



# TIMING OF POSSIBLE UPLIFT AT THE PERIADRIATIC FAULT SYSTEM EVIDENCED BY CAVE SEDIMENTS

## ČASOVNI VIDIK DVIGOVANJA OB PERIADRIATSKEM SISTEMU PRELOMOV, KI JE RAZVIDEN IZ JAMSKIH SEDIMENTOV

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### Abstract

**Andrej Mihevc, Philipp Häuselmann & Markus Fiebig: Timing of possible uplift at the Periadriatic Fault System evidenced by cave sediments**

Subhorizontal epiphreatic caves are good morphological markers of valley deepening or uplift processes, since they reflect the position of the spring, which is related to the valley bottom. In Northeast Slovenia, transpressional activity along the Periadriatic Fault System caused dextral strike-slip as well as possible uplift of the areas adjacent to the fault. The presence of four cave levels near the Periadriatic Fault System documents uplift processes; and, the datings presented here of two levels indicate a Plio-Pleistocene incision history. These dates are in accordance with cave and sediment datings in other parts of NE Slovenia, and they are in line with more recent activity of the conjugated Salzach-Enns-Mariazell-Puchberg (SEMP) Fault in the Northern Calcareous Alps. The major fault systems, therefore, seem to be active not only in the Miocene (as postulated elsewhere), but up to the recent Quaternary.

**Keywords:** valley deepening, cave, Periadriatic Fault System, cosmogenic dating, Slovenia.

### Izvleček

**Andrej Mihevc, Philipp Häuselmann & Markus Fiebig: Časovni vidik dvigovanja ob periadriatskem sistemu prelomov, ki je razviden iz jamskih sedimentov**

Subhorizontalne epifreatične jame so dobri morfološki kazalniki procesov poglobljanja ali dvigovanja doline, saj je na njihovi podlagi razviden položaj izvira, ki je povezan z dnom doline. V severovzhodni Sloveniji sta bila posledica transpresijske aktivnosti vzdolž periadriatskega sistema prelomov desnozmčni prelom in možni dvig območij ob prelomu. Iz štirih jamskih nivojev v bližini periadriatskega sistema prelomov so razvidni procesi dvigovanja, v tem prispevku predstavljeni časovni vidiki dveh nivojev pa kažejo na pliocensko-pleistocensko zgodovino vrezovanja doline. To datiranje je v skladu z jamskimi in sedimentnimi datiranjmi v drugih delih severovzhodne Slovenije ter z novejšo aktivnostjo konjugiranega preloma ob liniji Salzach-Ennstal-Mariazell-Puchberg (SEMP) v Severnih apneniških Alpah. Glavne linije sistema prelomov se torej zdijo aktivne ne le v miocenu (kot so domnevali drugje), temveč vse do recentnega kvartarja.

**Ključne besede:** poglobljanje doline, jama, periadriatski sistem prelomov, kozmogeno datiranje, Slovenija.

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## 1. INTRODUCTION

Several large fault systems in the Alps, such as the Salzach-Enns-Mariazell-Puchberg fault (SEMP [Plan et al., 2010]), or the Periadriatic Fault System (Fodor et al., 1998) are known to present strike-slip movement and may reflect differential uplift. However, it is often difficult to constrain uplift processes in time. Especially in the Alps, sedimentological and/or morphological markers are often absent at the surface due to rapid erosion and/or glacial incision. Since caves are usually tied to valley bottoms where their springs are situated, horizontal (epi) phreatic caves are good markers of relative erosional stillstand or of erosional events (Ford and Williams, 2007; Häuselmann et al., 2007; Wagner et al., 2010). Moreover, caves regularly contain sediments that can be dated by radioactive decay, such as speleothems (U-Th dating, up to 500-600 ka), or quartz-containing sediments (cosmo-

genic nuclides, up to 5 Ma). Dating of these sediments give a minimal age of the passage they were found.

