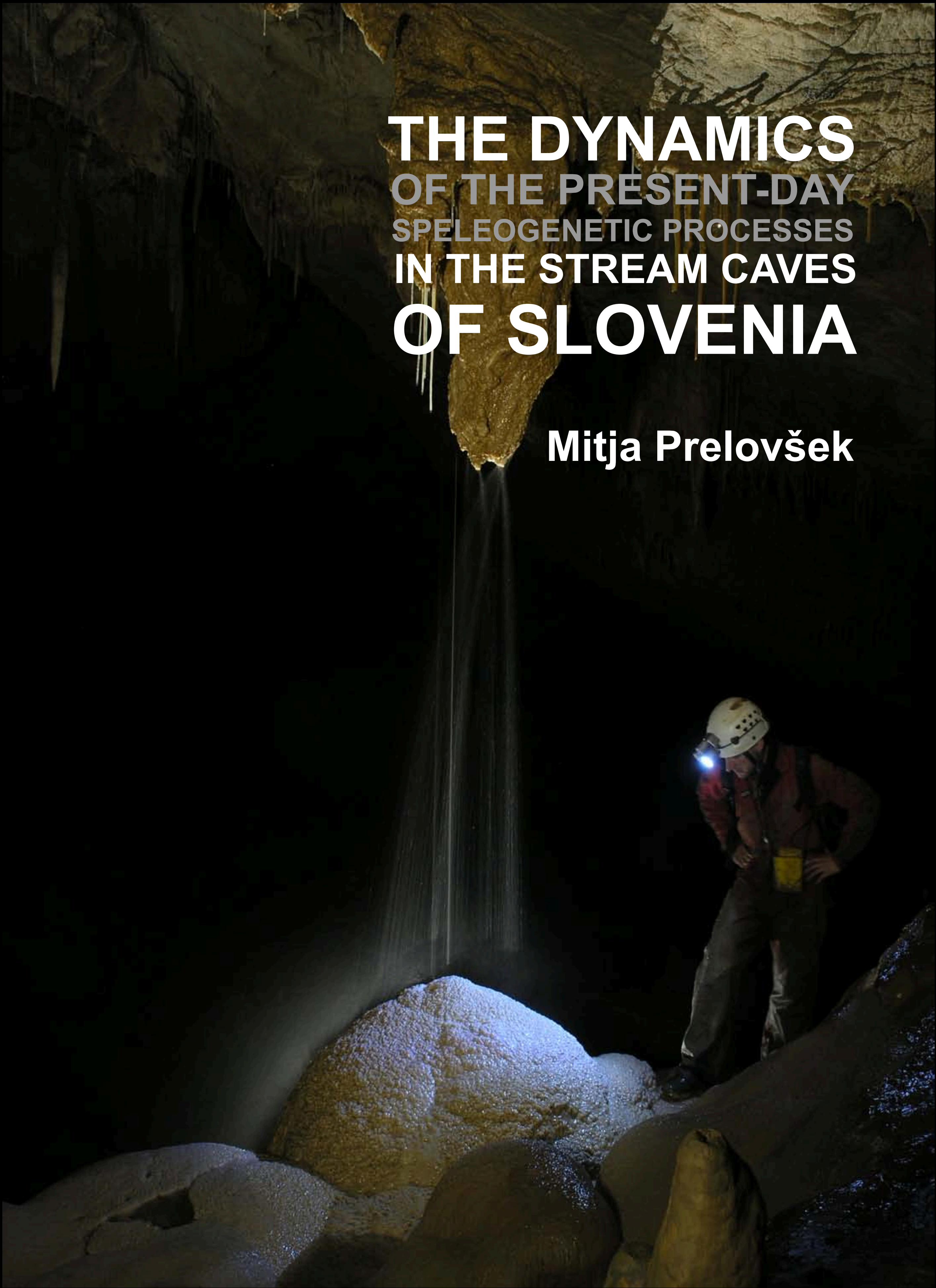
THE DYNAMICS OF THE PRESENT-DAY SPELEOGENETIC PROCESSES IN THE STREAM CAVES OF SLOVENIA

Mitja Prelovšek



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Mitja Prelovšek

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1
INTRODUCTION

1.1 FOREWORD

Nearly all current general knowledge related to the development of caves in limestone areas harkens back to the 19th century, some even to the 18th. At the beginning of the 20th century, the principal role of dissolution due to CO_2 from the soil, nearly all important chemical reactions that take place on karst surfaces and underground, principles of underground water flow and vertical hydrological zonation of karst massifs were all familiar. Several researchers defended their "universal" ideas with limited field observations but there were also some (e.g. E.A. Martel in 1896) that were already aware that "no theory about the origin of caves is universal" and "all of them are partly correct" (Lowe 2000; 30).

Many karstological studies during the 20th century brought shifts in emphases from general theories (e.g. water table controls) to investigations of individual underlying processes and mechanisms of cave development (White 2000) that deepened the understanding of the geomorphic evolution of karst surfaces and caves, hydrogeological functioning of karst aquifers, and chemical and physical processes that take place in the karst. General human development also helped fulfil the desire for intensive investigation in many karst regions and made possible deeper, longer, more efficient and scientifically supported cave exploration, especially due to the invention of the single rope technique in the second half of the 20th century. The second half of the 20th century also brought about greatly improved understanding of the chemical equilibrium and chemical kinetics of carbonate rock dissolution (White 2000). The quantification of speleogenetic phenomena made possible computer modelling of karst aquifer development, which is currently making great progress. The next step is the successful integration of modelling and field observation, which has already been done in some studies to an extent (Palmer 2007, Covington et al. in press).

