between the Eastern Alps and the Vienna Basin (Fig. 1B). This is a junction of the active left-lateral Salzach-Ennstal-Mariazell-Puchberg (SEMP) fault system and the southern part of the Neogene Vienna Basin pull-apart structure associated with the active left-lateral Mur-Mürz fault zone (Linzer et al., 2002; Plan et al., 2010). Regarding the regional tectonic stress field, the eastern part of the Eastern Alps and the western Pannonian basin are both a complex transition zone between the European, the Pannonian, and the Adriatic stress provinces, where horizontal as well as vertical stress decoupling is evident across the orogen (Reinecker and Lenhardt, 1999). The two caves are located about 3.5 km apart from each other (Fig. 2), so we assume similar tectonic stress fields in their surroundings.

The Emmerberg Cave is a 150 m-long karst cave which developed in Triassic Wetterstein limestone at a crest of the Fischauer Hills (Fig. 2). The altitude of the cave entrance is 430 m a.s.l. and the relative elevation is about 85 m above the local erosion base (the Neue Welt Basin). Due to its morphology and the relation to other nearby caves it is likely that the cave originated due to rising hydrothermal waters (hypogene speleogenesis; Plan et al., 2009). The remotest passage of the cave is dissected by a sinistral strike-slip fault (with dip direction/dip angle 342/86 and azimuth/plunge of the fault lines 254/05) with an active offset (i.e. younger than the dissolutional cave passage) of 4 cm. The fault is straight, open at places, partly filled with reddish clay, has no distinct syn-tectonic mineralization, and can be associated with the SEMP fault activity (Fig. 3).

The Eisenstein Cave is situated at the opposite slope of the Fischauer Hills facing the tectonically active Vienna Basin near its western marginal fault (Fig. 2). The 2.3 km-long cave is developed in limestone, breccia and sandstone of Miocene age; it has a crevice character along a suspected N-S-orientated fault (estimated from the position of the cave near the fault scarp of the Vienna Basin) filled by numerous huge boulders that result in a complex maze. The fault itself is not exposed within the cave. The deepest parts of the cave reach a hydrothermal water level 73 m below the entrance. The 15.5 °C hydrothermal spring, high CO_2 content in the air (up to 2%), characteristic morphologic features, and speleothems indicate phases of a hypogene speleogenesis or at least overprint (Plan et al., 2009). However, the cave profile and our new interpretation of the high-resolution digital terrain models of the cave surroundings show that the cave is associated with the detachment zone of a DSGSD superimposed on the Vienna Basin boundary fault (Fig. 4).