The Periadriatic Fault System is a transpressional dextral fault with several associated faults, along which the extrusion of the Eastern Alps and parts of the Pannonian Basin took place. Therefore, the Periadriatic Fault System is described to have a displacement of up to several 100 km. Its activity has been dated from the Cretaceous to the Miocene (Müller et al., 2001). However, a Plio-Pleistocene activity has been described (Fodor et al., 1998; Vrabec et al., 2006; Prince et al., 2015). In order to constrain and verify this single data point, other cave sediments that were datable were searched. In this paper, we successfully dated two of four caves in Tisnik Hill (Slovenia), which can give insight into uplift and incision processes near one of the fault systems.

## 2. SITE AND SAMPLING

The cave system studied here is located in Tisnik Hill in the Karavanke Mountains of Slovenia, but relatively close to the Austrian border (Figures 1 and 2). The Karavanke are characterized by narrow ridges that are lowering towards the East. Deeply incised valleys mostly follow the main trend of the mountain, but some of the rivers cut through the mountain chain, forming deep antecedent valleys. The modern network of fluvial valleys is filled with Quaternary sediments, mostly carbonate gravels.

The Karavanke are part of the Southern Calcareous Alps. They are built of Devonian and Carboniferous rocks. Mesozoic rocks are presented mostly by Triassic dolomites and limestones, but Oligocene pyroclastic rocks and Miocene siliciclastic rocks are also present.

Tectonically, the Karavanke Mountains are built of a series of overthrust sheets, cut in the N by the E-W-running Periadriatic Fault System and associated faults. The area around Tisnik Hill is bordered by two faults belonging to the Periadriatic Fault System, the Labot/Lavanttal Fault to the north and the Šoštanj Fault, both of them transpressional and dextral (Fodor et al., 1998).

Tisnik is a limestone hill that blocks the outflow of the small brook Ponikva (Figure 2). This brook, originating in Miocene conglomerates and sandstones, responded by creating four allogenic caves at altitudes of 500-760 m a.s.l., with the present-day baselevel being at 500 m a.s.l. In order to get information about uplift, information about the last (fluvial) activity of the caves,

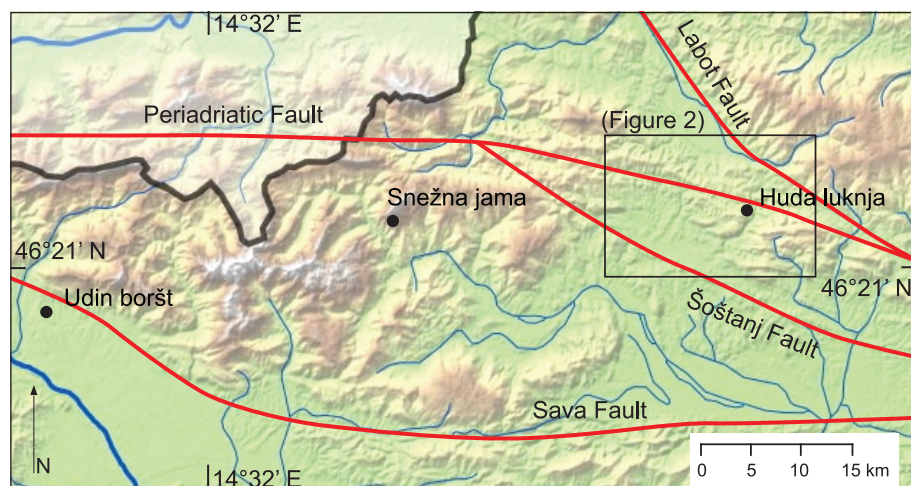


Figure 1: Simplified tectonic map with the faults (red lines) mentioned in the text, as well as the cave locations that were dated. The inset shows the location of Figure 2 as well as Huda luknja cave. Figure taken from [www.freeworldmaps.net](http://www.freeworldmaps.net), modified.

that is, a direct link between its allogenic catchment and the base level, has to be sought. Quartz pebbles are perfect in that respect, since they are clearly allogenic and brought in by a cave river, and they can be dated

by cosmogenic nuclides. In this article, we present the results of the datings, and we interpret the cave's genesis in relation to possible activity phases of the Periadriatic Fault System.