The knowledge of the underground karst is deepening but some ideas that have already become generally accepted beliefs still require comprehensive confirmation. One such generally accepted belief is dissolutional origin and the development of caves, which seems to be an ongoing process in all karst areas. But to be sure about that and to obtain more reliable insight into the dissolutional speleogenesis in stream caves, comprehensive field measurements are necessary. To begin this task, the methodology for dissolution rate measurements requires substantial improvement and testing in different karst environments. This has been done in this study and the experiences are presented in Chapter 2. On the basis of field data and experiences, detailed investigation was possible in the largest and the most interesting cave systems (Chapter 3). We asked ourselves how high dissolution rates are, how variable in space and time, where the highest and the lowest rates are, and what causes them. A temporally and spatially dense net of measurement locations made possible field observation of dissolutional phenomena and a reliable synthesis of results for each cave system. As a result, though several cave systems were chosen and limited information about dissolution rates were illuminated, we can be sure that they are correct since they are quantitatively based and therefore objective. Our research was carried out in known Slovenian Classic Karst that developed mainly on limestone and dolomite under the influence of relatively shallow - rarely as much as hundreds of meters deep - circulation of meteoric water.

1.2 THEORETICAL BACKGROUND

Comprehensively speaking, cave systems are formed through the action of *speleogenetic agents* which, given various *factors* and through various *processes* produce *speleogenetic features* within a *speleogenetic environment*.

The main **speleogenetic agent** in the karst is water, which transfers dissolved or partly weathered rock through karst massifs and also tears away weakly attached rocks/crystals. Water in a karst system is also a medium that transfers dissolved or partly weathered rock through a speleogenetic environment. Accordingly, water erodes, transport and accumulates material in/through caves as a part of a water and rock cycle (Natek 1987; 75). Universal physical and chemical laws, particular to the speleogenetic environment, define how much rock can be eroded/dissolved, transported or deposited. At a particular location, physicochemical properties of water (e.g. CO_2 concentration, Ca^{2+} concentration, temperature, viscosity, density) and some other conditions (e.g. velocity of flow, hydraulic head, structure, texture of rock, erosion base) are crucial factors in regard to the geomorphic action of water.

Speleogenetic processes are sequences of changes that occur through the actions of agents in a speleogenetic environment and may result in specific cave feature formation. It is generally accepted that the dissolution of carbonate rocks is the most necessary and important process for cave formation and development. Although we can debate the importance of dissolution in comparison with abrasion when channels are big enough for the transport of sediments, dissolution can be recognized easily from dissolution load in spring waters. It is clear that dissolution takes place in karst massifs, but the portion of dissolution involved in channel enlargement is usually unknown and therefore must still be estimated. Generally speaking, the amount of carbonate dissolved in a solution at equilibrium depends on the concentration of hydrogen ions. The latter is usually defined by CO_2 concentration in the air, with which the water is in contact. When all available CO_2 is used for dissolution, water becomes saturated.

The kinetics of the process is at least as important as the equilibrium. The highest rates are achieved when a concentration of individual ions is far from equilibrium (e.g. when water is highly undersaturated or supersaturated with respect to Ca^{2+}; Ford & Williams 2007; 65). The highest rate of dissolution or sinter deposition is controlled by a rate-limiting process which can be (a) a reaction on a crystal surface, (b) conversion of CO_2 to H^+ and HCO_3^- (or vice versa) in the water or (c) the transport of ions by diffusion in the diffusion boundary layer (Dreybrodt & Eisenlohr 2000). The rate of reaction can be lower due to impurities in the minerals which inhibit the surface reaction (Dreybrodt & Eisenlohr 2000). Some substances in the water (e.g. lead, copper, manganese, phosphates, sulphates, sodium chloride) affect equilibrium concentrations and/or the kinetics of reaction (Jennings 1985; 23).

Therefore, the amount and rate of dissolution is controlled by many speleogenetic factors. The influence of some of them have been studied theoretically and experimentally (Dreybrodt 1988, Dreybrodt 2004), but the variety and temporal variability of factors in the natural environment is usually too great to calculate and predict actual rates of processes. Therefore, several field techniques exist to measure dissolution rates in caves.

Although dissolution is (almost) inevitable for karst and cave formation, the variety and rates of other speleogenetic processes can be quite high, even in karst areas, especially if we are dealing with caves close to contact with non-karstifiable rock (corrasion, sedimentation of allochthonous material) or close to cave entrances in occasionally colder climates (mechanical breakdown). The latter is a logical consequence of mechanical disequilibrium in a karst massif, which is established after the caves are formed (Jennings 1985; 28). Biological weathering can, especially in a warm (20-25 °C) and humid climate, play an important role in speleogenesis (Jennings 1985, 32). Bacterial films exist practically all over the cave's wall and can be responsible for dissolution or deposition. All these processes can be complementary to or contrary to dissolution. The extent of the final form (cave system or individual micro-feature) depends on the rate of processes and available time. The latter is highly variable.