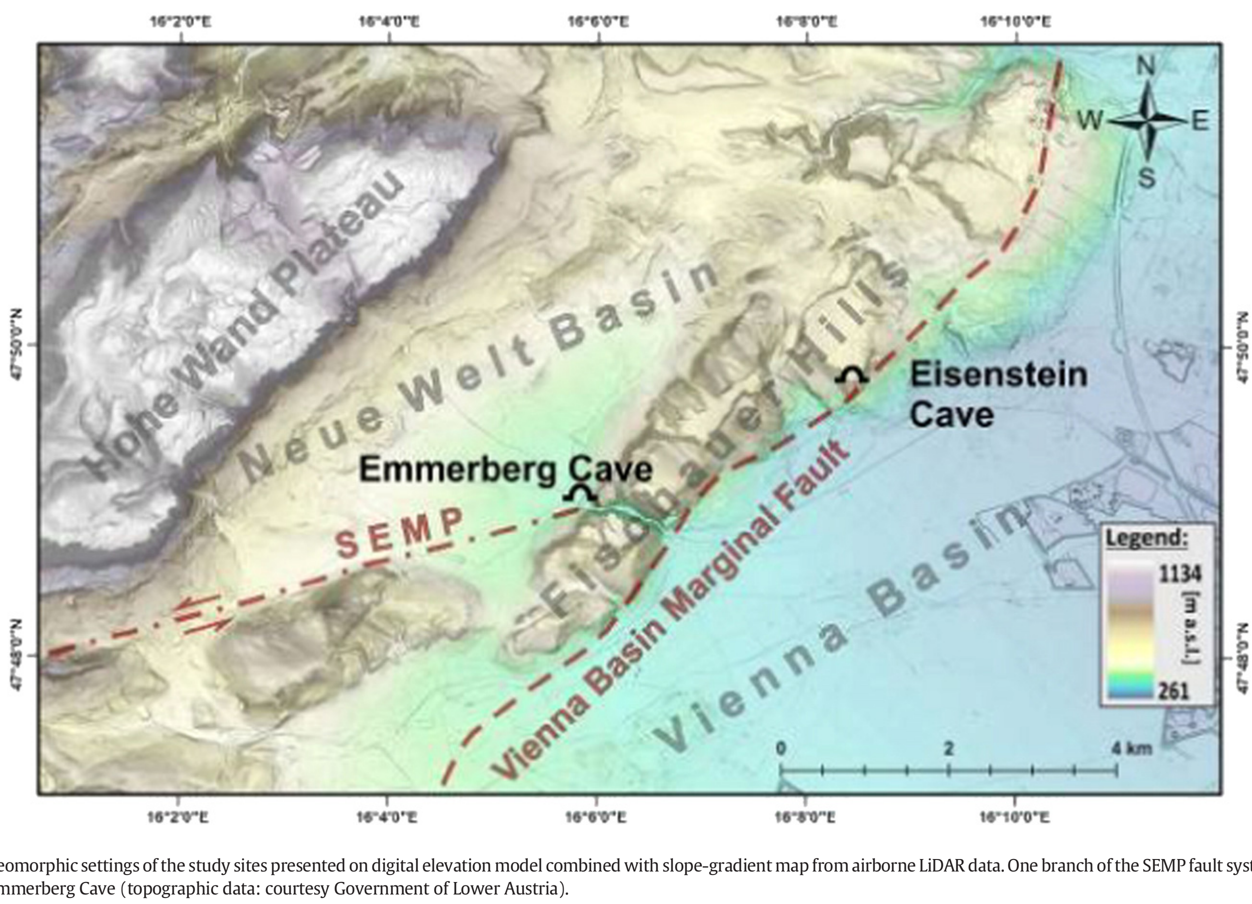

Fig. 2. Geomorphic settings of the study sites presented on digital elevation model combined with slope-gradient map from airborne LiDAR data. One branch of the SEMP fault system leads to the Emmerberg Cave (topographic data: courtesy Government of Lower Austria).