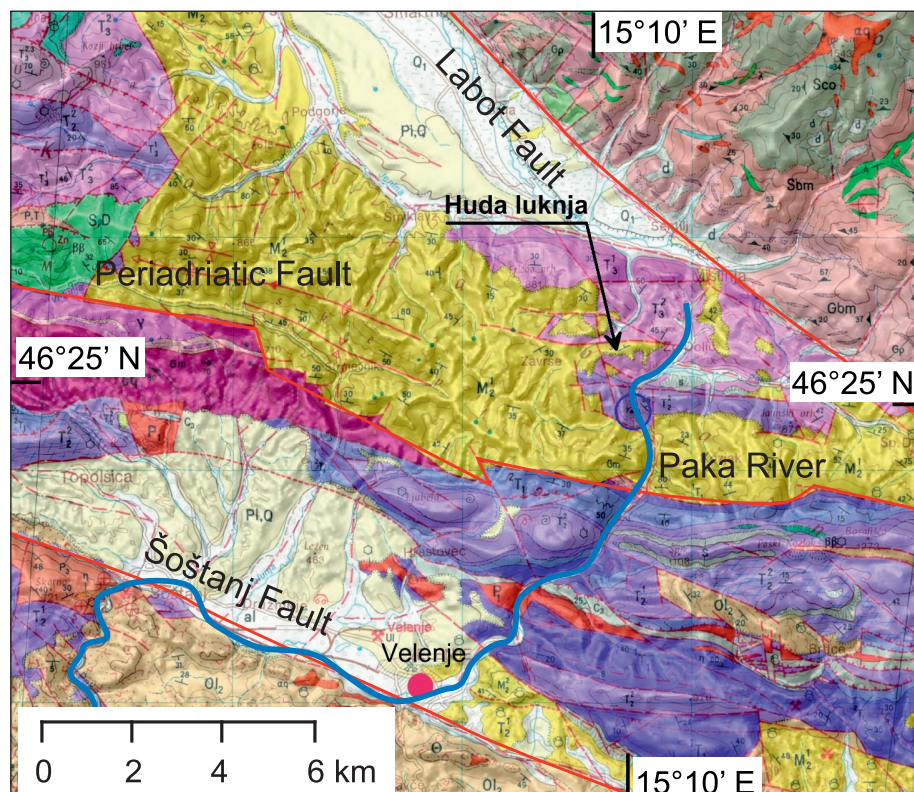


Figure 2: The position of Huda luknja on the geological map of Slovenia. Width of image 20 km. See also Figure 1 for placement.

