CAVE SEDIMENTS AND DENUDED CAVERNS IN THE LAŠKI RAVNIK, CLASSICAL KARST OF SLOVENIA

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1. ABSTRACT

Recent studies of denuded caverns ("unroofed caves") in Slovenia have revealed that features previously supposed to be exceptional occur widely as typical parts of the karst surface. This paper sets out to demonstrate that detailed, systematic, field mapping of denuded cave features ("surface caving") not only increases the number of caves known in a given area, but also yields a better insight into the spatial organization of cave systems, by casting more light upon their history. This paper sets out to present the results of "surface caving" in an area east of the Planinsko polje, within the classical karst of Slovenia. Here, observation of the sediments within denuded caves provides a means of recognizing individual cave system sectors that display apparently different histories of sedimentation, outwash and re-sedimentation, as well as possibly different sediment source areas. Additionally, such observations provide information about the spatial relationships of karst channels within a flow corridor.

2. INTRODUCTION

Most textbook authors mention "denuded underground phenomena" explicitly among their standard inventory of surface karst features. As a rule these examples are presented as curiosities, and cover only a small part of the full suite of endokarstic phenomena. Such an approach is one of passive recording, and tends not to promote active research designed to extract wider conclusions. Recognition of "roofless caves" (Mihevc, 1996, 1998; Mihevc and Zupan Hajna, 1996; Mihevc et al., 1998) revealed that features previously supposed to be exceptional actually occur as a typical part of the karst

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surface and the layer close beneath it (Šušteršič, 1999a). Though its discussion is limited deliberately to the cave sediments, this paper is intended to demonstrate that detailed, systematic, field mapping of denuded cave features increases the number of known caves in a given area. This approach also yields a better insight into the relationship between the geological setting and the spatial organization of cave systems, insofar as it casts more light upon their history. The paper sets out to demonstrate the power of the method, rather than to present new factual data.

Systematic study of denuded caves undoubtedly began during preparatory work for the construction of the motorway between Divača and Sezzzana (Classical Karst, southwest Slovenia). The whole area is an excellent example of contact karst, characterized by large active and dry horizontal, epiphreatic channels at several levels, draining an Eocene flysch territory towards the Adriatic. Even in "true" caves, it is evident that only a small part of the full system is actually accessible to humans. Most of the inactive part (assumed to be more than 80%) is choked by various sediments, predominantly flysch gravel and loam, deposited by sinking rivers. Though several impressive surface outcrops of large stalagmites were known previously, the first unroofed cave (about 200 m long) was recognized in 1994 (Mihevc, 1996). It was completely filled with still-recognizable cave sediments that were later cleared. Re - inspection of pre-existing infrared aerial photographs revealed that the course of this passage - and, by analogy, many others in the neighborhood - was clearly recognizable. Additional field indicators of buried caves were soon recognized, and this was followed by the discovery of several kilometers of "surface" extensions to the Škocjanske jame system (Mihevc et al., 1998).

A somewhat different approach to that used by A. Mihevc and his colleagues (Mihevc, 1996, 1998; Mihevc and Zupan Hajna, 1996; Mihevc et al., 1998) was adopted by the present author. It began as a detailed geomorphic mapping program on the karst surface in Laški Ravnik, intended as a framework for detailed study of solution dolines (Šušteršič, 1994). With recognition of the similarities and significance of unroofed cave channels, the recording of denuded underground phenomena became a systematic project on a complete cave system.

3. STUDY AREA AND GEOLOGICAL SETTING

Laški Ravnik (Fig. 1) forms part of a low-relief corridor about 18 km long and 1 to 3 km wide, lying about 3km northeast of Planinsko polje (south - central Slovenia). The area is generally flat and extremely rich in solution dolines (Šušteršič, 1994b). Some of the main streams of the underground Ljubljanica system are anticipated to flow beneath the area (Gospodarič and Habič, 1976), but no active stream cave has yet been found among a number of short cave fragments of evident phreatic origin.

