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NATURAL SPELEOTHEM DAMAGE IN POSTOJNSKA JAMA (SLOVENIA), CAUSED BY GLACIAL CAVE ICE? A FIRST ASSESSMENT

ALI JE NARAVNE POŠKODBE KAPNIKOV V POSTOJNSKI JAMI (SLOVENIJA) POVZROČIL PLEISTOCENSKI LED? PRVE OCENE

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Stephan Kempe: Natural Speleothem Damage in Postojnska Jama, Slovenia, Caused by Glacial Cave Ice? A First Assessment

Natural speleothem damage has been known from Postojnska jama for a long time. Schaffenrath was the first to depict broken and leaning stalagmites on his pictures from the interior of the cave. Hohenwart analysed some of these damages, clearly excluding rock fall or earthquakes as a cause. Here the author discusses the possibilities, which could cause natural speleothem breakage in general. The most promising cause is cave ice. It must have formed in caves during glacial maxima when permafrost spread throughout northern, eastern and central Europe. Consequently cave ice could be the most prominent factor in explaining non-recent speleothem damage. Next some of the historically known flowstone breakages from Postojnska jama are presented. These are discussed in view of cave ice and an *ad hoc* model for the genesis is given. In the side passages Pisani rov and Brezimenski rov there are masses of broken stalagmites and stalactites and speleothem fragments in precarious positions. Cave ice offers an overall process to explain these observations. Thus it is suggested that all or parts of the Postojnska jama were filled with ice during the Last and earlier Glacials. If accepting speleothem damage as a consequence of glacial cave ice, then it should be possible to use it as a marker facies for the extent of the zero temperature line during the various glacials.
Key words: speleothem, speleothem damage, speleoclimate, cave ice, Postojnska jama, Slovenia.

Izvleček UDK: 551.44

Stephan Kempe: Ali je naravne poškodbe kapnikov v Postojnski jami povzročil pleistocenski led? Prve ocene

Naravne poškodbe kapnikov v Postojnski jami so že dolgo znane. Odlomljene in nagnjene stalagmite je na svojih slikah prvi upodobil Schaffenrath. Nekaj teh poškodb je preučil Hohenwart in kot vzrok odločno izključil skalni podor ali potres. V tem prispevku avtor razpravlja o vzrokih za naravno lomljenje kapnikov. Kot najustreznejši vzrok se kaže jamski led. Ko so bila v višku glaciala stalno zamrznjena tla razširjena po vsej severni, vzhodni in srednji Evropi, je v jamah moral nastajati led. Zaradi tega je najustreznejši dejavnik, s katerim bi lahko razložili starejše poškodbe kapnikov. Nadalje je v študiji predstavljenih nekaj zgodovinsko izpričanih lomov kapnikov iz Postojnske jame. O tem teče razprava z vidika jamskega ledu in predstavljen je *ad hoc* model nastanka ledu. V stranskih Pisanem in Brezimenem rovu so velike količine polomljenih stalagmitov in stalaktitov v nenavadnih položajih. Jamski led je lahko tisti dejavnik, ki razloži ta pojav. Avtor domneva, da je bila Postojnska jama med zadnjim in prejšnjim glacialom zapolnjena z ledom. V kolikor bi se strinjali, da je vzrok poškodovanim kapnikom jamski led, potem bi nam lahko taki kapniki služili kot pokazatelji, do kod v podzemlje je v raznih glacialih segala izoterma 0°C.
Ključne besede: kapnik, poškodbe kapnikov, jamska klima, jamski led, Postojnska jama, Slovenija.

1. POSSIBLE CAUSES OF SPELEOTHEM DAMAGES

The question, why speleothems (a term coined by Moore, 1952) break, needs to be answered for every cave, cave passage and site individually. We know of caves which have more damaged speleothems than intact formations. So far not much information has been extracted from broken speleothems, in part because many processes can cause speleothem breakage (discussed, among others by Spöcker, 1933; Schillat, 1965; Moser & Geyer, 1981; Knolle, 1982; Kempe, 1989; and Pielsticker, 1998). The cause of speleothem damage can be grouped as follows:

A. Site-limited processes:

A) *Inkasion*

Detachment of ceiling speleothems because of overweight or because of corrosion of the interface between ceiling and formation; damage of floor speleothems by falling ceiling formations or blocks (a recent example of such rock fall is described by Kranjc, 1999, for Škocjanske jama).

B) *Mass wasting*

Inclined limestone layers containing caves can slip on claystone layers below causing speleothems to tilt and rupture along joints.

C) *Compaction*

Irregular compaction of sediment can cause tilting of floor speleothems, possibly uprooting larger stalagmites and rupture of floor flowstones.

D) *Erosion*

Undercutting of floor flowstone by water erosion or by sediment removal under drip sites, slip of sediments and associated floor flowstones.

E) *Crystal tension (?); Re-crystallisation (?).*

F) *Vandalism (!).*

2. Processes of local impact:

G) *Frost in entrances, in cold air traps and in caves at high altitudes*

Freezing and flaking of speleothems or freezing and expansion of wet sediments in entrance regions causing rupture of floor sinters. Polygonal patterns in cave soils, ice wedges.

H) *Inundation*

During an inundation the buoyancy forces of cave fills and the strength of fine-grained caves sediments can change, causing the shift of cave fills and associated speleothems; the wetting and drying of cave sediments during and after an inundation could lead to expansion and shrinkage of cave sediments and could cause tilting or slippage of speleothems as well.

Dessication

Long spells of dryness can cause gradual shrinking of sediment leading to the rupture and settling of floor flowstone, possibly also highly porous speleothems can be damaged by cycles of desiccation and wetting.

3. Processes of regional impact:

I) *Ice in caves during glacial periods*

This hypothesis goes back to Kyrle (1929-1931), Cramer (1932-1933) and Spöcker (1933 and 1981). During the build-up of ice and its thawing, ice can flow or slide, thereby stalactites and draperies can be sheared off the ceiling and stalagmites can be tipped over or sheared off their bases and displaced. Sinter enclosed in ice can be deposited on inclined surfaces or been left in precarious positions, i.e. at positions which would not be stable if deposited by falling.

J) *Earthquakes*
The hypothesis that earthquakes cause sinter damage has been re-iterated many times. To my knowledge the first to discuss this hypothesis critically was Hohenwart (1832a). Later the idea was taken up again by Becker (1929). Specifically tall, slender stalagmites should be overthrown by earthquakes. However, we find Holocene candle stalagmites of substantial size throughout Europe intact. This observation excludes regional earthquake damage for the last 12 000 years. For older damage certainly (J) is the more plausible hypothesis.

2. SPELEOTHEM DAMAGE IN VIEW OF PALEOCLIMATE

The decipherment of the causes of sinter breakage can give important clues not only to the development of individual caves but also to paleoclimate. Generally speleothems record, in their geochemical and isotopical variance, environmental changes above the cave (e.g., Kempe & Rosendahl, 1999, 2001). Because of the advance in dating techniques (U/Th TIMS dating of flowstone; e.g., Eisenhauer & Hennig, 1997) it became clear that in the wider region Central Europe the cold periods are associated with a hiatus in the deposition of sediments and speleothems. For sediments this is, for example, documented by the excavation in Divje Babe, Slovenia, during Oxygen Isotope Stages (OIS) 4 and 2, while the warm periods OIS 5, 3 and 1 (Holocene) are well represented (Turk et al., 2002). A similar finding was reported from a flowstone profile from the French Villars Cave. There the early Glacial (between 50 and 80 ka BP) as well as the high Glacial show substantial growth interruptions (Genty et al., 2003). Also in the Sontheimer Cave, Swabian Alb, speleothems dating from warm periods were found, while cold period speleothems are missing (Abel & Rosendahl, 2000). The missing cold period speleothem generations in Central Europe is easily explained, since in glacial periods, permafrost was wide-spread and long-lasting. It sealed the ground and prevented infiltration of seepage water.