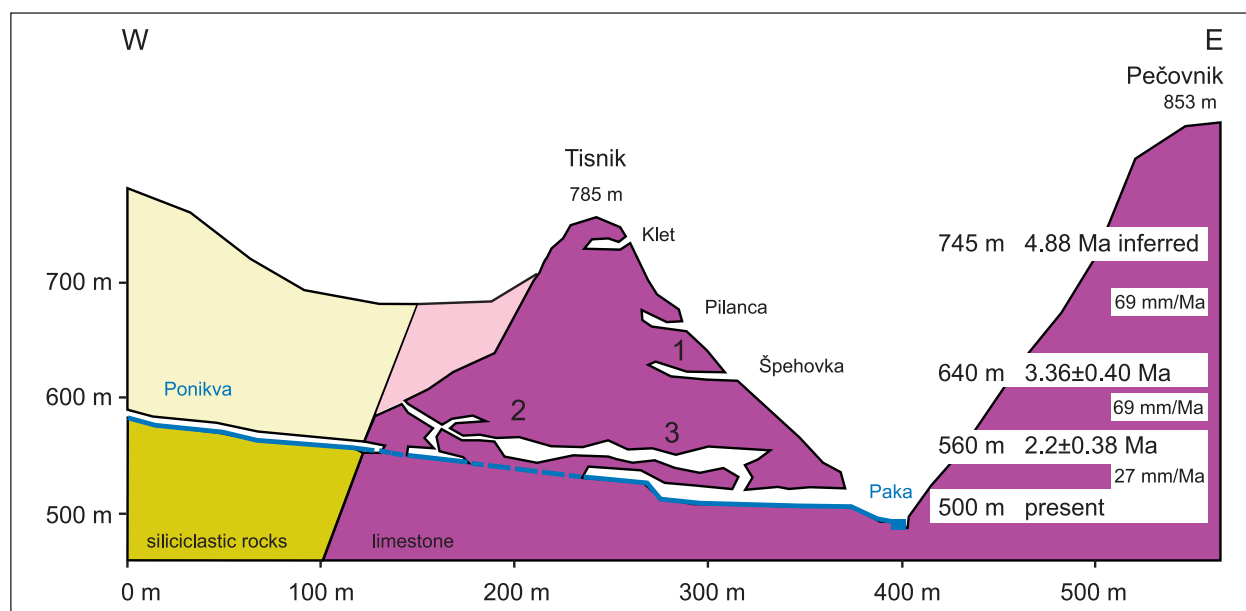


Figure 3: Schematic cross-section showing the position of the Huda luknja and Špehovka and other caves where sediments were sampled between the sinks of Ponikva and the canyon of Paka River. On the sketch, the locations of samples are marked with numbers. On the right side of the sketch, the ages of the sediments and the rates of valley incision are indicated. The uppermost age (4.88 Ma) is inferred with the same incision rate; this is thus not a measured age.

The brook Ponikva flows into Paka River, which is antecedent to uplift processes. It incised a more than 600 m deep narrow valley into dolomite and limestone. The bottom of the valley became the lowest part of the karst of Tisnik Hill. As Paka River was cutting down, following the uplift of the ridge, several levels of caves were formed. They could be perfect for dating the tectonic uplift of the ridge. Today, only four caves are accessible (Figure 3).

The uppermost cave, Klet, is only a small chamber with a lot of breakdown blocks from its ceiling. Due to its size and location, it is, however, quite clear that the cave belongs to the allogenic caves that were formed by the brook Ponikva. However, no siliciclastic pebbles could be found. The limestone overburden, moreover, is quite thin, and there might be large potential errors when dating with cosmogenic isotopes, since there is not enough shielding from present-day cosmic rays.

The second highest cave, Pilanca, is an ascending tube of large dimensions (4x2 m). Its bottom also con-

tains a lot of breakdown from the ceiling, however its morphology, with scallops on the walls, clearly points to a speleogenesis in epiphreatic conditions. Since no siliciclastic material was found, a digging campaign was organized, however, digging to the bottom of the cave also yielded no siliciclastic pebbles.

The third cave, Špehovka, has its entrance at 637 m. The cave is a simple passage slightly upward, partly filled with fluvial sediments consisting of clays, silts, sands and some pebbles. The sample was taken at 640 m a.s.l., in a passage that was filled with fluvial sediment. The pebbles had up to 5 cm in diameter.

Huda luknja is located at 503 m, only 5 m above river Paka. The cave is a show cave that presents two levels, the upper one is around 550 m asl. In the lower level, the present brook Ponikva continues to flow towards Paka River, the cave is thus still active. Large quartz pebbles were collected from two profiles which seemed not to have been resedimented. The profiles were in the upper part of the cave near Jazbina at 570 m and 550 m.