Speleogenetic processes are dependent upon **speleogenetic factors** that define how intensively an agent will influence the karst massif and what kind of influences can be expected. They are numerous and various and range from the geological (e.g. degree of fracturization, chemical composition of rocks, texture and structure of rock), to the hydrological (e.g. CO_2 concentration, Ca^{2+} concentration, temperature, flow velocity, sediment load, presence of other ions), the meteorological (e.g. external and cave temperatures, CO_2 concentration in the air, degree and direction of ventilation) and the biological (e.g. density of organisms and their metabolic processes). Some factors increase the solubility of carbonates or increase dissolution rates (e.g. small grains of calcite-micrites, low water Ca^{2+} concentration, high water CO_2 concentration, high flow velocity, mixing of saturated waters with different CO_2 concentrations, transition from laminar to turbulent flow, presence of other acids (sulphuric acid, nitric acid) and some diluted salts (sodium chloride); some decrease the solubility of carbonates or decrease dissolution rates or lead even toward calcite precipitation (e.g. large crystals-sparites, high water Ca^{2+} concentration, high degree of poorly soluble rock impurities, presence of dolomite, small or decreasing CO_2 concentration in the water, presence of metal ions (lead, zinc, copper, manganese), presence of common ions with $CaCO_3$ or $CaMg(CO_3)_2$, presence of bases) and others have bidirectional influence (e.g. temperature of water, organic acids, microorganisms, phosphates, presence of magnesium) (Sweeting 1972, Jennings 1985; 22, Dreybrodt 1988, Dreybrodt 2000; Dreybrodt & Eisenlohr 2000, Ford & Williams 2007, Srdoč et al. 1985).

Speleogenetic features/forms are geomorphic features that developed under the action of speleogenetic processes within cave systems. They can be a result of a single process or a combination of processes (polygenetic features). Since the early and main topic of geomorphology (and speleology) was dedicated mainly to forms and their (sometimes very subjectively determined) geneses (Gams 1962; 3, Natek, 1987), descriptive literature on features is far more common in speleology in comparison with that which discusses speleogenetic processes or factors.

Features that can be found in caves are numerous by type, genesis and individual morphology. A comprehensive study of cave rock features is presented by Slabe (1995). Nevertheless, the genesis of even some basic and well-studied features (e.g. scallops) is still not fully explained. The genesis of scallops is generally attributed to dissolution (Curl 1966 & 1974 after Slabe 1995; 19, Goodchild & Ford 1971 after Slabe 1995; 20, Lauritzen et al. 1983, Lauritzen & Lundberg 2000, Ford & Williams 2007; 256-259), while some authors attribute at least the initiation to corrasion (Renault 1968; 563 after Slabe 1995; 20, Häuselmann 2002; 8), since they can be found on the surface of almost insoluble rocks (e.g. granite).

Speleogenetic environments are three-dimensional spaces where speleogenesis takes place. Usually, they are divided into several zones regarding the prevailing medium that fills the voids in the karst massif (air or water; permanently, occasionally). Two main zones are usually put forward (vadose and phreatic). In the vadose, water percolates downwards planarly and usually make contact with soil CO_2. Since such water is highly undersaturated, the majority of dissolution takes place within this zone (Smith & Mead 1962 after Jennings 1985; 156, Gams 1966b, Williams 1963 & 1968 after Ford & Williams 2007; 94, Sweeting 1966 after Ford & Williams 2007; 94). Contact with air is absent in phreatic zone, where the water moves due to a hydraulic head in a full pipe flow. The portion of overall dissolution in a phreatic zone is estimated usually at 5-20 %, in rare cases up to 40 % (Ford & Williams 2007; 94). Nevertheless, dissolution in the phreatic zone takes place at relatively small reaction surfaces; therefore, dissolution rates can be relatively high (Gunn 1986; 382). Dissolution in the phreatic zone also has significant geomorphological and hydrological importance, since it makes possible the drainage of extensive non-karst regions.

Because of high secondary porosity and fluctuation of water levels between vadose and phreatic zone, the epiphreatic zone is often enlightened. This zone (also referred to as the epiphreas, floodwater zone, temporarily flooded zone) can be defined with the highest and the lowest piezometric water level in a karst massif (Gams 2003; 46) or the zone that is regularly flooded (Häuselmann 2002; 8, Häuselmann et al. 2003). According to Swinnerton (1932 after Gabrovšek 2005) and Rhoades & Sinacori (1941 after Lowe 2000), the majority of underground water moves along the water table at the top of the phreatic zone due to its having the most direct connection between sinks and springs and also due to high secondary (or tertiary, according to Ford & Williams 2007; 104) porosity. The latter is a result of long-term evolution, in which the epiphreatic zone seems to be particularly effective for cave formation (Sweeting 1950 after Jennings 1985; 148, Palmer 1984 after Jennings 1985; 148, White 1988; 269-271 after Gams 2003; 46). According to Ford & Ewers (1978) and Ford & Williams (2007; 129-130), the degree of secondary (or tertiary) porosity in the epiphreatic zone strongly depends on fracture density – the higher it is, the shallower is a water flow through the phreatic zone (such (sub)horizontal flow can also take place in the epiphreatic zone). Nevertheless, some researchers (e.g. Jeannin et al. 2000; 345-346, Häuselmann et al. 2003) agree to the special suitability of the epiphreatic zone for the formation of (sub)horizontal flow but do not agree that there is a relation between the (sub)horizontal caves in epiphreatic zone to high fracture density (and the four state model described in Ford & Ewers (1978), since some areas (Siebenhengste-Hohgant-Lake of Thun) also exhibit the formation of passages around 200 m below the water level, although the rock is densely fractured.