But this is only one aspect because, with sinking winter temperatures, cave ice must have formed, just as it is formed in many of the alpine caves of today. Average annual temperature need not to fall below 0°C to form ice, just the energy balance within a cave needs to favour ice formation in winter, i.e. cold winter air must be able to sink into the cave and cool it from the inside. This needs to happen before surface permafrost begins to seal the water bearing joints year-long. It is well conceivable that most Central European caves were filled with ice more or less completely. Three phases have to be assumed: the build-up of ice, the stagnation during permafrost and the thawing of ice. We now know that during OIS 4 and 3 short-term oscillation, the Dansgaard-Oeschger Cycles, ca. 1500 a in duration, punctured the climate record (Dansgaard et al., 1993). At marginal permafrost regions, freezing and thawing of cave ice may have therefore occurred many times over. In fact, even in areas outside of permafrost, cave ice may have formed during the Last Glacial Maximum (OIS 2) at least once.

During the build-up of cave ice and during thawing, ice parcels may start to flow under their own weight or may slip on inclined surfaces. This movement of ice can possibly explain the wide-spread damage of speleothems in European caves associated with growth hiatuses.

The often advanced alternative hypothesis that earthquakes are responsible for such damage could be verified only if these damages can be dated to have occurred during warm growth periods. So far nobody was able to do exactly this. Knolle (1982) claimed that speleothem damage observed in caves of the Iberger/Harz was caused by earthquakes. However, they are most probably all glacial, at least no

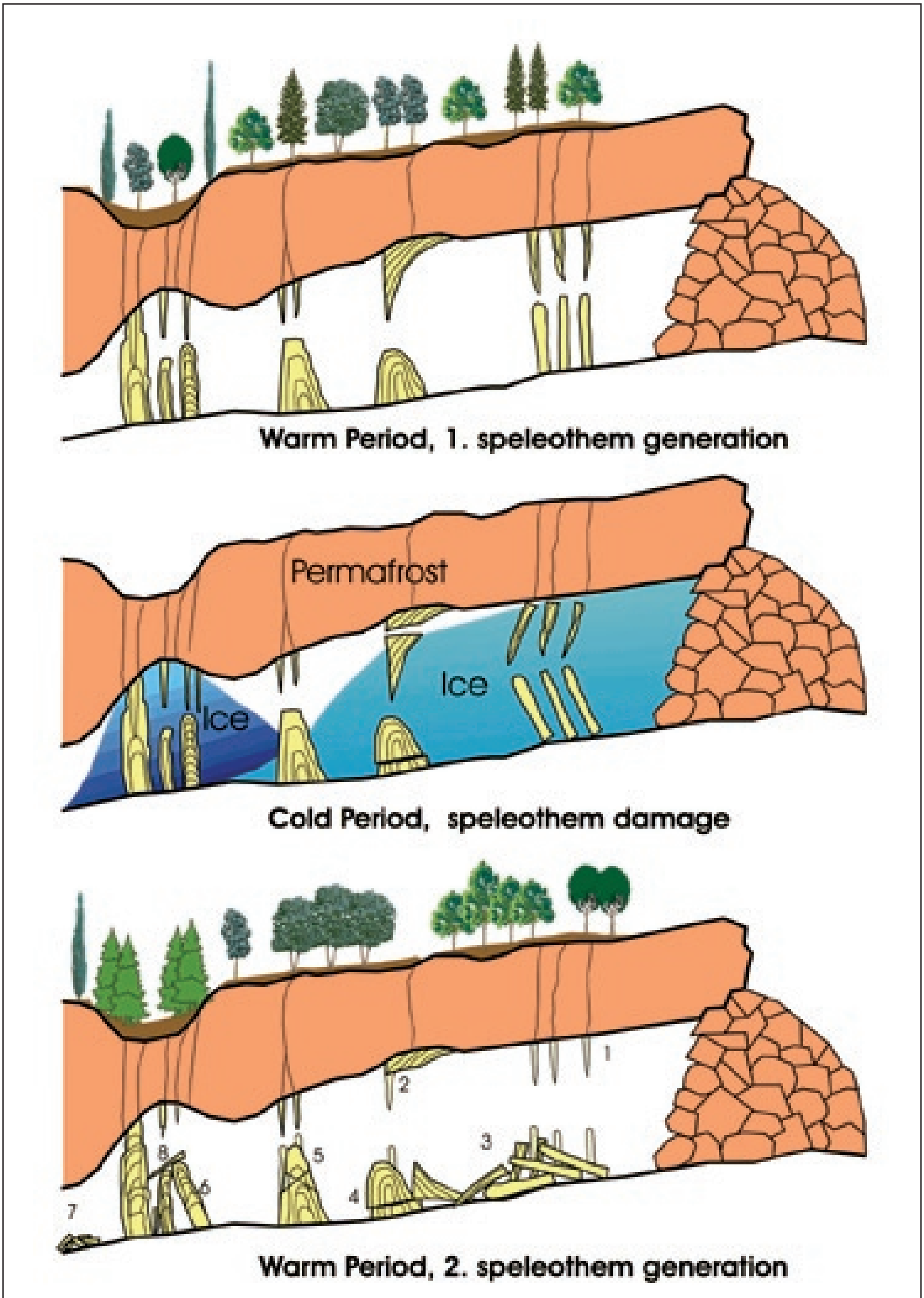

Fig. 1: Types of damage of Speleothems caused by cave ice (for explanation see text).

Holocene dates have been demonstrated. Only in the Langenfeld Cave/Weserbergland dated Holocene damage occurs (Schillat, 1965). However, it was not caused by regional or global earthquakes, but the damage is most probably associated with the slippage of the cave-bearing Jurassic Korallenoolith limestone Formation and the underlying Hersum Formation on the Ornatenton Formation, composed of claystone dipping towards the valley (case "B" above). The Langenfeld Cave offers therefore no conclusive proof for earthquake speleothem damage in Central Europe (Kempe, 1989).

3. TYPES OF SPELEOTHEM DAMAGE POTENTIALLY CAUSED BY ICE

The ice-related damages (Kempe, 1989; Kempe & Rosendahl, 2003) can potentially cover a wide range of phenomena. Figure 1 gives an overview of these. In detail one can expect:

1. Missing ceiling formations of older generations.
2. Sheared-off stalactites and draperies, deposited on top of floor speleothems.
3. Broken and deposited stalagmites.
4. Sheared-off stalagmites which have been shifted from their base but still stand upright.
5. Cracked conical stalagmites.
6. Tilted and leaning stalagmites.
7. Moraine-like piles of floor flowstone.
8. Precariously placed ceiling formations.

If one observes all these phenomena in one cave, then it will be difficult to find an alternative hypothesis for these speleothem damages. Specifically phenomenon 8, precariously placed speleothems, is almost impossible to explain by any other mechanism. It involves placement of broken stalactites on sloping surfaces or the placement of loose pieces on wall ledges or their insertion at places where they could not have fallen to.

In addition to speleothem damage freezing and cave ice can leave other traces:

- Cryoturbation in cave sediments.
- Solifluction deposits.
- Transport of gravel without evidence of flowing water.
- High collagen content of fossil bones.
- Loss of uranium due to "leaching".
- Scratch marks on cave walls.