Like the whole of the Classical Karst of Slovenia, the area investigated lies on the Adriatic sub-plate, a part of the African macroplate. The contact with the European continent lies about 80km to the north. During the last 2 Ma, changes in the motion of the Adriatic sub - plate have led to the establishment of several dextral strike - slip faults of Dinaric trend (i.e. southeast to northwest direction). As a reflection of its 12 km displacement and ongoing neotectonic activity, the Idria Fault is usually considered the

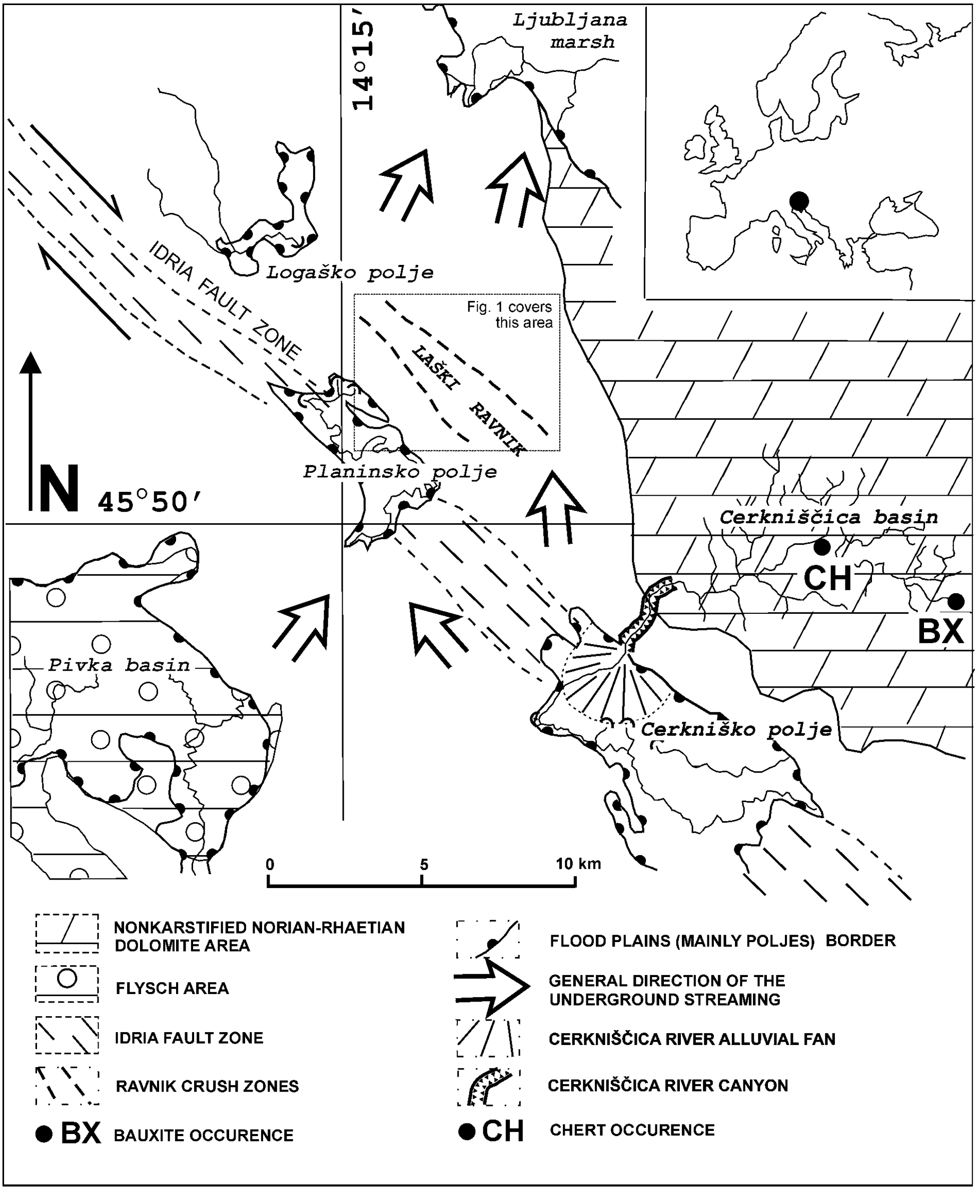

Figure 1. Location of the study area, showing important geological details.

most important. Statistical study of cave fragments in the general area revealed that the earliest cave systems were formed before the displacement along the Idria Fault (Šušteršič, 1996, 2000), i.e. 2 Ma ago. The conclusion reached was that most of the present underground streams make use of partly - adapted channels, inherited from a hydrogeological situation essentially different from the present one.