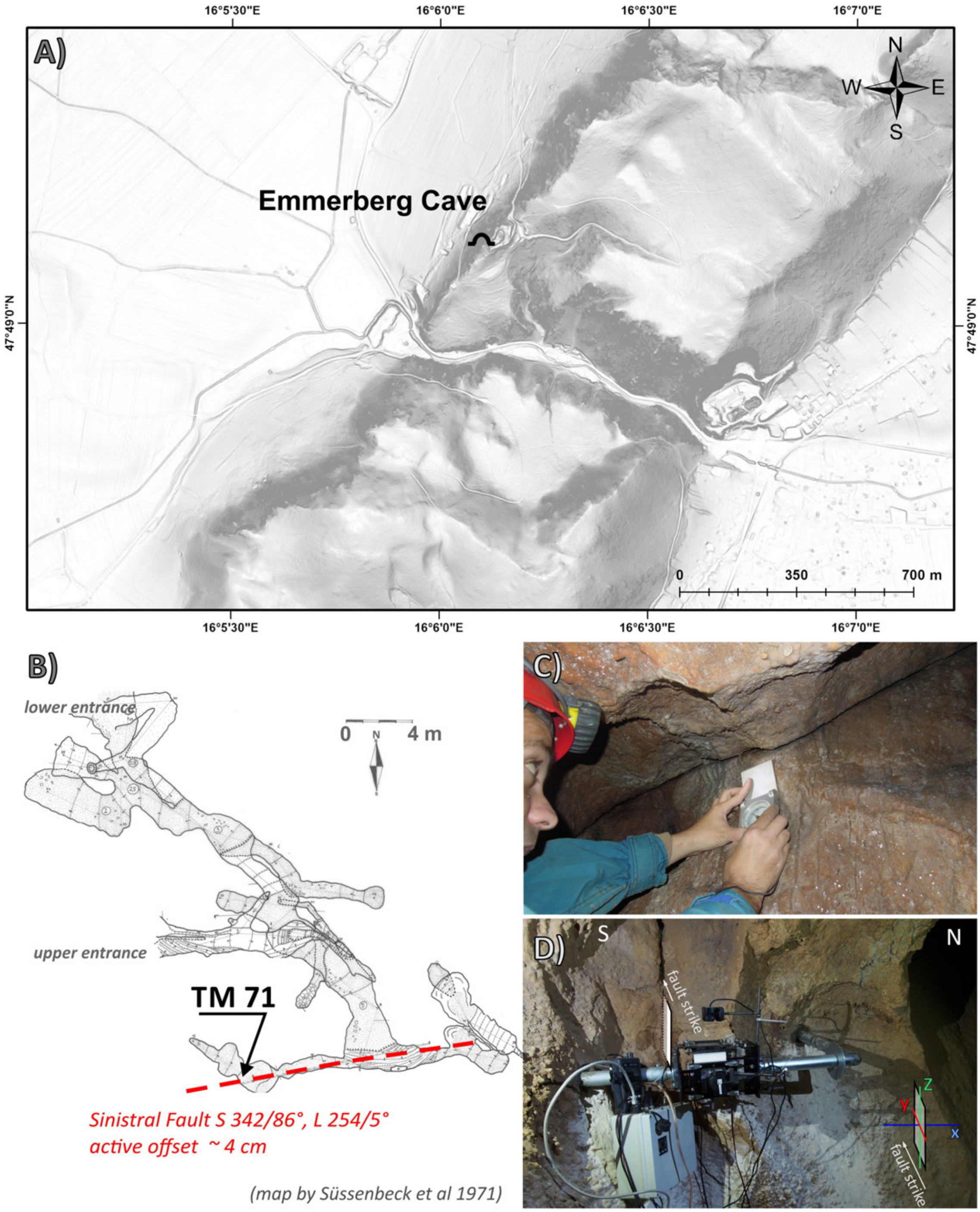

Fig. 3. The Emmerberg Cave: A) slope-gradient map of the cave surroundings from airborne LiDAR data (topo data: courtesy Government of Lower Austria), B) speleological map of the cave with location of the monitored fault and crack gauge TM71 device (after Süssenbeck et al., 1971), C) close view at the fault plane (note the apparent dextral character of the offset due to upward view), and D) on-site situation of the TM71 device.

Therefore it can be seen as a crevice cave that was in some parts significantly overprinted by hypogene speleogenesis.

4. Results

4.1. Fault-slip activity

The first displacement event was recorded on 25 November 2013 in the Emmerberg Cave (Fig. 5) with 2 μm compression and 1 μm sinistral slip, and the western part of the fault relatively opened of about 0.02°. The rotational opening of the fracture already started one data-reading prior to the registered slip (Figs. 5 and 6). This event, although it was on the limit of the resolution of our TM-71 devices, is in agreement with the macroscopically documented active fault kinematics.