Advance and retreat of permafrost could have led to quite a wide spectrum of other features. For example could deep-seated permafrost, which melted from above, leave the top meters of limestone without drainage. Caves, otherwise dry because of their position high above the karstic water table, could therefore temporarily fill with water. Such late flooding events could leave corroded speleothems. Such a flooding is for exampled recorded by corroded speleothems in the Zoolithen Cave near Burggailenreuth, Frankonia (e.g., Kempe, 1996).

4. POSTOJNSKA JAMA, THE FIRST CAVE FOR WHICH SPELEOTHEM DAMAGE HAS BEEN DEPICTED AND DESCRIBED

The problem of speleothem damage was already noticed in the first half of the 19th century. Possibly the first correct pictures of fallen stalagmites were made by the engineer and artist Alois Schaffenrath (10.7.1794 – 14.9.1836). His aquatint pictures were the basis for copper plates and

Fig. 2: Reprint of the original aquatint picture, which served as basis for Plate 12 from Hohenwart 1832a, Alois Schaffenrath's „View of the area at the laces (Jabots), 550 Wiener Klafter from the Entrance". To the right are the "laces" a prominent flowstone curtain, to the left is the Broken Pyramid and in the background are the Large and the Small Cypresses.

Fig. 3: Recent view of the Hohenwart's Plate 12 with the Broken Pyramid to the left. On the floor the tracks of the modern cave train.

Fig. 4: The lower breakage of the Schaffenrath Pyramid. Note the slip of the upper piece to the left relative to the stump.

Fig. 5: The backpack stalagmite on the Schaffenrath Pyramid.

lithographs published by Franz Josef Hannibal Graf von Hohenwart (24.5.1777 – 2.8.1844) in his impressive guide to the Adelsberger Grotte (Postojnska jama) (Hohenwart, 1830, 1832a, 1832b; reprint 1978).

Schaffenrath sketched the first scenes already in 1821 on the order of Emperor Franz I, i.e. only three years after the main part of the Adelsberger Grotte was discovered (on 14.4.1818 by the worker Lukas Čeč during the preparation of the lighting of the big dome for the visit of Franz I). Schaffenrath in his function as engineer was also the one who constructed the first bridge across the Piuka (the pillars of which still stand), who made plans to improve the pathway through the cave and who conducted the first survey of the cave. He was therefore well acquainted with the cave because of his many visits there.

Hohenwart published a total of 19 plates made by Döbler (12) and M. Charl (7) after the originals of Schaffenrath (now in Ljubljana), each eight, five and six in the three volumes of the guide. On four of these plates toppled stalagmites are clearly depicted. These are Plates 12: *Ansicht der Gegend zu den Schapodeln (Jabots) genannt* (view of the area called „at the laces (jabots)“), 14: *Ansicht des Säulensturzes bey den sogenannten beschwerlichen Durchgange* [the German grammar error is original] (View of the column-crash at the so-called cumbersome passage), 17: *Ansicht der höchsten Kuppe des sogenannten Calvarienberges* (view of the highest top of the so-called Calvary Mountain) and 18: *Ansicht des Tropfbrunnens* (view of he the Drip-Well).

Even more, Hohenwart describes - probably for the first time in literature - broken speleothems and discusses the causes of damage (1832a, p. 2) (translation by author; original text see Appendix 1):

“Also the forceful changes in the grotto show that nature rules after own laws - un-

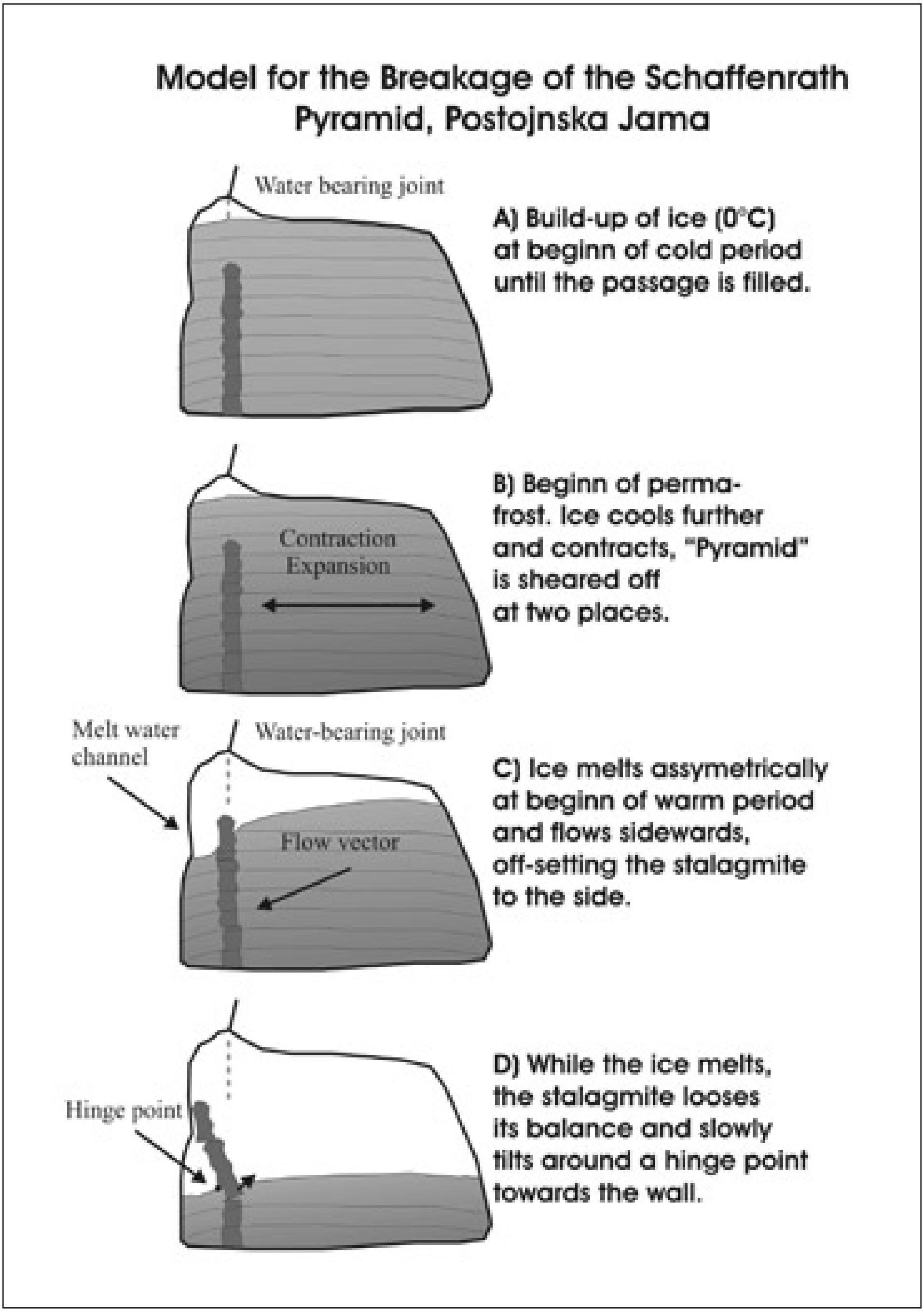

Fig. 6: Ad hoc model of the breakage of the Schaffenrath Pyramid.

Fig. 7: The Doorstep, a prominent stalagmite group just before the inner train station in the main passage.