### 3. METHODS

The burial age method involves the measurement of two isotopes ( $^{26}\text{Al}$  and  $^{10}\text{Be}$ ) that are produced by cosmic radiation in quartz near the surface prior to burial.  $^{26}\text{Al}$  and  $^{10}\text{Be}$  accumulate at a ratio of about 6.8:1 (Balco et al., 2013) in quartz grains with a rate of a few atoms per gram of quartz per year. Sufficiently deep burial (more than 10 m) of such quartz-rich sediment in a cave assures shielding from further cosmic rays. After burial, the  $^{26}\text{Al}$  and  $^{10}\text{Be}$  concentrations in the sample are only affected by their relative decay resulting in a decrease in the  $^{26}\text{Al}/^{10}\text{Be}$  ratio. This ratio measured can be used to derive a burial age (Gosse and Phillips, 2001; Granger and Muzikar, 2001). The upper limit for measurement of the  $^{26}\text{Al}$  and  $^{10}\text{Be}$  isotope pair is around 5 Ma. A prerequisite of the burial dating technique is that samples have been exposed long enough to cosmic rays and accumulated sufficient cosmogenic nuclides prior to burial. A second prerequisite is that samples should not have been buried in a terrace before having been washed into the cave, as this would make the age older. Unfortunately, this cannot be determined a priori in the field.

In the laboratory, about 100 g of quartz were extracted and purified from bulk samples by magnetic and density separation and selective chemical dissolution. Quartz was dissolved in a 5:1 solution of concentrated HF and HNO<sub>3</sub> and spiked with about 0.25 mg  $^9\text{Be}$ . Al

and Be were separated and purified by ion chromatography and selective precipitation. Precipitates were oxidized and mixed with metal powder for accelerator mass spectrometry (AMS).  $^{10}\text{Be}/^9\text{Be}$  and  $^{26}\text{Al}/^{27}\text{Al}$  nuclide ratios in the sample and procedural blanks were measured at Purdue University (USA). Stable aluminium concentrations were determined by ICP-OES. The measurement of the procedural blanks yielded  $^{10}\text{Be}/^9\text{Be}$  ratios  $\leq 5 \times 10^{-15}$  and  $^{26}\text{Al}/^{27}\text{Al}$  ratios of  $<0$  to  $13 \times 10^{-15}$ . With the exception of the relatively high Al blank (relativized by the high error of  $\pm 18 \times 10^{-15}$ ), the blanks thus show that the measurements were good and the standards clean.

The isotope concentrations can also be used to infer paleo-erosion rates of the source area prior to burial of the clasts. This is accomplished by backward modelling the quantity of nuclides present prior to the burial coupled with local production rate estimates.

The pre-burial  $^{26}\text{Al}/^{10}\text{Be}$  ratio ( $\sim 6.8:1$ ) is basically not influenced by production rate and thus elevation (Nishiizumi et al., 1989; Stock et al., 2005) and therefore burial ages remain unaffected by altitude changes in the source area. However, the pre-burial erosion rates are based on measured isotope concentrations and elevation-dependant production rates. They are therefore only rough approximations.

#### 4. RESULTS

Table 1 gives the results of the measurements. All results were normalized for a  $^{10}\text{Be}$  half-life of 1.39 Ma (Chmeleff et al., 2009; Korschinek et al., 2009). The un-

certainities represent the analytical error only. The erosion rates are approximate, since the altitude and further shielding problems at the surface are unknown.

Table 1: Results of the dating campaign.

| Cave        | Sample | Altitude of catchment (a.s.l.) | Altitude in cave (a.s.l.) | $^{26}\text{Al}$ ( $10^3\text{at.g}^{-1}$ ) | $^{10}\text{Be}$ ( $10^3\text{at.g}^{-1}$ ) | $^{26}\text{Al}/^{10}\text{Be}$ | Burial age (Ma) | Pre-burial erosion rate ( $\text{m.Ma}^{-1}$ ) |
|-------------|--------|--------------------------------|---------------------------|---------------------------------------------|---------------------------------------------|---------------------------------|-----------------|------------------------------------------------|
| Huda luknja | HL     | 600                            | 550                       | $204 \pm 39$                                | $90.7 \pm 6.42$                             | $2.25 \pm 0.46$                 | $2.26 \pm 0.38$ | $10 \pm 2$                                     |
| Huda luknja | PM     | 600                            | 570                       | $351 \pm 40$                                | $148 \pm 9.01$                              | $2.38 \pm 0.31$                 | $2.13 \pm 0.25$ | $11 \pm 1$                                     |
| Špehovka    | SP     | 650                            | 640                       | $109 \pm 23$                                | $83.3 \pm 3.46$                             | $1.31 \pm 0.28$                 | $3.36 \pm 0.40$ | $10 \pm 2$                                     |