One day later, on 26 November, a slip started also at the monitored dislocation in the Eisenstein Cave (Fig. 6). During this event, the eastern block subsided about 40 μm towards the Vienna Basin, rotated about 0.015 grad along the horizontal axis (lower part of the fracture opened) and the crack extended about 30 μm with a

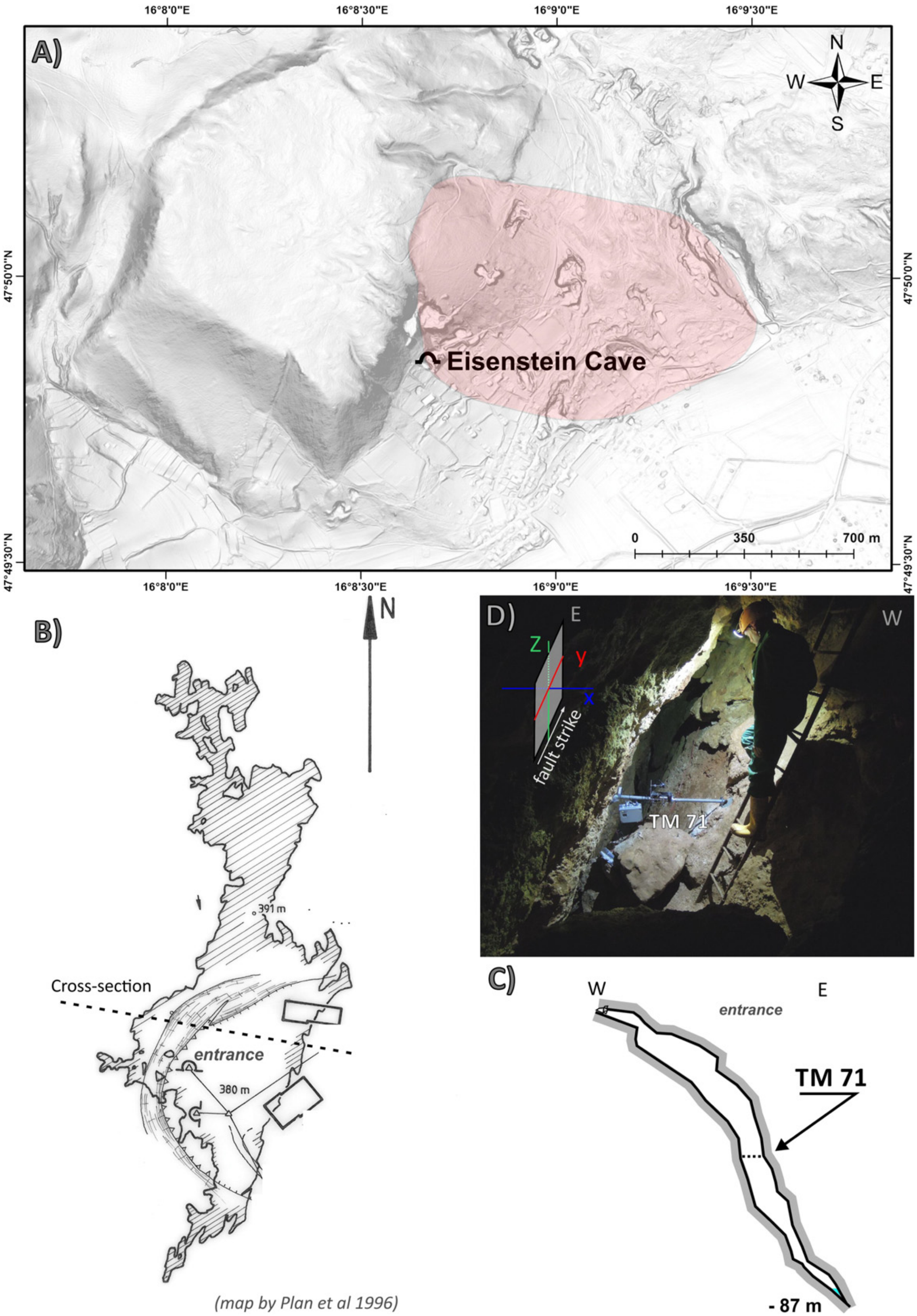

Fig. 4. The Eisenstein Cave: A) slope-gradient map of the cave surroundings from airborne LiDAR data with marked deep-seated gravitational slope deformation in red (topographic data: courtesy Government of Lower Austria), B) speleological map of the cave (after Plan et al., 1996), C) highly simplified cross section of the cave with location of the crack gauge TM71 device, D) photograph of the TM71 device.