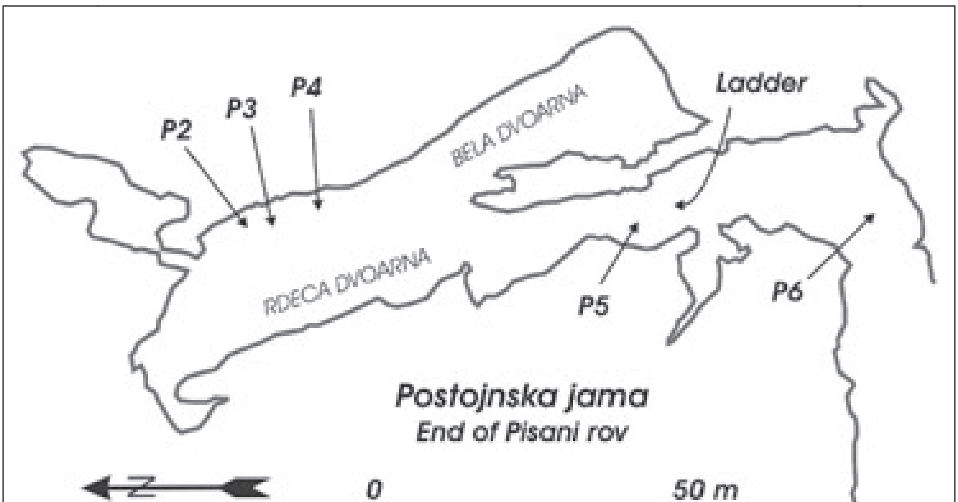

Fig. 8: Sketch map of the sites of observed speleothem damage at the end of Pisani rov (compare Table 1).

known to us - in this netherworld.

The common opinion about these alterations in such underground caves is that weak vaults cave-in due to earthquakes and that loose stems fall from above and that those stalactite-columns which do not adhere strongly enough at their junction to the ceiling are precipitated. The careful observer, however, discovers that many alterations cannot be explained by this common opinion.

Many alterations in this part of the Grotto (i.e., in the main passage) cannot be noticed any more because the tireless effort of Ritter von Löwengreif to make the floor smoother for the ease of the

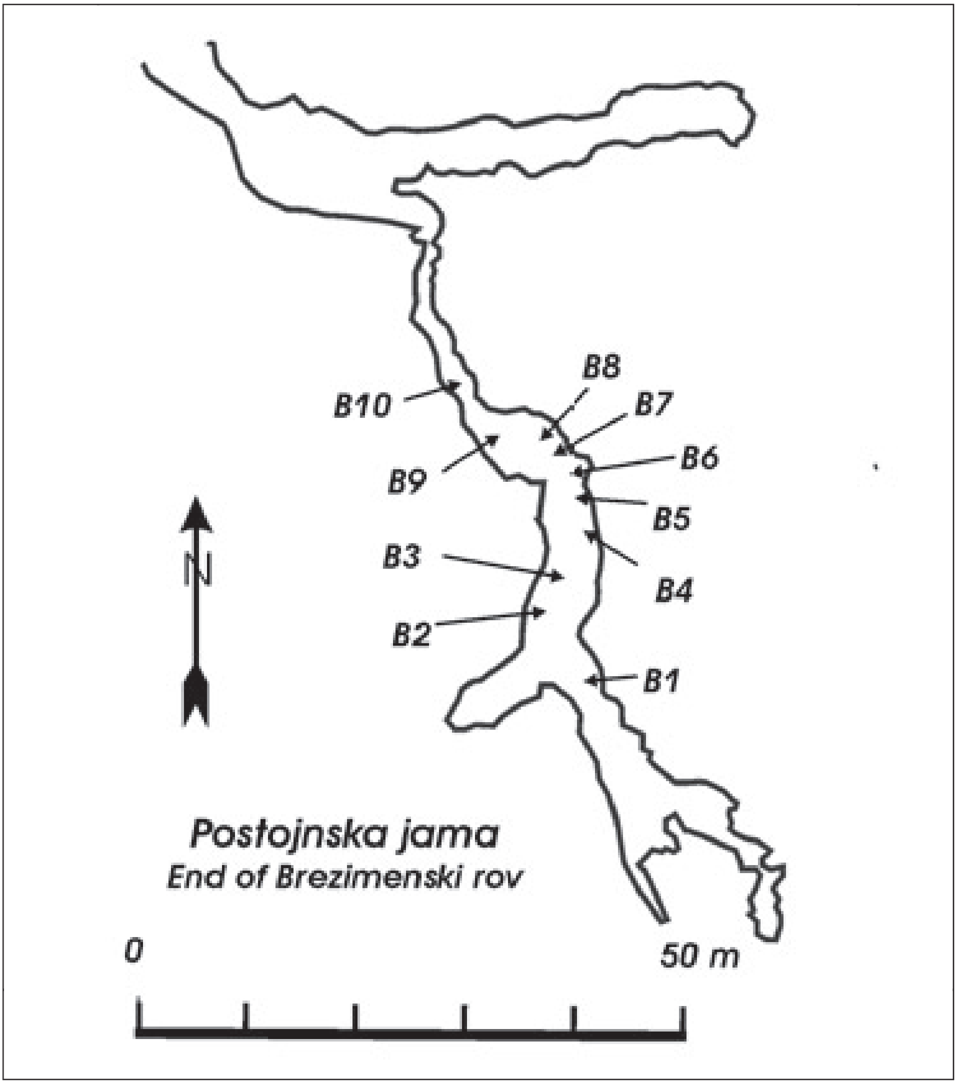

Fig. 9: Sketch map of the sites of observed speleothem damage at the end of Brezimenski rov (compare Table 2).

visitors has removed all obstacles. Deeper in the cave, however, one still can find places where, as it was the case before in the now accessible parts of the Grotto, the entire ceiling is closely occupied with perpendicular stalactite-columns and where nevertheless often a three to four shoe in diameter measuring broken stalactite-column rests oblique across the width of the passage.

It appears that the column did not fall from the ceiling because there is no place where it should have been hanging. But from where – as everybody will ask – did it come to this place and in this situation which is occupies at present? Can we think of a power – without loosing us in lively fantasies of immeasurable forces - which was able to bring this several thousand pounds heavy mass from a distant place to that site where it now rests firmly?

Overall it seems inexplicable how - without a human force - some of those columns of flowstone in this Grotto could have been broken.

Similar to that column in the Dancing Hall which leans broken on its neighbour, one finds in this Grotto several columns broken in the middle, one or one and a half klafter (Wiener Klafter measuring ca. 1.9 m) from the floor, the upper part toppled and resting on the ground next to the column or often only shifted from its place and leaning on the unhurt column standing next to it.

Even if one assumes human forces one cannot explain the situation resulting from the breakage of some of the columns."

This analysis sounds very modern. It is in extreme contrast to some of the geologic discussions of the time, such as the volume of Buckland, published 1824, who invoked the biblical Deluge to

Fig. 10: Eastern Wall of the Brezimenski rov towards its end. Note the stalactites stacked along the wall with different orientations. Also note young white sinter.

explain cave bear bone deposits. None of this is even vaguely mentioned in the text. Rather Hohenwart rigorously analyses the in-situ evidence and excludes some of the processes mentioned in the list of possible causes, among them vandalism (human forces), earthquakes and ceiling breakdown. In fact, if Hohenwart would have known about the ice-age (the idea of which was publicized during the same time) he might have come to the conclusion that cave ice was the force which could have caused the observed speleothem damage.

5. SPELEOTHEM DAMAGE IN THE MAIN PASSAGE

On March 8th and 11th, 2003, I looked at some of the broken speleothems depicted by Schaffenrath, specifically I was intrigued by the leaning column depicted on Plate 12 (Fig. 2). The modern view of this scene is given by Figure 3. Hohenwart (1832a, p. 7) comments this column as follows (full text describing Plate 12 is given in Appendix 2):

"On the left side, across of the laces (i.e., the jabots or the prominent flowstone curtain on the right hand side of the passage) is a broken Stalagmite-Pyramid, which is worthwhile of the attention of the visitor. Two and a half shoes (one shoe being 33 cm i.e. a total of ca. 80 cm) from the floor is this column or pyramid broken. Since there is no external injury visible, no stone is found nearby which could have caused this breakage of the column when falling from above, it is the cause of awing research. The column leans on the wall and bends where possibly its point of gravity is found

Fig. 11: Stumps of sheared-off stalactites at end of Brezimenski rov.