Structurally the area is a monocline, with beds dipping at 25° to 30° towards the westsouthwest. The oldest beds, in the east, comprise Middle Triassic clastic rocks and dolomites. These are overlain by the c.6,850 m - thick Dinaric carbonate sequence, topped in turn by Eocene flysch deposits on the western side. The study area coincides with the contact between Jurassic and Cretaceous rocks. Early mapping identified a c.300 m - wide outcrop of coarse-grained secondary dolomite at the top of the Jurassic sequence, whereas more recent fieldwork has revealed that in fact, rather than a single dolomite package, there is an interfingering of wider or narrower dolomite/limestone stripes (Fig. 2).

The low-lying Ravnik corridor runs parallel to the Idria Fault, which lies about 2 km to the southwest, running in the Dinaric (NW to SE) direction. Additionally, two lineaments, until recently only partially recognised as major crush zones, run parallel to both sides of the Ravnik. As demonstrated in the following discussion, these tectonic lines act as delimiters between zones of somewhat different cave sedimentation, whereas minor fractures appear to be insignificant in this respect (see Šušteršič, 1998a).

A previous statistical study of the known cave distribution within the Ljubljanica sinking river basin (Šušteršič, 1996, Fig. 5) showed a slightly increased cave density in the general area of Laški Ravnik, but no obvious distinctive peak. At that stage it seemed reasonable to assume that the increased cave density could be interpreted as a reflection of the presumed main underground streams of Ljubljanica that pass beneath (Gospodarič and Habič, 1976). Subsequent study revealed a previously unknown cave system, with a morphology that simply could not be attributed to development by water from the present Ljubljanica river system.

Mapping at 1:5,000 or larger scale began in 1994, with the seemingly un-ambitious intention of providing a wider background for a detailed study of solution dolines (Šušteršič, 1994b). Not only solution and collapse dolines (Šušteršič, 1998a), but also geological structure and lithology, as well as karren fields and other small - scale superficial karst phenomena, including outcrops of what was previously described as *terra rossa*, were mapped on separate sheets. The area is entirely covered by dense coniferous forest, so all of the mapping was done in the field, and potential over-simplifications that are common in remote sensing interpretations were avoided.

In the Najdena jama-Vranja jama-Jama Kloka cave system (Šušteršič, 1994a) the bedding plane partings on the (Cretaceous) limestone-dolomite contacts acted as inception horizons - i.e. these planes were most prone to early karstification (Lowe and Gunn, 1997). Based on the experience gained in this study, special care was directed into investigation of the (Jurassic) limestone-dolomite contacts. Thus, the presence of several outcrops of denuded cave channels became apparent.

The area studied by Mihevc and his colleagues, included large, horizontal, epiphreatic caves. In contrast, all of the features currently accessible on the surface of Laški Ravnik were originally deep phreatic, oblique (reflecting the dip of the enclosing strata), and relatively small. All of the denuded channels in the area are filled with a variety of clastic sediments, and localized flowstone deposits also occur. Where visible and washed clean, the channel walls are seen to be modified to some extent by small-scale spalling.

The set of "derived" denuded underground karst phenomena that is now detectable at the surface is much larger than was previously believed. With recognition of this abundant information, it soon became clear that the organization of the cave system is far more structured, and much less chaotic, than was ever imagined previously, and the