The temporal and spatial variations of karst processes and factors are very common. From the viewpoint of dissolution, large differences in dissolution rates are observed within even one flood pulse. Nevertheless, speleogenetic processes are so slow that such short time scale variations are often neglected. Usually from several 10,000s to millions of years are needed for the formation of a substantial cave system. The dating of cave sediments confirms the very old age of several systems (see Zupan Hajna et al. 2008 for details). During such a long period, speleogenetic factors particularly and related processes can change significantly. Change of climate is the most obvious factor, although some significant changes in the catchment area, the tectonic position of the karst massif and the position of inflow/outflow are possible. Therefore present-day speleogenetic activity can be understood as just a moment during the long-term evolution of a cave system, while it remains important for the understanding of present-day relations in different climatic-geomorphic settings.

1.3 FOCUS OF RESEARCH, POSED PROBLEMS, APPROACH

The title of this book frames the subject of this work in time, theme and space:

- **temporal framework** (actual, present-day activity and its short-term (daily, monthly, yearly) variation),
- **thematic framework** (speleogenetic processes and their relations to factors and features) and
- **spatial framework** (stream caves usually in the epiphreatic zone).

In contradistinction to the numerous studies on fossil speleogenesis we decided to focus on **present-day geomorphic activity**. The latter has mostly been disregarded in the past due to a prevailing interest in long-term geomorphic evolution. But we should always be aware that evolutionary studies are based on the interpretation of recent morphology and present-day connections between features, factors and relevant processes. Therefore, the study of present-day phenomena will provide us good insight into the connection between processes, factors and forms and should reflect all the complexity of geomorphic activities as well as provide missing quantitative data on dissolution and sinter deposition rates in stream caves.

The second reason for studying present-day **speleogenetic processes** is the limited knowledge regarding their rates and variation in known cave systems. Gabrovšek (2005) states that for the understanding of karst and its evolution one has to study and understand the basic processes behind it. The process of dissolution is the core of the geomorphic activity of the karst and knowledge about it is necessary. Basically, there are two approaches to this: empirical (from large to small scales; knowledge comes from field observations) and analytical (from small to large scales; knowledge of basic principles of physics and chemistry results in an understanding of complex cave system networks; Gabrovšek 2005). The analytical approach was substantially deepened in recent decades by physicists and chemists while empirical studies of processes are rare even today.

In the past, present-day processes and factors were, in the field, mostly defined by the study of cave morphology on the basis of known relationships between morphology, processes and factors. This provides us the opportunity to interpret relevant processes and factors from morphology. Such an approach (Lauritzen et al. 2000, Fig. 1.1a) was and remains common in geomorphology and speleology. It is very effective and justifiable in an environment where the relations are clear, sometimes even visible, and processes act relatively rapidly. In caves, processes are usually slow, and, since the rock is transformed into solution, also invisible but observable. Changes in the hydrological role of underground passages are also common (Gospodarič 1976, Šušteršič et al. 2002). Additionally, the connection of karst processes and climatic conditions (trough CO_2 concentration, temperature and amount of precipitation) makes the relationship even more complicated. But can we really relate present-day morphology with present-day processes in caves with a long evolutionary history? What if present-day morphology is inherited from the past; e.g., the pre-Holocene period? We can at least suspect

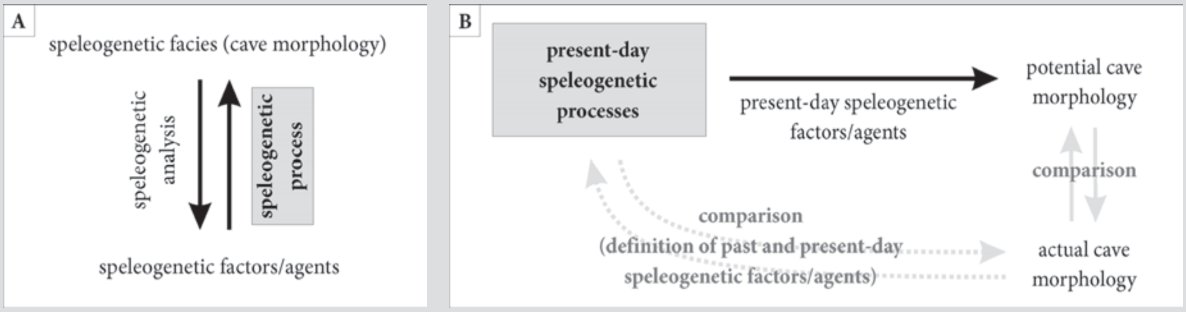

Figure 1.1. *Approach to "speleogenetic analysis" suggested by Lauritzen et al. (2000; A) and approach used in this book (B) to interpret speleogenetic relations between present-day processes, potential morphology, present-day factors/agents and their relations to present-day morphology.*

that due to morphologically, hydro(geo)logically, climatologically (and anthopogenically) induced changes of factors that define processes, present-day morphology does not necessarily correspond to present-day processes.