Fig. 12 a-e: Pictures of a complex area of sinter damages photographed from various angles. The Arabian numbers refer to detached speleothem fragments referred to in the text. The roman numerals denote the two intact stalagmites. Arrows indicate direction of displacement of stalagmite fragments. The small map marks the site of the individual areas with speleothem damages discussed in this paper.

in the leaning state, similar to a cut young tree which would bend when falling against another tree. This is not an optical illusion since the Pyramid really is curved in its upper part. Even more, it is not only curved, it also has a second column attached, created after the breakage, and growing in the direction which once may have had the broken column. The Pyramid is also noteworthy in having a quiver-like structure. The quivers follow each other regularly, interrupted by little ledges all the way to the top. No other pyramid is similar to this column and the admiration which is caused by it is even larger when one looks at the ruptured interface where the upward pointing surface is already smoothed with flowstone by later drip water while the upper interface has the appearance like a broken tree, i.e. that some parts are longer and others shorter so that the rim has a seesaw structure, not showing the characteristic of broken stone, which breaks with edges, scallopy and uneven. The various wood-like protrusions allow light to pass the interface and that one can see clearly how much of the rupture has been sealed by new flowstone."

The Schaffenrath Pyramid is a ca. 5 m high, regularly grown stalagmite broken twice (Fig. 3). The lower rupture is today ca. 80 cm above the floor, just as described by Hohenwart. However, the picture of Schaffenrath shows that the stump must have been ca. 2 m high (Fig. 2, compare persons standing by it). Either Hohenwart was in error, or the cave had been filled-in already in the late 1820s up to the height of today's cave-train tracks.

The upper bend of the stalagmite is not seen on the Schaffenrath picture, it is correctly hidden

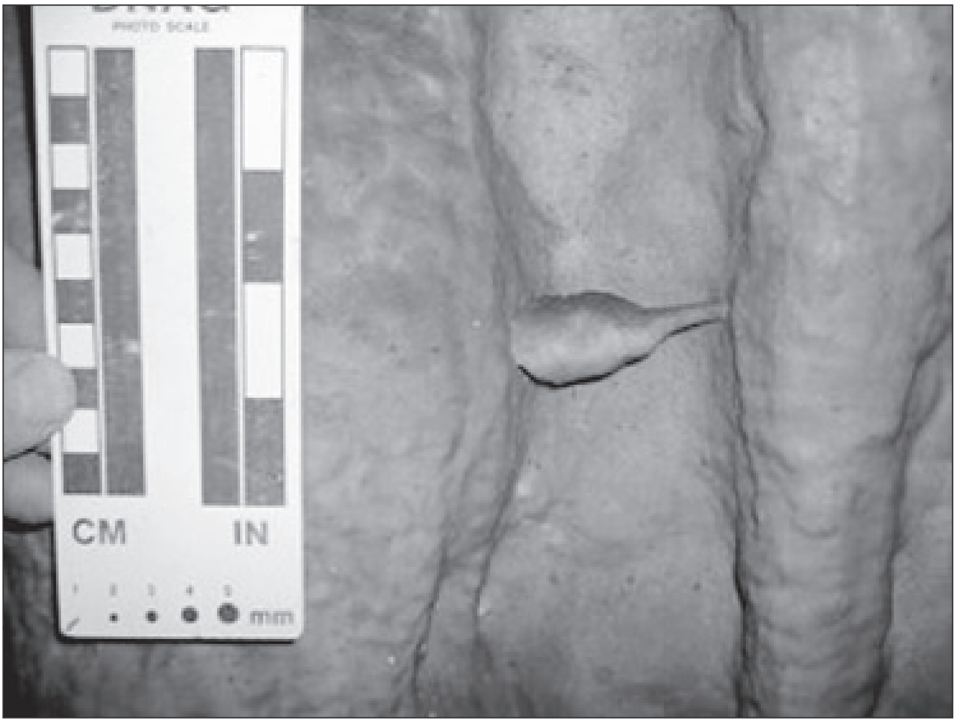

Abb. 13 a, b: Fragile stalactite, stuck between two folds of a wall curtain. Note closure of curtain folds above the stalactite.

behind a protrusion of the wall. Most probably this is not a bend but a second break, covered by modern flowstone i.e. the Pyramid is composed of three pieces: a 0.8 m high stump 1.8 m in circumference, a 3.6 m long middle piece tilted at 30° from the vertical and a ca. 1.5 m perpendicular end piece. The leaning piece touches the wall 3.6 m above the floor at a ledge on the west wall of the cave. Its lower end (Fig. 4) has slipped on the stump outward as if the piece turned at a hinge-point, somewhat at its middle.

The "backpack" stalagmite already noticed by Hohenwart (Fig. 5) is 1.8 m above the breakage and has increased the circumference of the middle piece to 2.3 m illustrating that quite some time has passed since the column was broken.

Because of this specific situation it is difficult to explain the breakage of the column. Hohenwart has already excluded several possibilities. Since the stump is upright we can exclude overweight, sediment compaction or sediment erosion as causes as well. A breakage by an earthquake is also not likely since the Large Cypress, a stalagmite of similar dimension a few meters farther into the cave, has not been toppled and because the breakage did occur away from the floor, i.e. the breakage did not occur at the highest possible leverage.

Cave ice remains as a plausible explanation. This is in line with the observation that modern flowstone has covered the rupture interfaces and that a new stalagmite formed (the backpack stalagmite).

Figure 6 depicts an *ad-hoc* model using cave ice as an agent to explain the breakage of the Schaffenrath Pyramid (for more details see also Kempe & Henschel, 2003).

Cave ice will form during the initial cooling of the advancing Glacial. As the cold winter air cools the cave from the inside, ice will accumulate at places where drip water enters the cave, i.e. at the places where stalagmites grow. The cave does not need to be filled with ice completely but ice can be concentrated at various places where water can still enter before permafrost seals the ceiling entirely. Further cooling to below freezing can cause contraction of the ice mass. The cubic expansion coefficient (ß) of ice (D'Ans & Lax, 1949, p. 749) is 21.3*10-5/degree. The linear expansion coefficient (α) is 1/3 of ß. On a length of ca. 10 m ice can shrink by 0.7 mm/°C. A cooling of 5°C (or a warming) can move the ice mass by 3.5 mm, possibly already enough to shear the column off its base. Figure 6 sketches the possible order of events. At the end of the cold period seepage starts again and the cave ice begins to melt. Melt water gullies can dissect the ice and cause an asymmetry in the ice mass. This could lead to slow ice movement, again an opportunity to shear speleothems encased in ice from their bases and/or shift them slightly sideward. Further melting finally reaches a state, where the de-stabilized column began to tilt around a hinge point, moving the lower part of the middle piece outward pressing some of the ice upward. This could be a slow process, much unlike to toppling the column by an impacting earthquake wave. Possibly the upper breakage - which we did not have time to study - occurred at this time.

The ice related forces acting on each stalagmite are different, depending on passage dimensions, ice volume and rapidity of the changes. This can explain why, for example, the Large Cypress did not yield to cave ice pressure or why one of the stalagmites in the Dancing Hall was sheared off and leaned on its neighbour, which itself stayed undamaged. For earthquake damages however, the length of the lever and the diameter of the column should be the determining parameters.