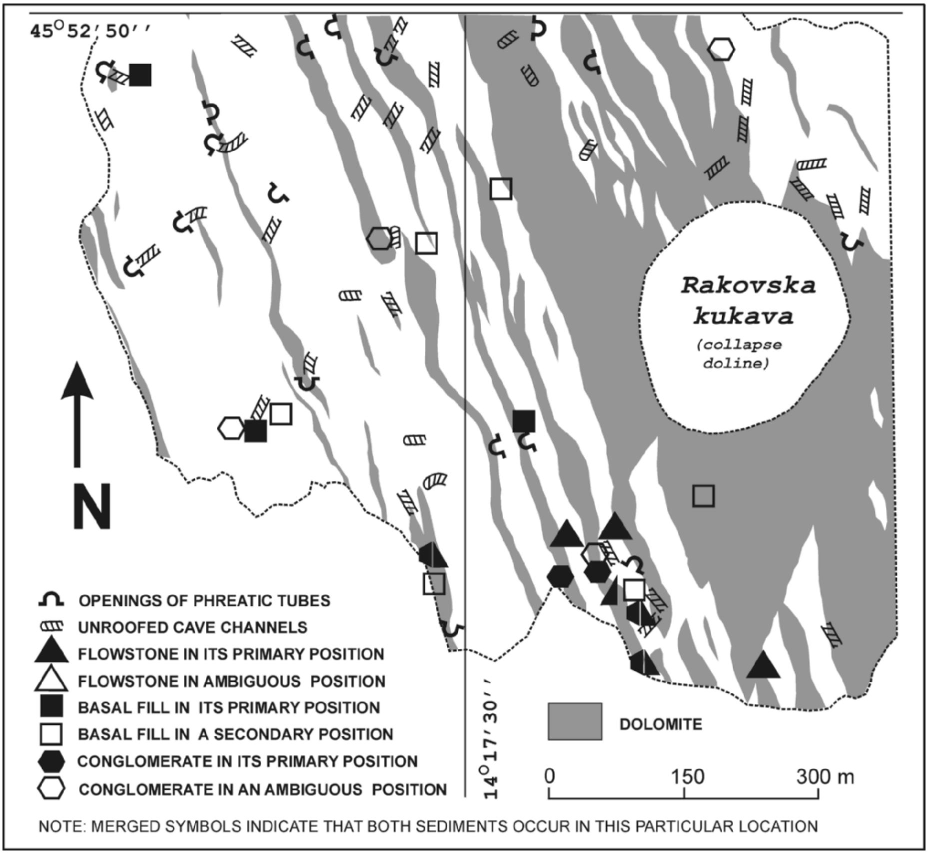

Figure 2. Morphological and sedimentological indicators of denuded caves in the southern part of the study area. Note: Combined symbols indicate that both sediment types occur at this particular location. The blank area indicates the position of a collapse doline.

relationship to the geological structure and lithology appear much clearer than before. Additionally, the application of "surface caving" has led to the identification of some previously unsuspected features, such as *phantom caves* and *aureole flowstone*.

4. CHANNELS AND SEDIMENTS

The known set of denuded underground karst phenomena includes morphological features and various cave sediments that are preserved, intact or reworked, at the karst surface.

4.1 Directly Detectable Channels

Except for some vertical vadose shafts, which appear to be very young, all of the cave channels identified to date are wholly phreatic in origin, and most of them are sediment-filled (Fig. 2).

The most common sequence of denudational decay of an average, unroofed, inclined, cave, synthesised on the basis of observations at various sites, is presented in Fig.3. Because the process is continuous, the "stages" illustrated are intended merely to represent "milestones", rather than defining seemingly discrete phases of development.

After the corrosional front (cf. Gams, 1997) has touched the roof of the infilled cavern, the loosened blocks in the arch will settle down into the loam (Fig. 3, "stage" B). Now, "floating" blocks appear to disintegrate faster in the abundant soil that has developed from former cave sediments (Geršl et al., 1999), and for some time an unroofed cave looks like a green, grassy strip between the clints.

Commonly the loam is gradually washed away, so that a trench-like depression appears within the former cave (Fig. 3, "stages" C, D). Once the sediment has been removed completely, denudation continues from the bottom of the former cave and acts preferentially downwards. So, until chaotic weathering finally erases the "trench" completely (Fig. 3, "stage" E), the "negative volume" of the cave is imprinted into the formerly underlying parent rock. Considering the deepest depression of this kind still recognizable is about 2m deep (Šušteršič, 1998b, Fig. 4), and assuming an average denudation rate of 65 m Ma^{-1} (Gams, 1966) such trenches may survive for at least 30 ka. In cases where the outwash of loam is faster than previously described, an overhang will appear during "stage" A (Šušteršič, 1997, Fig. 2).