Since the connection between present-day features/factors and features seems to be questionable or at least for the most part unconfirmed, a different approach for interpretation is suggested (Fig. 1.1b). The advantage of such an approach is the separation of the study of morphology and processes (with factors), which seems to be problematic in the study of temporally limited phenomena. Rates of present-day processes can also provide us with rough estimations of time needed for feature formation if actual processes (with factors) are harmonized with the development of actual features and factors not significantly changed in the time required for feature formation. Usually the age of features has been calculated from dated cave deposits that overlay or are in any other known temporal relation with features (Bosak 2002; 201), which is the only way to define the age of features if no connection is found between actual morphology and actual processes.

The measurement of processes and relevant factors provide us data for the definition of potential morphology in cave passages. Potential morphology can then be compared to actual ones and this offers us the opportunity to see discrepancies and the extent of inherited features. At this point a major deficiency becomes apparent, as we have almost no data (especially) about present-day processes (and factors). It is hard to believe that from the middle of the 19th century, when dissolution was recognized as the main process in cave formation, until now, we still lack direct measurements of dissolution rates in caves. This deficiency is characteristic on a world scale (Gunn 1986).

Since the already measured (e.g. Smith et al. 1995, Gams 1996, Mihevc 2011; 64, High & Hanna 1970 after White 2000; 151) and estimated dissolution rates from measurements of factor/agents (Palmer 2007) are usually low in karst streams, we had to test and improve the methodology in order to begin our work. The micro-erosion meter (MEM) seems to be inappropriate for expected annual μm differences and for short-term (weekly, monthly) measurements, since large errors are expected at places with very low rates (Spate et al. 1985). Therefore we substantially improved the methodology for dissolution and sinter deposition rate measurements using limestone tablets. The use of limestone tablets for cave measurements as described in Chapter 2.2 plays a crucial role in the determination of low dissolution rates over relatively very short periods. The simplicity of the developed methodology makes possible measurements at numerous locations and consequently spatial and temporal comparison of results and enhanced reliability of conclusions.

Stream caves in epiphreatic zone represent one of the most attractive parts of karst aquifers. They often conduct the greatest portion of underground water flow and are from both the hydrological and geomorphological perspective very important. They also represent the easiest accessible part of a karst aquifer. Where it was possible, we took into account the cave system instead of one stream cave because the whole system yields more information about the integrity of the speleogenetic environment (Häuselmann 2002).

2

RESEARCH METHODS

Research methods used in this study were mainly devoted to the measurement of processes. Present-day dissolution or sinter deposition rates can generally be measured using the following methodology:

- **micrometer** (MEM; High & Hanna 1970 after White 2000, Spate et al. 1985, Mihevc 1993, Mihevc 1997, Mihevc 2001),
- **limestone tablets** (Gams 1959, Delannoy 1982 after Gams 1985, Gams 1986, Gams 1996, Newson 1971 after Gunn 1986; 383, Trudgill 1975 after Gunn 1986; 383, Sweeting 1979; 64-65), and
- **hydrochemical method** (solute load and discharge; Pulina & Sauro 1993, Ford & Williams 2007).

Measurements with MEM and with limestone tablets are highly site-specific and are highlighted in this study. MEM has been used frequently on bare surface rock, while limestone tablets have usually been used for dissolution rate measurements in soils, much more seldom in caves. The intensity of dissolution in the whole aquifer was usually calculated using hydrochemical data and discharge from karst springs.

The biggest challenge of measurements in the karst is the **low intensity of karst processes**, while the processes involved in non-karstic areas are usually much more intensive. In most cases measurements in the karst should last several years to be sure that results are truly representative. Therefore, in the short term the disadvantage is uncertainty of accuracy and reliability of measurements. Using a micrometer, the accuracy amounts to the usual 10 µm to up to 0.01 µm per measurement (Trudgill 1977; 253), but the amount of error, which is at low rates and at high frequency measurements relatively higher, represents a serious problem (Spate et al. 1985). Hydrochemical measurements offer us much better insight into the short-term temporal variations of dissolution and are extensively used over vast karst areas to calculate chemical denudation rates (see Komac 2005; 129-134 for details). But from such results we cannot obtain the rate of passage enlargement since we lack many variables (i.e. reaction surface, rate of process in different parts of an aquifer). These problems can be avoided if we are measuring the same parameters (solute load and discharge) between two measurement points at which distance and reaction surface is known. The condition for such measurements is that the processes are faster than the accuracy of the method, that we have significant length of passage and that hydrochemical changes are not a consequence of any tributary. This is rather hard to obtain.