minor dextral component. This particular motion is in good agreement with the suspected kinematics of the DSGSD. The sum of displacement reached 0.05 mm from 26 November to 28 November and then it stopped. Since then, there was no more slip activation in the Eisenstein Cave until April 2015. It should be noted that there was an intensive rainfall event prior to the movement reaching

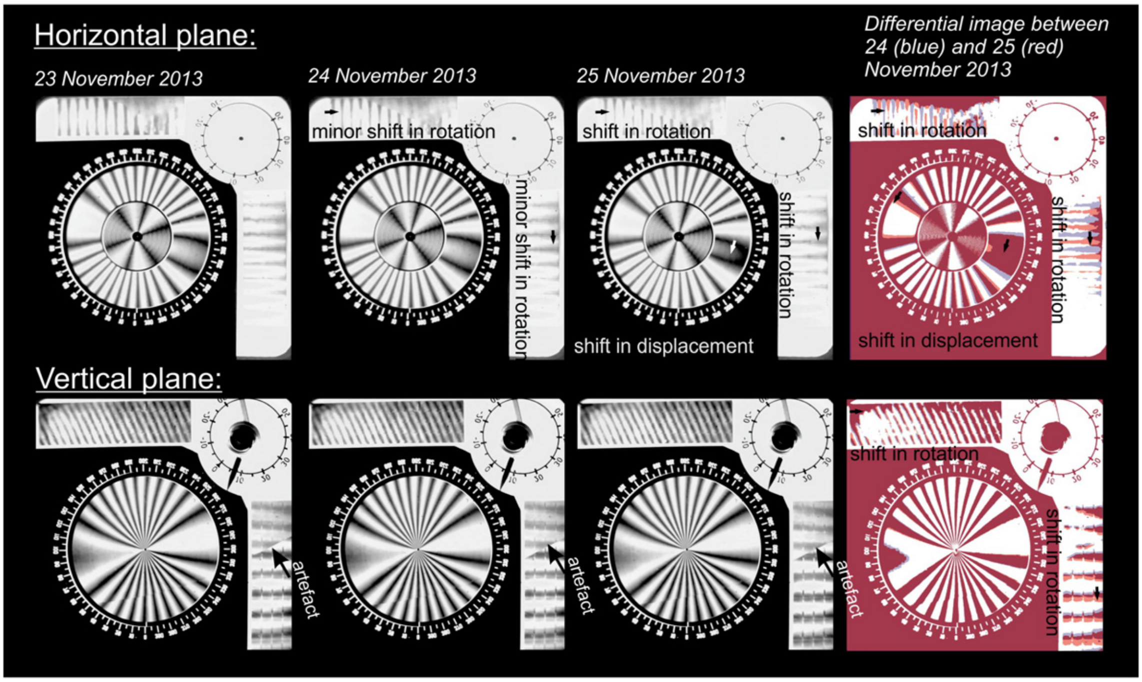

Fig. 5. Moiré patterns of the November 2015 event recorded in the Emmerberg Cave on the horizontal and vertical planes; differential images (right) illustrate the shift in the moiré pattern. Note the artificial change due to water between glass indicators.

65 mm in ten days with the highest concentration in the three days prior to the event (data from the Wiener Neustadt station of ZAMG, Fig. 6).

Nine days later on 2 December 2013, the fault in the Emmerberg Cave experienced another micro displacement event when the joint opened about 40 μm and the southern block subsided 10 μm towards the valley (Fig. 6). This was probably a subsequent gravitational relaxation following the previous sinistral event.