We also inspected some of the other areas in the main passage, specifically the large column leaning across the passage at the "Cumbersome Passage", (Plate 14, Hohenwart, 1832a) below which the cave-train track now runs. The area has many more fallen stalagmites and other interesting features which merit a closer study (for some initial comments see Kempe & Henschel, 2003).

Interesting is also a stalagmite group further north, shortly before the interior train station (Fig. 7) which Hohenwart (1832b, p.5.) already mentioned: *„A remarkable column is found on the right side. It is broken and rests across two other columns just like a doorstep. On it a white stalagmite grew up again.“* At first impression the Doorstep-Stalagmite seems to have knocked off - in falling - the tip of another stalagmite, which did not fall outward but inward and kept leaning on a third column. This impression is, however, wrong. When looking closer, it becomes clear that first the Doorstep was broken, next two stalagmites grew on it on both ends and then the smaller one was broken and tilted towards its modern position. Thus, if accepting the cave ice hypothesis, we have the record of two cold periods, interrupted by a longer, warmer period. The Doorstep itself could, for example, have grown during OIS 5, and it may have been broken during the cold phase OIS 4. The

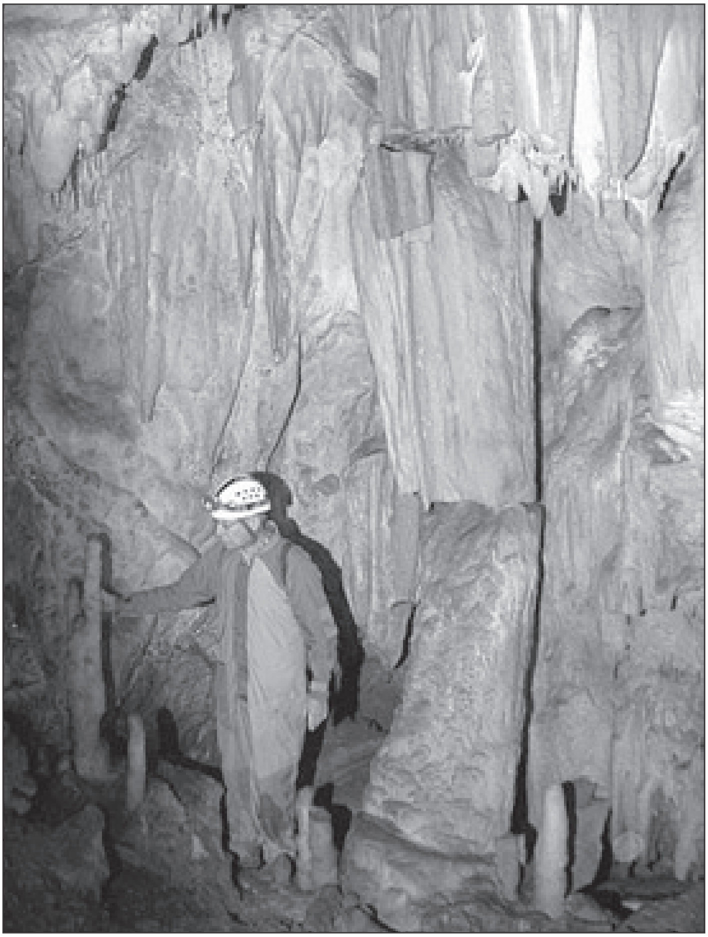

Fig. 14: Large column broken in three places and leaning to the wall in mid-column.

new stalagmites may have grown during OIS 3, which was longer than the Holocene and may have provided enough time for a substantial, more than 2 m high new stalagmite (left in Fig. 7). During OIS 2 (the Last Glacial Maximum) the small stalagmite on the right in Figure 7 was broken, and in OIS 1 (the Holocene), only marginal new flowstone formed at this site.

6. SPELEOTHEM DAMAGE IN THE SIDE PASSAGES

As remarked by Hohenwart, the side passages contain many more examples of broken speleothems, specifically the ends of Pisani rov (Colourful Passage; formerly Erzherzogs Johann Grotte) and Brezimenski rov (Nameless Passage). Here we find a very large range of different damages. Tables 1 and 2 summarizes the observations made. The positions of sites (except for P1) are given in Figures 8 and 9.

I did not have the time to prepare sketch maps of the various places but we made a series of digital photographs, which will serve to illustrate some of the observations made at the end of Brezimenski rov in more detail. This part of the cave is not reached easily. It is therefore visibly free from anthropogenic damage. Here we find a wide spectrum of naturally broken speleothems.

Most characteristic and very common are detached stalactites which are stacked on ledges along the wall well above the floor (B1; Fig. 10). Stalagmites occur in such places as well, some of them broken midway. At the ceiling almost all stalactites and draperies have been sheared off (B4; Fig. 11).

There are many details which are most puzzling. For example on a ledge at the W-wall (B3; Fig.

Fig. 15: Lower part of large column, offset by 10-15 cm towards the wall.

12 a-e) one finds a group of broken speleothems (ceiling height at this location 3 m) composed of two stalagmite base fragments (1, 2), two broken stalactites (2, 3), one curtain fragment (5) and two intact stalagmites (I and II), 70 and 80 cm tall, respectively. The stalagmite fragments, 22 cm (1) and 23 cm (2) in diameter, are shifted off their bases towards the north by 3 to 5 cm. Their original upper parts must be somewhere on the floor and were not identified in the short time available. It is most astonishing that these fragments, ca. 20-30 cm high, where not thrown off the wall. At first view the two intact stalagmites (I and II) seem to keep the fragments from tumbling off the wall. When viewed

Site	*Location*	*Type of Damage*
P1	N- of Entrance of Pisani rov in Main Passage	Large (3.6 m long) stalagmite leaning on wall. It slipped off the 2 m wide and 2 m high inclined stump. The stump itself shows another horizontal fracture with some movement. The stalagmite apparently had contact with a drapery at the ceiling. The stump is overgrown with a few dm of modern flowstone. Next to the stalagmite is a large and wide column, which is undamaged.
P2	NE-Corner of Rdeča Dvorana	A, large, ca. 3 m long, former column fell S-wards away from the former and slid off its stump. The column rests on other broken stalagmites and the stump is overgrown with small new stalagmites. West of the stump rest another massive fallen stalagmite, ca. 1.5 m in length and 1 m in diameter, also overgrown with new stalagmites. Where this fragment came from remained unclear. Nearby, at the wall is the surface of a rock or the base of a stalagmite covered with small rubble, including small stalagmite fragments, which is cemented and overgrown with modern flowstone (possibly remnants of a cave ice moraine??)
P3	NE-Corner of Rdeča Dvorana	A group of three small stalagmites on an elongated flake of ceiling rock (?) covered with flowstone. In-between two of the stalagmites rest the broken-off top of a stalagmite, most probably the former top of the one growing in the middle. It rests in a position were it should have rolled down further if thrown there by an earthquake. The fragment is now firmly fixed by modern flowstone.
P4	NE-Corner of Rdeča Dvorana	A large group of dozens of broken stalagmites, stalactites and other ceiling formations concentrated in one corner. Some of the stalactites rest pointing the same direction. One candle stalagmite broke in three. At the wall there are three peculiar candle stalagmites, all white and seemingly of the same generation, one is however leaning and overgrown by another almost in form of an “X”. On a block, a few m away from the wall three pieces of curtains rest on a slope were they could not have rested on when thrown there by an earthquake. This corner of the Rdeča Dvorana looks like after an explosion, so much damage is concentrated just in one place.
P5	Above ladder	A > 1m long fragment of a complex stalactitic curtain fell head-over from the ceiling and rests, inclined by 45°, on some stalagmites. The fragment is now firmly inter-grown with the stalagmites.
P6	In the hall before the ladder	The top from a 25 cm wide stalagmite from a medium-sized stalagmite group is missing. The stump is still a meter high. Here we had the impression the stalagmite had been taken off with a stone saw for museum purposes. We do not think that this is a natural breakage. The cut face has overgrown since the removal by a 2 cm large stalagmite.