The best opportunity to obtain the results we are seeking, which has rarely been used in the past, is the calculation of dissolution or sinter deposition rate from weight loss of limestone tablets. Weight loss is relatively easy to measure with accuracy up to 0.001 mg and since we are dealing with a quite high reaction surface, very precise data can be obtained. This finding led us to improve the methodology of using limestone tablets for measurements in caves and to use it as a basis for dissolution and speleothem deposition rates from 2005 onwards.

Six years of measurements is very little time in comparison with the lengthy speleogenesis of some caves (the active ponor cave Markov Spodmol currently contains between 0.78 and 3.58 Ma old sediments, but the cave is even older; Zupan Hajna et al. 2008; 247). Therefore, results of short-term measurements can be presented only as mm/a, while other, higher units (mm/ka, mm/Ma) are not acceptable or are even extremely hazardous (Gunn 1986, Trudgill 1986; 499, Trudgill 1994; 113, White 2000). In higher units (mm/ka or mm/Ma), only data obtained from long-term average rates should be reported. Generally speaking, the longer the measurements are taken, the longer the results can be extrapolated. Nevertheless, we can expect some time limitations of such measurements since factors can change significantly with changes in the influence of the environment (i.e. changes of tectonic settings, changes in drainage basin, climate change, land cover…). Accidentally or not, Kunaver (1978) recognized that measurements with a MEM (from -20 to -100 μm/a) obtained in one year on the surface of the Kanin plateau fit very well with the average dissolution rates (from -15 to -80 μm/a), which were defined from pedestals formed after glacial retreat at the end of the Pleistocene. Much better results can be obtained if the rates are measured frequently – from such results we have insight into the temporal variability of processes and can acquire some crucial information regarding factors which control the rates of processes.

Another problem is spatial extrapolation. To what extent can we interpolate and extrapolate rates of processes in space? The available MEM and limestone tablet results from high alpine karst (Kunaver 1978) and also lowland areas (White 2000) show that variability or rates even within medium-sized features (i.e. doline, slope) can vary considerably. A similar level of variation in the soil was recognized by Trudgil et al. (1994, Crabtree & Trudgil 1985), who exposed 240 limestone tablets transversally to a slope at different depths. Similarly to temporal extrapolation, spatial extrapolation depends on the variability of factors which control the rates of processes. Nevertheless, the variability of factors along underground water flows in stream caves seems to be lower. Therefore spatial variability should not be as high as in the soil, epikarst or vadose zone. In spite of this, several measurements should be made to confirm this statement, especially at places where factors can change significantly (i.e. at changes from free surface flow to pipe flow and vice versa, at confluences due to averaging and mixing corrosion, at changes of water velocity, turbulence, etc.). Measurements at several places and measurements of reliable factors provide important insight at least into the magnitudes of spatial variability of processes.

2.1 MICROMETER MEASUREMENTS

The micrometer, generally known also as the micro-erosion meter (MEM), since we are usually measuring erosion (however not always), was quite extensively used in the evaluation of chemical denudation rates on bare karst rock. It was developed as early as the 1960s (Spate et al. 1985), first used by High and Hanna (1970 after Ford & Williams 2007) and later improved by several researchers, including as the traversing micro-erosion meter (T-MEM; Furlani et al. 2009). During our measurements, we used a MEM from the Karst Research Institute ZRC SAZU, which had already been used by Mihevc (1993, 1997, 2001) in some caves and on the surface. It consists of a micrometer gauge connected to an equilateral triangular iron plate with 3 triangularly arranged legs at the corners, which lock precisely into stainless steel studs set into the rock surface. The micrometer gauge is placed several millimetres from the centre of the iron plate, which enables us to make three different measurements at each measurement location. The resolution is about 10 µm. Accuracy depends also on (Spate et al. 1985):

- errors due to temperature changes of the MEM,
- errors due to temperature changes of the studs and the rock,
- errors due to probe erosion.

The exact value or error depends on temperature changes, material from which the micrometer is formed, the softness of the rock, the number of measurements and the care while taking measurements. Higher temperature differences (between individual measurements on one side and rock and instrument on another) and probe erosion represent the most serious errors, which may amount to even more than 20 µm per reading (Spate et al. 1985). Of yet more concern is the fact that the error of measurements often exceeds the dissolution rates that were measured with a micrometer. In Yarrangobilly cave (Australia), where erosion rates are from 0 to -137 µm/a (with median value -8 µm/a!), the error was estimated to be between ±8 and ±22 µm (Spate et al. 1985). Therefore, annual MEM measurements are not reliable in stream caves that exhibit very low erosion/dissolution rates or where the errors (i.e. due to temperature changes) can be high.