4.2. Seismicity

The national Austrian seismic network registered no seismicity during or immediately before the time period of these fault-slip events (from the 24th of November to the 2nd of December). However, a distinct earthquake of M = 3 occurred on 11 December 2013, at 17:14:10 p.m. UTC in Bad Fischau with the epicentre about 6.4 km ESE of the Emmerberg Cave and 4.4 km SE of the Eisenstein Cave at 47.8° N and 16.18° E. The hypocentre was 14 km below the ground surface. Given the sparse network geometry, the manual ZAMG solution of focal mechanism for this event cannot be better constrained than shown in Fig. 7.

The focal mechanism of the earthquake suggests either a flat/steep E-W normal faulting where the western part relatively subsided or oblique SE-NW reverse faulting. This is somewhat unusual for the ongoing sagging tendency of the Vienna Basin. Such an event of magnitude M = 3 at the given depth would consume a fault plane of a few 100 m², with a displacement of 1 cm or less.

5. Discussion

The presented slip event, which we observed from mid-November to beginning of December 2013 along with two monitored fractures (Fig. 7), brings new and exciting data on recent geodynamics of the transition zone between the Eastern Alps and the Vienna Basin.

The event started with the fault activation in the Emmerberg Cave accommodating about 2 μm compression and 1 μm sinistral slip on 25 November 2013, which was fully in agreement with the macroscopically documented past fault kinematics. It is acknowledged that these recorded displacements are at the limit of the instrumental resolution of the TM-71 (see, for example, Marti et al., 2013 and Rowberry et al., in print). However, as the pattern of the moiré fringes clearly changed during this event (Fig. 5) also rotating its axis of symmetry of about 1° and local air temperature did not change significantly, we are sure that these displacements are not an instrumental noise or an artefact from thermal/volumetric changes.

One day later, the gravitational mass (micro) movement activated on the opposite side of the mountain ridge in the Eisenstein Cave and it continued on three consecutive days. Further, the fault in the Emmerberg Cave experienced also a subsequent gravitational relaxation on 2/3 December 2013, when the joint opened and the southern block subsided towards the valley, while the original sinistral tectonic displacement remained irreversible. The process was followed by the M = 3 earthquake in Bad Fischau on 11 December 2013.

We unfortunately cannot fully exclude that the activation of the mass movement in the Eisenstein Cave was co-triggered by water saturation, as relatively intensive rainfall of a total of 65 mm, mostly concentrated in three days, occurred before this event. Later on, there was no more future activation of the mass until April 2015 even after much heavier rainfall on 7–16 May 2014, when 117 mm of rainfall occurred. Therefore it seems to us that, although the deep-seated gravitational deformation was saturated and loaded with water, it would have stayed stable without a triggering impulse. We suspect that the triggering impulse could have been given by a much deeper lithospheric tectonic process indicated here by the sinistral strike slip in the Emmerberg Cave one day in advance.

These observed displacements that occurred near the ground surface more than 10 km away from the future M = 3 earthquake hypocentre, had surely no direct influence on the hypocentre to generate or trigger such an earthquake as elastic tectonic strain built-up, earth