Table 1: List of investigated sites of speleothem damage in Pisani rov.

closely, however, the fragments 1 and 2 do not touch the stalagmites I and II, i.e. the stalagmites most probably belong to a later generation and where not the reason that the base fragments stayed on the ledge. Even more puzzling is the 20 cm long stalactite (3) which is shoved underneath fragment (1). It also must have been moved northward in order to end up at its current position. On top of the two stalagmite fragments rests a twin-stalactite (4), 12 cm wide, also pointing roughly N-S. Its longer half has an intact tip and is 58 cm in length; the shorter part is missing its tip and is only 42 cm long. In the niche along the wall, another fragment, 14x10 cm large, of a ceiling curtain is noticed. All five detached speleothems are firmly fixed in place by post-detachment flowstone.

One can exclude that the current situation arose from vandalism, earthquakes or any other cause because of the following reasons: Vandalism could not explain why two stalagmites next to each other would be broken twice with the bases remaining *in-situ* shifted in the same direction. Also, if they would have been destroyed intentionally, then at least one of the bases should have slipped to where it would be halted by the intact stalagmites. In addition there are no chisel or hammer blow marks whatsoever. An earthquake, energetic enough to detach the stalagmites breaking them twice, would also have displaced the bases until they would have been caught by the upright stalagmites (II

Site	*Location*	*Type of damage*
B1	Ledges on eastern and western wall	Various fragments of stalactites, curtains and some stalagmites rest on a ledge. On the eastern wall there is a stalagmite, which rests 20 cm from its stump. On western wall rests a large collection of broken stalactites and stalagmites.
B2	Centre of hall	A group of stalagmites, of which half apparently consist of stumps of sheared off stalagmites slightly covered by modern flowstone. The other half appears to be candle stalagmites of modern origin, much lighter in colour. One is ca. 2 m tall.
B3	On eastern wall	A complex arrangement of two stalagmite stumps, themselves sheared off their bases, and two stalactites, one of which is tucked underneath one of the stump.
B4	On ceiling	Stumps of sheared off stalactites and draperies.
B5	On eastern wall, among labyrinth of curtains.	A small stalactite/soda straw stuck about 0.5 m above the floor between two folds of a wall curtain. A set of 5 small broken stalactites bundled together in a corner. A 50 cm long stalagmite sheared off the base and tilted. All fixed by thin modern flowstone
B6	On western side of passage	A pile of broken stalactites and stalagmites on the top of a slope as if shoved together by a big broom.
B7	On north-facing slope	A ca. 2 m long stalagmite pointing steeply down slope. Masses of broken sinter all stabilized by a thick layer of white modern flowstone.
B8	At NE-Wall, at the bottom of a depression	A 3m high column, broken at 3 interfaces and bend towards the wall in the middle. The lower section of the column slipped off the stump toward the wall. At the base upright standing broken stalactites.
B9	At western wall	A pile of broken stalagmites and stalactites, on top a large piece of drapery in a very unstable position, stabilized by a thin veneer of modern flowstone.
B10	On ledge of eastern wall	Several pieces of a drapery on a ledge, some protruding from the ledge. A stalagmite-stalactite column unbroken with a strangely bend stalactite for which no explanation exists.

Table 2: List of investigated sites of speleothem damage in Brezimenski rov.

and II). Even more unlikely would be the horizontal placement of a stalactite fragment underneath another broken speleothem. Also the point of gravity of the double stalactite (4) is barely inside of the edge of fragment (2) it rests on. This is not the situation a stalactite would come to rest when thrown off the ceiling 3 m high by an earthquake. None of the fragments would have been broken by their shear weight either and they where not detached by dissolution at their interface to the country rock. Also there is no sign that the passage had been filled with sediment. On Figure 10c one can see that the underside of (5) is white, while the upper surfaces are brown in colour. This brownish varnish therefore must be caused by splash water which slowly deposits new flowstone coloured with iron-oxides on upward pointing surfaces.

All in all, the only reasonable explanation remaining for the situation encountered here is cave ice. Its movements could explain the observed breakage, and its slow melting (possibly alternating with renewed freezing), could explain the seemingly precarious placements of the stalactite fragments. The in tact stalagmites (I and II) which must be several 1000 years old, also illustrate that the ice-driven event could have happened in the Last Glacial.

Figure 13 (a, b) shows another intriguing speleothem (B5): A 6 cm long stalactite fragment consisting of a conical stalactite with a soda straw at its tip. This very fragile speleothem got stuck between two vertical folds of a wall drapery and was fixed there by a very thin layer of new wall flowstone. The folds close above the stalactite, making it impossible, that this speleothem fragment had fallen vertically into this position.

Again it is not conceivable how any other process but slowly melting ice could have brought this speleothem specimen to its current position.

Further north in the passage, on the eastern wall, at the bottom of a depression in the passage, a large, almost 3 m high, broken column is found, leaning to the wall (B8; Fig. 14). The column is broken in three places: At its base, in its middle and near the ceiling. The entire situation looks as if the column has received a large punch in mid-column, pushing its middle to the wall. In addition it slipped also on the stump by 10-15 cm (Fig. 15). In the middle a large wedge-like section flaked off. Apparently the pressure between the forward edges of the upper and the lower fragment had been so large as to detach its front edge. At the ceiling, the breakage is rather irregular and extends to some curtains on the right.

What process could have caused such damage? Obviously either a large pressure had been applied horizontally mid-column, or, alternatively, the column had been compressed with a much higher pressure vertically to such a point that it bent and broke. Could the vertical pressure have been applied by an earthquake, putting the column into a wrench when the ceiling and the floor moved towards each other? But does an earthquake do that? Cold climate conditions on the other hand could explain both the horizontal and the vertical hypothesis: The column is found at the lower part of a medium-sized hall sloping upward to the south. This slope has many broken speleothems as well (B7; B6); witnesses of the former ice fill. One could imaging that towards the end of the cold period, a large mass of ice, detached from the slope, slipped down and crashed into the column. Vertical pressure could be generated under cold conditions when the water-logged sediment started to freeze and to expand, until the strength of the column was surpassed. Clearly we need much more data regarding the mechanics of speleothems before we can reconstruct direction and size of pressure causing such damage to a column at least 50 cm in diameter.

7. CONCLUSIONS

The observations presented here substantiate the conclusion that much of the speleothem damage in Postojnska jama was caused by cave ice. Consequently the cave must have been subjected - at least locally - to freezing temperatures. This may have happened several times in the past. Some of the damage is rather young, suggesting that freezing temperatures were also reached during the Last Glacial.

Since the cave is situated south of the Alps this appears at first surprising. However, considering that Postojna is in view of the Julian Alps, that the main passage of Postojnska jama is at 525 m above sea level and that the Adriatic was dry during the Glacial so that it could not mediate climate, one can easily understand that the area was subjected to a harsh, winter-cold continental climate during past cold periods. In addition the geomorphological situation of the cave aids in cooling it in some of its sections. This is because the plateau above the cave is dotted with large and deep-reaching dolines. North of Pisani rov we find Jeršanova Dolina, which reaches down to 539 m and buried the former continuation of the passage. These dolines are natural snow and cold air traps. Fresh air even today flows into the cave through the side passages originating from these sources.

Speleothem damage is reported also from other caves in the area, suggesting that glacial cave ice must have been a wide-spread phenomenon. The speleothem dates published by Mihevc (2001) for the area of the Divača Karst (east of Škocjanske jama) show, that the formation of frost debris and of solifluction cones ended in the caves 16 000 years ago. After that the Holocene flowstone generation began to form uninterrupted.