2.2 MEASUREMENTS WITH LIMESTONE TABLETS

The first observations of dissolution using limestone tablets (also known as limestone plates, limestone discs, rock tablets, micro-weighed tablets or weight-loss tablets) were made by Chevalier (1953 after Gams, 1959) and later by Gams (1959). In the 1960s, an extensive plan for dissolution measurements in the caves of Slovenia was proposed by Društvo za raziskovanje jam Ljubljana (Society for Cave Exploration Ljubljana), most probably under the influence of Gams. This plan was never realized. Although the first measurements were made in stream caves, later measurements with limestone tablets were dedicated to dissolution measurements in soil. The greatest expansion of the use of such measurements occurred between 1978 and 1983, when extensive measurements were carried out all around the world under the leadership of the Commission on Karst Denudation at UIS (Gams 1985). Limestone tablets were used in many local studies mostly to evaluate dissolution rates at the point of soil-rock contact (Trudgill 1975 after Gavrilović & Manojlović 1989, Jennings 1977 after Gavrilović & Manojlović 1989, Trudgill 1977) and later (Day 1984 after Gavrilović & Manojlović 1989, Gavrilović 1986 after Gavrilović & Manojlović 1989, Sbai 1993, Trudgill et al. 1994, Urushibara-Yoshino 1999 after Ford & Williams 2007, Plan 2005). Very rarely limestone tablets were used in caves (Chevalier 1953 after Gams 1985, Gams 1959, Rebek 1964, Delannoy 1982 after Gams 1985, Gams 1996), probably because of the difficulty of fixing them.

The methodology of limestone tablets is based on weight-loss during exposure. If we know the reaction surface (the area of the limestone tablet) we can transform weight-loss into metric units (i.e. µm/a). This simple calculation shows that we can measure dissolution or sinter deposition rates very precisely in comparison with the micrometer if we are using analytical balance. This led us to start with short-term measurements of dissolution and flowstone deposition rates in the Slovene underground karst.

2.2.1 Preparation of limestone tablets

Limestone tablets used by Gams (1985) and in this study were made of borehole cores from the Lipica limestone quarry. The limestone is of Senonian (Upper Cretaceous) age. It contains 97.7-98.7 % of CaCO3, 0.21 % of MgO, less than 0.1 % of SiO2, 0.05 % of Al2O3 and 0.05 % of S, 0.007 % of Fe2O3, (GAMS 1985; 365). According to Folk's classification, Lipica's limestone is micrite to biopelmicrite. According to Gams (1985; 365), the density of the limestone is 2,710 kg/m3, while our measurements, based on the weight and volume of 235 limestone tablets, showed a slightly lower value (2,688 kg/m3). The latter value was used for transformation of units from grams to millimetres with Eq. 2.1.

$$D = \frac{\Delta m}{\rho \times A \times t} \qquad \textit{(Equation 2.1),}$$

where D is a dissolution or sinter deposition rate, Δm change in weight of the limestone tablet, ρ is the density of limestone, A the exposed surface and t the time of exposure.

The diameter of the limestone tablet was always 41 mm, while the thickness ranged from 2.6 to 3.5 mm by Gams (1979; 73) and from 5 to 8 mm in our measurements. Before weighing, Gams (1985) dried limestone tablets in an oven at about 110 °C and then cooled them in silica gel.

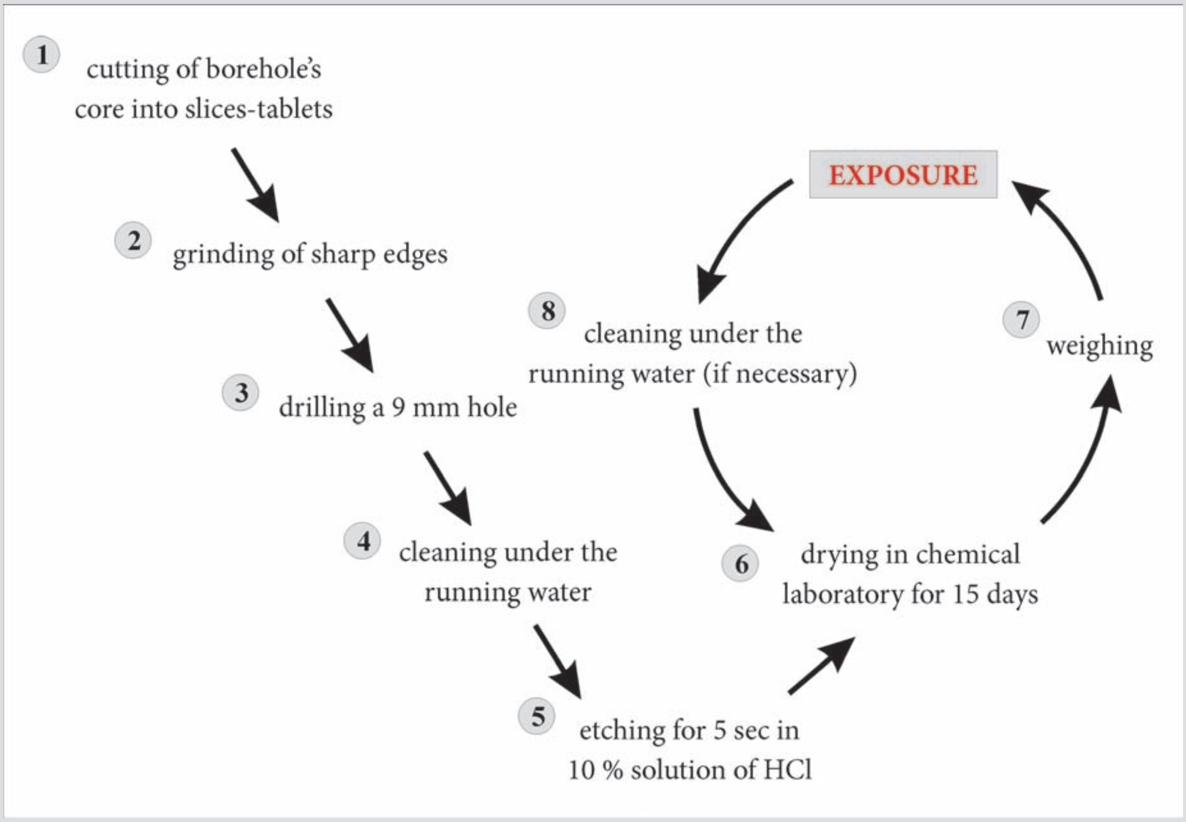

Figure 2.1. *Procedure from preparation to final weight calculation of limestone tablets and their treatment after exposure.*