#### 5. DISCUSSION

The dated ages were both expected as well as unexpected. It was expected that the upper cave was older than Huda luknja, which was the case. The high age of Huda luknja itself, on the other hand, seems somehow surprising. Both these ages overlap in error, so we can consider them to have the same age.

The relatively high age of  $\sim 2.2$  Ma just 50 m above base level may be explained by two mechanisms: One explanation is that there was only about 50 m of uplift in these last 2 Ma. This would give good age constraints on the activity of the Periadriatic Fault System, and would therefore be an interesting data point. The other explanation would be that these sediments were buried in a terrace before having been washed into the cave. As a consequence, their "cave age" would be too high, and the real uplift would be higher. As already explained above, neither the dating procedure nor the deposition mode can rule out that possibility.

However, both the assumed catchment at that time as well as the altitude where the sediment is found in Špehovka is again 50-90 m above the one of Huda luknja. The corresponding age is 3.36 Ma. The age difference of 1.1 Ma is also relatively large compared to the altitudinal difference, so the probability that the ages represent "true" ages of fresh sediment washed into the cave is high.

Assuming the ages are correct, we can calculate the incision rate of Paka River between the cave levels. From Špehovka level to the upper level of Huda luknja we get

69 m/Ma, and from the upper level of Huda luknja to the present level we get 27 m/Ma. This translates into a larger uplift in Pliocene, followed by a smaller incision rate within the Quaternary.

In the vicinity of Huda luknja, concretely in the Savinja valley to the west, and the Mislinja valley to the north, Mencin Gale et al. (2019) analysed fluvial terraces in intramontane basins, and estimated the long-term Plio-Pleistocene incision rate due to uplift to 0.01-0.05 mm/a. These values are similar to, albeit a bit lower, than our values, and correspond well to our findings.

As already described for Snežna Cave (Häuselmann et al., 2015), we can estimate that the Periadriatic Fault System may reflect transpressional uplift around the Plio-Pleistocene boundary. This is in accordance with Fodor et al. (1998). The present activity of the fault is evidenced also by modern GPS data (Vrabec et al., 2004, 2006).

Further to the west, the Sava Fault, which is also a lateral fault to the Periadriatic Fault System, seems to have been active in the Quaternary (Jamšek Rupnik et al., 2012). Dating of the Udin Boršt conglomerate (Mihevc et al., 2015) indicated an age of 1.86 Ma, which is younger than the caves from Tisnik, but in accordance with morphological observations.

The documented recent (118 ka) activity of the conjugated SEMP fault in the Northern Calcareous Alps (Plan et al., 2010) is again concordant with general Plio-Quaternary activity.

## 6. CONCLUSION

As a conclusion, we can state that the Periadriatic Fault System and its associated faults may reflect transpressional uplift of the area in Plio-Pleistocene times, despite the fact that they seem to be (at least partially) momentarily silent, as stated in Garcia et al. (2010). Therefore, our data is also in contrast with Garcia et al. (2010) which state that "geochronological ages show no evidence for tectonic movements younger than mid-Miocene...". It is well known that Slovenia has an intense tectonic activity during the Holocene. Our data show that uplift in the

area of the Periadriatic Fault System re-became intense around the end of the Miocene and beginning of the Pliocene (stopping sedimentation and starting erosion in Tisnik and Raduha). The age of the Udin Boršt conglomerate indicates that rapid uplift of the Karavanke and subsidence of the Sava Basin mainly occurred in Pleistocene, in a time where the possible uplift rates at the Periadriatic Fault System already seemed to be minimal again (no more large incision of Paka during the last 2 Ma).

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