4.2 Fine - Grained Cave Sediments

The structures discussed above (Fig. 3, "stages" C to E) have partly been washed clear of sedimentary fill and are thus relatively easy to recognize as cave remnants. More commonly, deposits of cave infill remain virtually untouched as the cave walls disintegrate (*primary position* - Figs.3, A; 4), and the outcrop of a denuded cave looks similar to a lens of loam at the surface.

The most widespread fill material is reddish brown (2.5 YR 4/4, 5 YR 4/4) loam with a minor admixture of relatively large oolitic bauxite pebbles (derived from the Late Triassic - Carnian - beds) and coarse clasts of black chert. Pilot X-ray diffraction analysis revealed mostly muscovite/illite, plus mixed-layer clay minerals of illite/montmorillonite type, chlorite plus mixed-layer clay minerals of chlorite/montmorillonite type, calcium montmorillonite, and diaspore plus gibbsite, or just traces of bauxite minerals (Mišič, 2000). The mineral composition is not as uniform as might be expected, and further research, intended for application of factorial analysis, is in progress. A potential sediment source area in the present Cerkniščica River basin (Fig. 1) appears obvious at first glance, but similar outcrops of bauxite and chert do also appear at other sites that are not much more remote.

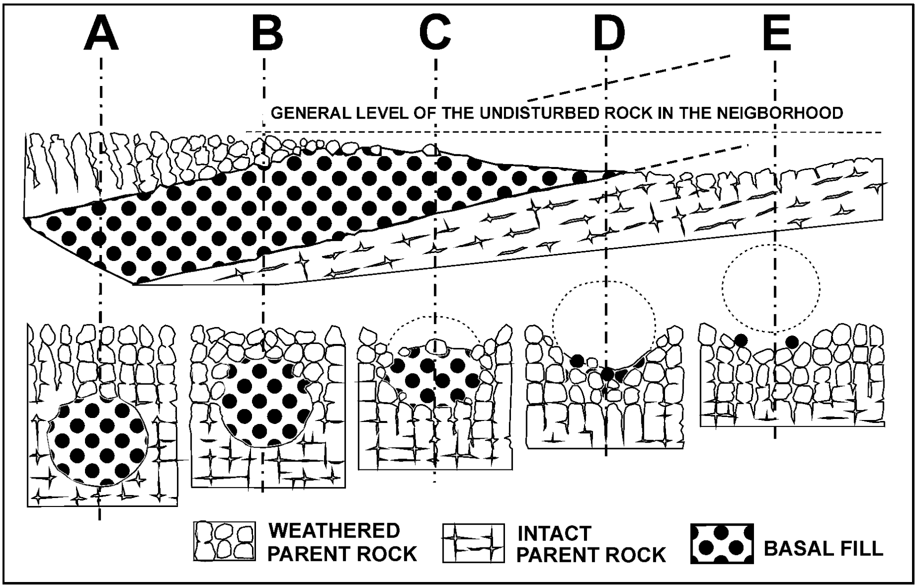

Figure 3. Stages in the gradual decay of an inclined, sediment-filled, phreatic channel, showing longitudinal section (above) and cross sections (below).

A: Original phreatic channel, not yet influenced by the zone of surface-weathering.

B: The sediment-filled channel is intersected by the surface-weathering zone. Breakdown of the channel ceiling takes place, and the fill supports large isolated blocks of parent rock.

C: The passage ceiling and the upper parts of its walls are removed as surface downcutting continues. Washing-out of sediment is somewhat faster than general surface lowering, and a small depression develops at the surface. Large insoluble clasts gradually concentrate in the floor of the depression.

D: Most of the cave walls have been removed, together with most of the former infill. Fragments of decayed flowstone and insoluble pebbles are preserved along the line of the former cave floor.

E: Both the cave and its parent rock have been totally denuded. A slight secondary depression persists within the new land surface for some time. Insoluble pebbles preserved in its former floor are the only evidence of the original cave's presence. Remnant concentrations of loamy infill are preserved only locally, within isolated pockets.