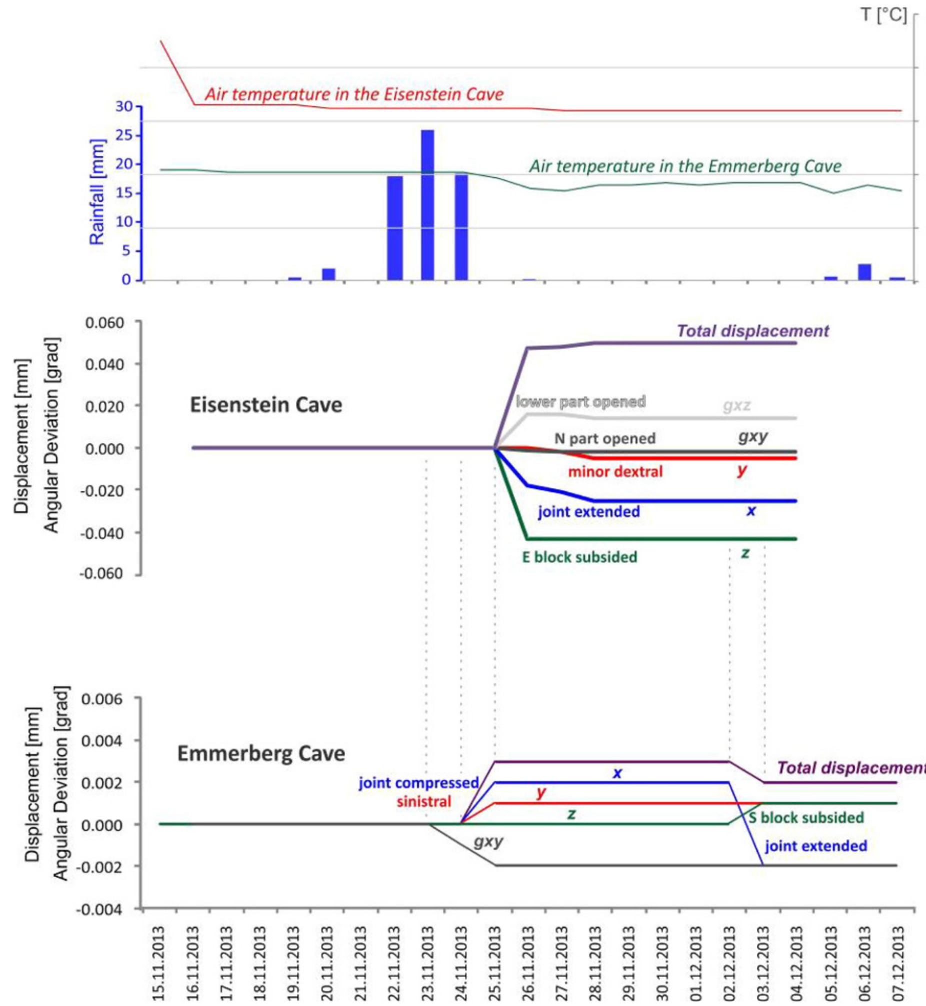

Fig. 6. Results of the fault-slip monitoring in the Emmerberg and Eisenstein Caves showing all spatial components of the movement: x = horizontal displacement perpendicular to the fault plane, y = horizontal displacement parallel to the fault plane, z = vertical displacement, gxy = rotation along the horizontal plane, gxz = rotation along the vertical plane. Rainfall data from the nearby station in Wiener Neustadt (about 6.5 km E of the Eisenstein Cave; see location on Fig. 1B) are presented in the upper part of the figure (rainfall data: courtesy of ZAMG).

tides, atmospheric pressure changes and transient seismic waves from remote earthquakes exhibit more stress changes on the hypocentre than the observed micrometer-displacements on the ground surface.

On the other hand, we suspect that both these displacement events indicated a regional elastic tectonic strain, which could be expected to occur prior to the 11 December 2013 Bad Fischau earthquake similarly to those effects reported by e.g. Kawakata et al. (2006); Tronin (2010); Grant et al. (2011); Whitehead and Ulusoy (2013) or Wu et al. (2013). For more solid interpretations and conclusions we would, however, need much more independent data and comprehensive numerical modelling. We only can notice that these first tangible data evidenced reasonability of such precise measurements for studying the relation between active tectonic deformations and their effect on triggering of DSGSD and other types of landslides.