The region of periglacial speleothem damages may already end southeast of Lubljana. This at least is the result of a first inspection of Županova jama and Kostanjeviška jama. Both caves show only very limited natural damage to their speleothems. The ceiling speleothems are generally much larger than in Postojna and show only very few missing pieces, which can easily be explained by other processes than cave ice.

Therefore the regional mapping of speleothem damages, their forms and their frequencies could deliver important information about glacial temperature distributions and therefore aid in the exploration of the terrestrial paleoclimate.

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Appendix 1: Possibly the first discussion of the phenomenon of broken speleothems in the literature (Hohenwart, 1832a, p. 2)

„Auch die gewaltsamen Umstaltungen in der Grotte zeigen, dass die Natur nach eigenen, uns unbekannten Gesetzen in dieser Unterwelt wirke.

Die allgemeine Meinung über die Veränderungen die sich in derlei unterirdischen Höhlen ergeben, gehet dahin, dass durch Erderschütterungen die schwachen Gewölbe einstürzen, die losen Stämme von der Höhe herabfallen, und die in ihrer Basis nicht stark genug an der Decke befestigten Stalaktiten-Säulen herabgestürzt werden. Ein aufmerksamer Beobachter entdecket dagegen, viele Veränderungen welche sich nach dieser allgemeinen Meinung nicht erklären lassen.

Viele Veränderungen sind in diesem Theile der Grotte nicht mehr so bemerkbar, weil die unermüdete Anstrengung des Ritters von Löwengreif, zur Bequemlichkeit der Grotten-Besucher den Boden geebnet, folglich alle Hindernisse hinweggeräumt hat. Tiefer hinein findet man jedoch noch jetzt Orte, in welchen, wie es früher der Fall, in den jetzt gangbar gemachten Theilen der Grotte war, die ganze Decke dicht mit senkrecht herabhängenden Stalaktiten-Säulen besetzet ist, und dennoch liegt oft schief über die Breite der Grotte, eine drei bis vier Schuh im Durchmesser haltende Stalaktiten-Säule gebrochen!

Von der Decke scheint es, fiel sie nicht herab, weil kein Raum leer ist, wo sie gehangen hätte. Aber woher, frägt Jeder sich, kam sie also an die Stelle, in die Lage, die sie gegenwärtig einnimmt? Kann eine Kraft denkbar sein, welche diese mehrere tausend Pfund wiegende Masse, ohne einer die lebhafteste Phantasie überflügelnden Grösse der Gewalt, von einem fernen Platze dahin, wo sie nunmehr fest gebannet ruhet, zu bringen im Stande gewesen wäre.

Überhaupt scheint es auch unerklärbar zu sein, wie ohne Anwendung einer Gewalt menschlicher Kräfte manche Säulen des Tropfsteins dieser Grotte brechen konnte.

So wie die Säule am Tanzsaale gebrochen an ihrer Nachbarin lehnet, findet man in dieser Grotte mehrere Säulen in der Höhe von einer, bis einer und einer halben Klafter vom Boden an gerechnet, in der Mitte abgebrochen, die obere Spitze herabgestürzt, oder neben der Säule am Boden liegend, öfters auch, nur etwas von ihrer Stelle gerücket, und an die neben ihr stehende unverletzte nur angelehnet.

Selbst in der Vermuthung der Anwendung menschlicher Kräfte findet die Frage über das Ergebniss des Bruches mancher Säule, keine hinreichende Lösung."

Appendix 2: Description of Plate 12 (Hohenwart, 1832a, p. 7).

„Fünfhundert fünfzig Klafter vom Eingange erreichet man die Jabot's gewöhnlich die Schapodeln genannt, wie sie die Plate Nr. 12 dargestellt. An der rechten Seite der Wand senkt sich ein feines hell durchsichtiges ausgezacktes und einen Hahnenkamm ähnlich gefaltetes Tropfstein-Gebilde, in einer Neigung von 45 Graden aus der Wand hervortretend gegen den Boden, und erregt billig die allgemeine Bewunderung: wobei zu bemerken kömmt, dass hier der Kalkstein in seiner Nacktheit sich zeigt, da dieses Gebilde aus dem nackten Kalkstein geflossen ist. Die Halle ist vier und eine halbe Klafter (i.e. ca. 5 m) hoch, geräumig, und der Luftwechsel hier und in der ganzen Grotte vortreflich. Auf der linken Seite, diesen Jabot's gegenüber, ist eine abgebrochene Stalagmiten-Pyramide, die nicht minder die Aufmerksamkeit der Grotten-Besucher auf sich zu ziehen verdienet. Zwei und halben Schuh vom Boden ist diese Säule oder Pyramide abgebrochen. Da keine äussere Verletzung an ihr zu bemerken, kein Stein in der Nähe befindlich ist, der durch seinen Fall von oben auf die Säule diesen Bruch hätte bewirken können, so erregt derselbe staunendes Forschen. Sie lehnt sich an die Wand, und krümmte sich dort, wo ihr Schwerpunct in dieser schiefen Stellung seyn dürfte; gerade so, wie ein junger Baum sich krümmen würde, wenn er abgefällt, im Sturze begriffen, von einem anderen Baume angehalten würde. Diess ist nicht optische Täuschung, denn die Pyramide hat wirklich oben eine Krümmung. Allein sie ist nicht nur gebogen, sondern hat auch eine zweite Säule aufsitzen, die nach dem Bruche erzeugt, in jener Richtung fortwächst, welche die nun gebrochene einst gehabt haben mag. Diese Pyramide ist ferner merkwürdig, weil sie köcherartig gebaut ist. Die Köcher reichen von unten bis zur Spitze, folgen in kleinen Absätzen regelmäßig auf einander. Ihr ist keine andere Pyramide in der Grotte ähnlich, und die Bewunderung die sie anspricht, wird noch größer, wenn man die Basis im Bruche der stehenden Säule betrachtet, weil sie nach dem Bruche herabgefallenen Tropfen den unteren Theil vertropft, und glatt gemacht haben, wogegen der Obertheil so gebrochen erscheint, wie ein Baum zu brechen pflegt, nämlich dass einige Stücke länger einige kürzer somit dieselben fast zähneartig und also nicht wie ein Stein gebrochen wind, der kantig muschelicht oder uneben bricht. Die verschiedenen holzartigen Zacken machen, dass man mit dem Lichte ganz bequem den Bruch durchsehen und betrachten kann, somit deutlich sieht, wie sich dieser Bruch bereits stark wieder vertropfet hat.

Herr Schaffenrath hat diese Ansicht mit seiner gewohnten Genauigkeit aufgenommen; in dem weitern Hintergrunde werden dann noch zwei Pyramiden bemerkbar, von welchen die eine die grosse, die andere die kleine Cypresse heisst. Artig nimmt sich hier der Grottengang aus, der aus weissen und grauen Kalkstein bestehet, fünf Klafter hoch ist, und eine verhältnissmässige Breite an den Wänden aber keine Tropfstein-Gebilde hat. Die grosse Cypresse stehet ganz vereinzelt und frei, und hat eine von allen Seiten schief aufsteigende Basis, wie diess noch bei keiner vorhergesehenen wohl aber bei mehreren nun folgenden Pyramiden der Fall ist. Sie hat drei Klafter Höhe (d.h. 6 m), achtzehn Zoll im Durchmesser, und scheint aus einem röthlichen Tropfsteine zu bestehen, Die kleine Cypresse ist ganz der vorigen ähnlich, nur um die Hälfte kleiner, und auf der Oberfläche wie erstere mit erhabenen Zeichnungen geziert.