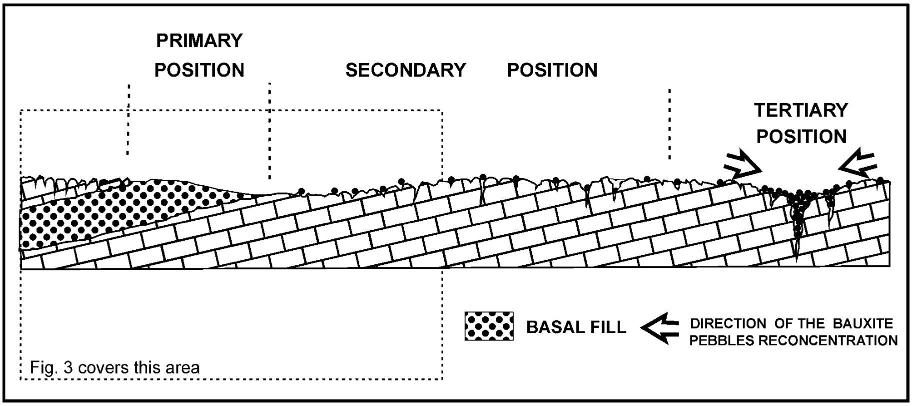

Figure 4. Possible positions of the cave infill.

Because no flowstone is found on the underlying cave walls, such sediments appear to have been deposited in the original cave systems when they were completely water-filled. As these deposits are nearly ubiquitous, and lie beneath most of the other preserved cave sediments, the sediment is referred to as *basal fill* (Šušteršič, 1998b).

At some locations all of the parent rock around, and some beneath, the previously filled cave has disintegrated, whereas the insoluble basal fill remained on the subsequent land surface *(secondary position,* Fig. 4*)*, where it would gradually be dispersed by continued terrain lowering. Locally it is still possible to distinguish the resultant pattern by observing concentrations of bauxite pebbles and chert on the modern land surface. In some cases they can be related to an adjacent outcrop of a denuded cavern, or at least to a recognizable inception horizon. Such features are referred to as *phantom caves.*

Ongoing terrain lowering would increase sediment dispersion and possibly re-concentrate any insoluble pebbles into newly formed pocket deposits (*tertiary position,* Fig. 4).

4.3 Laminated Sandstone

Partly cemented quartz sand was described formerly as an "exotic" sediment (Šušteršič, 1998b, p.128). Since then, other occurrences have been found, unfortunately mostly in obscure situations. However, it is now clear that the sediment in question is composed of fine quartz sand, cemented by calcite, which was later partly disintegrated again by ongoing surface chemical weathering. Some lamination is evident in unaffected "sandstone". Visual inspection reveals no significant differences from a number of similar occurrences distributed all over the Julian Alps and Dinaric Alps of Slovenia (Habič, 1992). As the "sandstone" generally lies lower, topographically, than the *basal fill*, and at one location lies just below its *secondary position*, it may be hypothesized that the *laminated sandstone* is older than the *basal fill.* Further research is in progress.

4.4 Coarse - Grained Cave Sediments

Outcrops of conglomerates that were deposited in now - denuded caves, are much less common. Clast size varies greatly, from coarse sands to large pebbles a few centimeters in diameter. The clasts are predominantly of Upper Triassic dolomite (which might originate from the same area as the oolitic bauxite discussed previously), with an admixture of Jurassic limestone clasts that are probably more local. Many of the dolomite pebbles were hollowed out during vadose diagenesis. Small quantities of bauxite and chert occur too, but it is not yet possible to say whether they were brought in as part of the stream load or simply admixed on the spot. Coarse rubble, originating from the channel roof or walls, is present locally.

Generally, the conglomerate displays typically alluvial features, such as graded bedding and laminated sedimentation. The matrix, which is loamy, ranges from barely present to comprising more than 70% of the rock. In the latter case, large pebbles are found "floating", supported by the matrix. At some locations flowstone occurs with the conglomerate. Unfortunately, no large clear section of a profile including conglomerate and flowstone has yet been found. Nevertheless, it appears that there were several alternating phases of conglomerate sedimentation and flowstone deposition. As flowstone is an indicator of subaerial sedimentation, its mere existence indicates that at the time of conglomerate sedimentation the conditions in the cave system were no longer deep phreatic.