6. Conclusions

Despite all of the above mentioned uncertainties, we can conclude that by means of high-accuracy 3-D measurements along the faults in caves, we were able to record both the active-tectonic and slope-failure related displacements, which seem to be correlated. They both occurred prior to the local M = 3 Bad Fischau earthquake of 11 December 2013. This suggests that tectonic deformations could play a higher role in the activation of slow mass movements in the area than expected. This could be of great importance for those unstable masses, where transformation into catastrophic gravitational slope failure is to be expected. For better interpretations and conclusions from our sites, we need a much longer period of observation to have more events to be analysed, and verification by independent methods, like e.g. numerical modelling.

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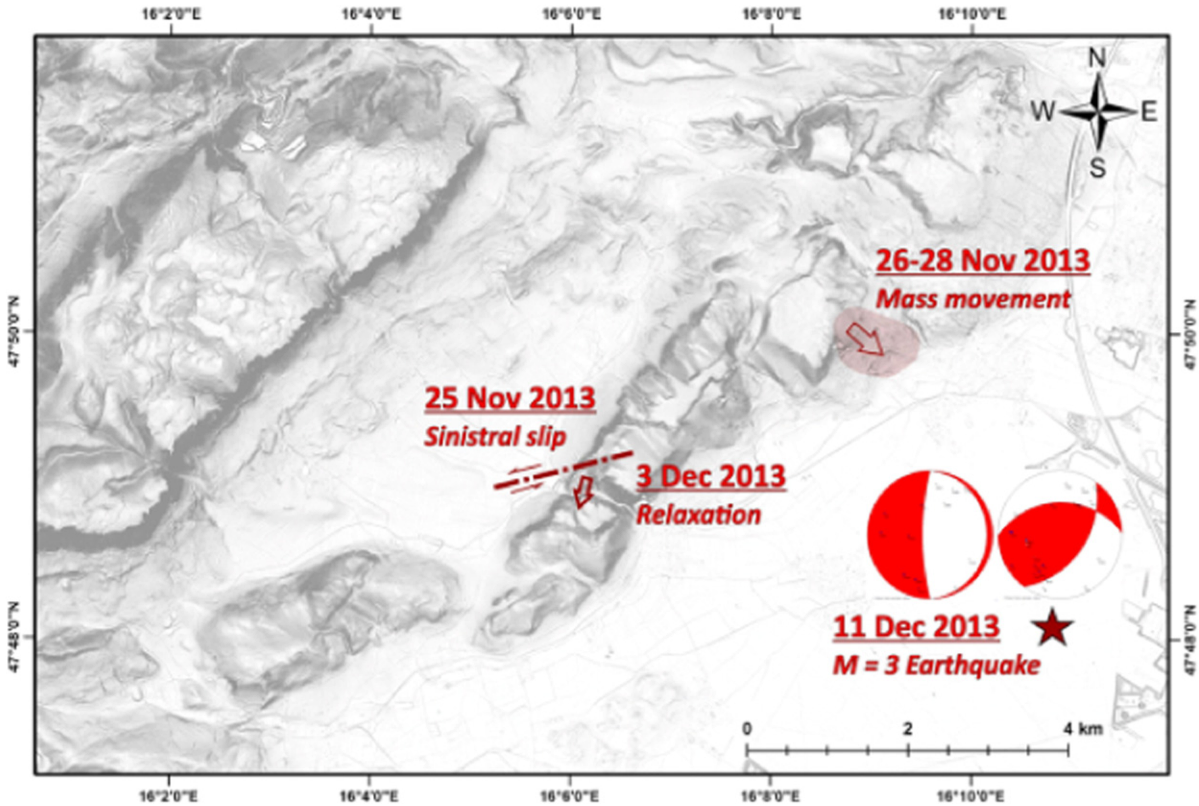

Fig. 7. Spatio-temporal presentation of the observed active-tectonic events, including two versions of the manual ZAMG solution of focal mechanism for the M = 3 Bad Fischau earthquake, shown on the slope-gradient map from airborne LiDAR data (topographic data: courtesy of Government of Lower Austria).

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