4.5 Flowstone in the Denuded Caves

Little can be said about the flowstone. It is evident that it is younger than the *basal fill*, as it lies above it, but it is also contemporaneous with the conglomerate. Relatively dry periods of flowstone deposition alternated with possibly catastrophic flood events, during which gravel-laden water rushed into dry caves. Determination of the age of the flowstone deposits in the denuded caverns is clearly beyond the reach of the U-Th series method. Following a single failed attempt, at Bergen University (Mihevc, 2000), no further direct attempts have been made to measure their date(s) of emplacement.

The completely recrystallized flowstone is of various types, ranging from nearly pure glassy calcite to heavily clay-stained formations. Most is in the form of wall-flowstone or half-stalactites. Flowstone cave bottom crusts and massive stalagmites are also found, whereas true stalactites appear to be absent. As mentioned above, with very few exceptions most of the flowstone is found associated with conglomerate. Flowstone crusts survive on the walls of nearly completely washed-out caverns, or in the form of highly corroded flowstone "clints". Much of the flowstone appears either within confirmed former caves or in situations where the presence of a former cave is at least strongly implied.

Some deposits occur in fractures and other narrow openings, which may be completely filled with the flowstone. Typically, such deposits did not grow concentrically from the walls inwards, as they might in true shafts or dome pits, but from one wall towards another, until the whole space was consumed. Without exception these occurrences are no more than 20m from a larger (at least 5m) cavern. This flowstone variety is described as *"aureole flowstone"*, and its origin is still a matter of discussion (Šušteršič, 1998b).

One possible explanation is that it was deposited at comparatively great depth beneath the surface, where the rock mass is relatively poorly ventilated. Saturated percolation water in small voids could generally not give up its surplus CO_2, except where close to larger, better ventilated, caverns. Consequently, the rocky mass around better - aired voids became impregnated with flowstone, whereas vadose water channels farther away remained free of flowstone.

5. THE LAŠKI RAVNIK CAVE SYSTEM

"Surface caving" should, in theory, provide details of a planar section through a cave system and thus give much more information about its 3-D pattern than any other speleological method, especially if the channels are inclined. On consideration of the visible morphological and sedimentological information, the exhumed cave segments detected in the Laški Ravnik are quite clearly of deep phreatic origin.

5.1 Organization of the Cave Maze

Though more than 100 surface occurrences of denuded caverns have been noted, their dimensions have not yet been measured precisely enough to allow fair statistical analysis. Nevertheless, the disposable data imply strongly enough that such phreatic mazes are fractal, as concluded by Curl (1986). If the positions of these channels are considered relative to the lithology, it becomes clear that most of the phreatic tubes lie within or close to one or other of the upper or lower limestone/dolomite contacts. In this way, D.J.Lowe's Inception Horizon Hypothesis (Lowe and Gunn, 1997), arguing that primary tubes are formed along only a small number of somehow favoured bedding planes within the stratigraphic column, appears to be proven on a large scale. It indicates especially that bedding planes marking trans-bedding contrasts are among the most prone to early karstification.

Minor faults do not appear to affect the system to any great extent, except that major phreatic jumps are likely to be found in their close neighbourhood.

5.2 Distribution of the sediments

At least from the viewpoint of cave fill, the spatial distribution of cave sediments implies that the system must be split in two parts, separated by the NE Ravnik crush zone (Fig. 5). The best - studied area is on the western side. There, the *basal fill* must have been deposited within the channels when the system was still phreatic.

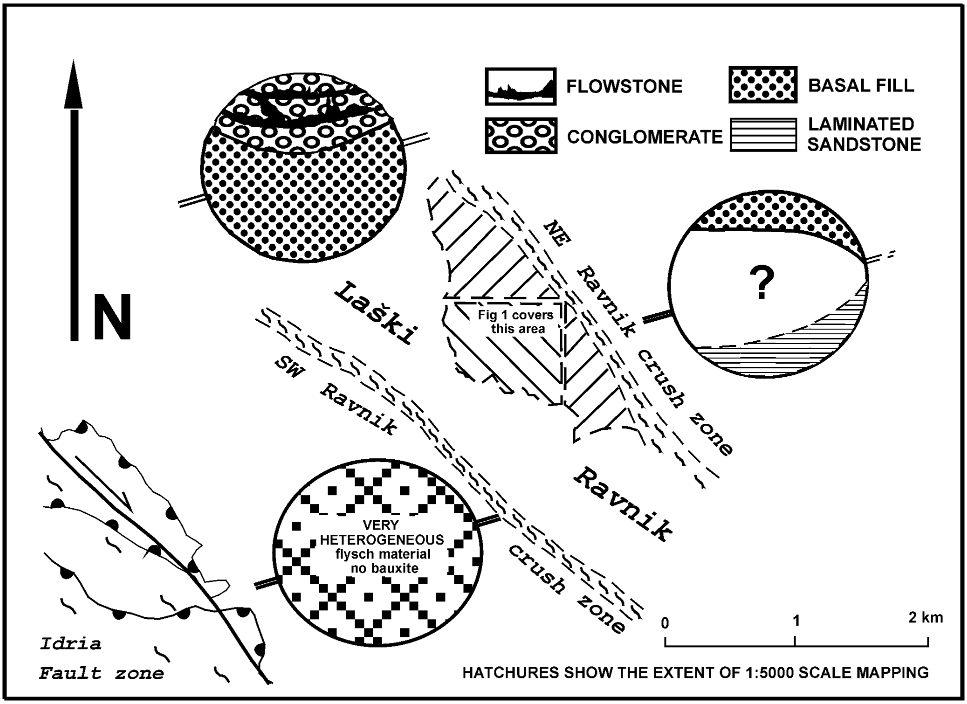

Figure 5. Cave sediment distribution within the study area. The ovals represent idealized cross-sections of infilled phreatic tubes.

The length of the time gap between the *basal fill* deposition and the last phase of partial outwash is unclear. At a time when conditions were to some extent similar to today's, with catchment area boundaries comparable to modern ones, flowstone development and conglomerate sedimentation apparently took place under vadose conditions. On one hand, the dolomite pebbles within the conglomerate do not differ from those in late Pleistocene gravel in the Cerkniščica river alluvial fan in the Cerkniško polje (Gospodarič and Habič, 1979). On the other, conglomerate-filled caves are exposed in the slopes of most of the larger collapse dolines, which suffered their essential transformation during the last glacial episode (Šušteršič, 1998a). Based on the nature and the number of pebbles in the conglomerate, one may conclude that the conglomerate (and flowstone) sedimentation took place during the Pleistocene, but not at its very end.

The situation on the other side of the same crush zone is rather different. The *basal fill* is preserved at higher elevations, whereas *laminated sandstone* appears at lower elevations. In areas where laminated sandstone has not been found, there are some larger caverns, which are accessible to humans. Close to the caverns are larger, unroofed, caves containing *basal fill* (Geršl et al., 1999). No conglomerate has yet been found in this area.

It is evident that only during emplacement of the *basal fill* was sedimentation comparable in cave systems on both sides of the crush zone. Because the other sediments differ completely across the crush zone, it can be concluded that the history of the cave systems on opposite sides might also be quite different.

Unroofed caves and, consequently, the sediments within them, have not yet been studied systematically westward of the southwest Ravnik crush zone. According to some pilot analyses, the loamy component of the fill is quite heterogeneous, and locally it may overlie flowstone. Bauxite pebbles appear to be completely absent, whereas an admixture of flysch-derived quartz sand is obvious.

6. CONCLUSIONS

Two conclusions may be drawn.

Firstly, observation of sediments within the denuded caves provides a way to recognize individual sectors within the cave system with possibly different histories of sedimentation, out-wash and re-sedimentation, as well as possibly different sediment source areas.

Secondly, a wide crush-zone may function not only as an obstacle to karst water movement (as suggested by many hydrogeologists), but may also act as a delimiter between tectonically-defined blocks, each of which may record a different history of sedimentation and, possibly, of speleogenesis.

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