A similar procedure was advised by Goudie et al. (1981; 143). Due to repeatable measurements with individual limestone tablets, we avoided such a procedure by drying the tablets in a chemical laboratory for 15 days. Instead of drying in an oven, we implemented a correction factor for the amount of water which remained in the limestone tablets after 15 days of drying. The whole procedure from the preparation to final weighing of the limestone tablets is represented in Fig. 2.1.

In phase 1 (Fig. 2.1) a core with a diameter of 41 mm was cut into 5-8 mm slices. The probability of chipping at the edges was reduced in phase 2. Drilling was done underwater. Due to the fragility of limestone, a small hole with a diameter of 4 mm was drilled through the tablet at the beginning and enlarged to 8 (9) mm from both sides. This phase was followed by cleaning under running water, during which we washed away all small particles of limestone. The final elimination of fine particles was achieved in phase 5, when the surface of the limestone tablets approached closer to the natural roughness. Afterwards, limestone tablets were dried in a chemical laboratory for 15 days. During this period of time the majority of water evaporated from the limestone tablets and the weight became only humidity-dependant (semi-stable). Weighing (phase 7) was done with the analytical balance Sauter 404/13 with resolution 0.1 mg and accuracy of about ±0.4 mg. Using this procedure 906 limestone tablets were prepared.

After exposure, we gently cleaned the limestone tablets (phase 8) if this was necessary. Cleaning was usually done in cave streams. Phases 6 to 8 were applied at all times when the limestone tablets were exposed to water in stream caves.

2.2.2 Test study

An 8-month-long test of the methodology was done at 85 locations mainly on the high and low Dinaric karst of Slovenia. Limestone tablets were exposed to low and high water levels, at some places to very harsh environments (e.g. Škocjanske Jame). Shortly after installation limestone tablets were affected by very high discharges since the amount of precipitation exceeded the 10-year recurrence interval. Limestone tablets were attached to cave walls with an iron screw with nut and felted washers (Fig. 2.2). Later on, testing of the methodology was also done parallel to measurements on study cases (Chapter 3).

The results are presented and discussed in detail by Prelovšek (2009) – here only some methodological experiences are highlighted since they were important for further measurements (study cases; Chapter 3) and error estimation. The prevailing process was dissolution but sinter deposition should not be neglected since this prevailed at more than 20 % of measurement places. Rates are very low, as can be seen from the median (-1.5 μm/a) and the arithmetic mean (-7.4 μm/a). Values were strongly concentrated (more than 32 % of measurement places) near the arithmetic mean in the class between -10 and 1 μm/a. At 44 % of measurement locations, rates are too small to be reliably detected with MEM within 10 years! The large difference between the arithmetic mean and the median shows some relatively high outstanding values. The highest dissolution rates are stronger than -100 μm/a and the highest sinter/tufa deposition rates over 100 μm/a.

Due to similar meteorological conditions in the laboratory during weighing before and after exposure, the influence of relative humidity on the tablets' weights can be neglected, but in different meteorological conditions can be important.

Some limestone tablets that were exposed to allogenic streams were damaged by corrasion/abrasion; therefore, actual dissolution rates are lower. Bed load material makes, due to the chipping of edges, results irrelevant and unusable.

The highest dissolution rates were characteristic for Krka's right tributaries, where measurements were usually performed at illuminated springs. Nearby measurements in stream caves, where dissolution rates were much weaker, and visual etching on the limestone tablet's surface, proved that they were significantly altered by biocorrosion, which was also evident at some other measurement places. Measurements at springs and in stream caves behind them can show very different values.

Very different local factors result in very different local dissolution rates. The highest spatial variability was observed between Lekinka cave and Postojna cave system, where the ratio of dissolution rates amounts to 36:1, even though the caves are less than 1 km apart. Another very important dissolution rate factor is related to vertical microlocation in the underground passage. For example, in Lekinka cave, the dissolution rates greatly weaken with height, although all limestone tablets were flooded (though at the highest level for a very short time).

Due to the use of iron screws, nuts and washers, excessive dissolution due to iron oxide was observed at several measurement points. Since it occurs very randomly and without noticeable logical explanation (even along the same stream), it cannot be easily predicted and theoretically quantified for other measurement places. The problem can be avoided by using stainless steel (inox) or plastic screws, nuts and washers.

Resistance of limestone tablets to fast flows (e.g. Škocjanske Jame) and precision was satisfactory to the point where it was appropriate to continue measuring. Nevertheless, to improve the precision of the methodology some corrections are suggested in the following chapter.

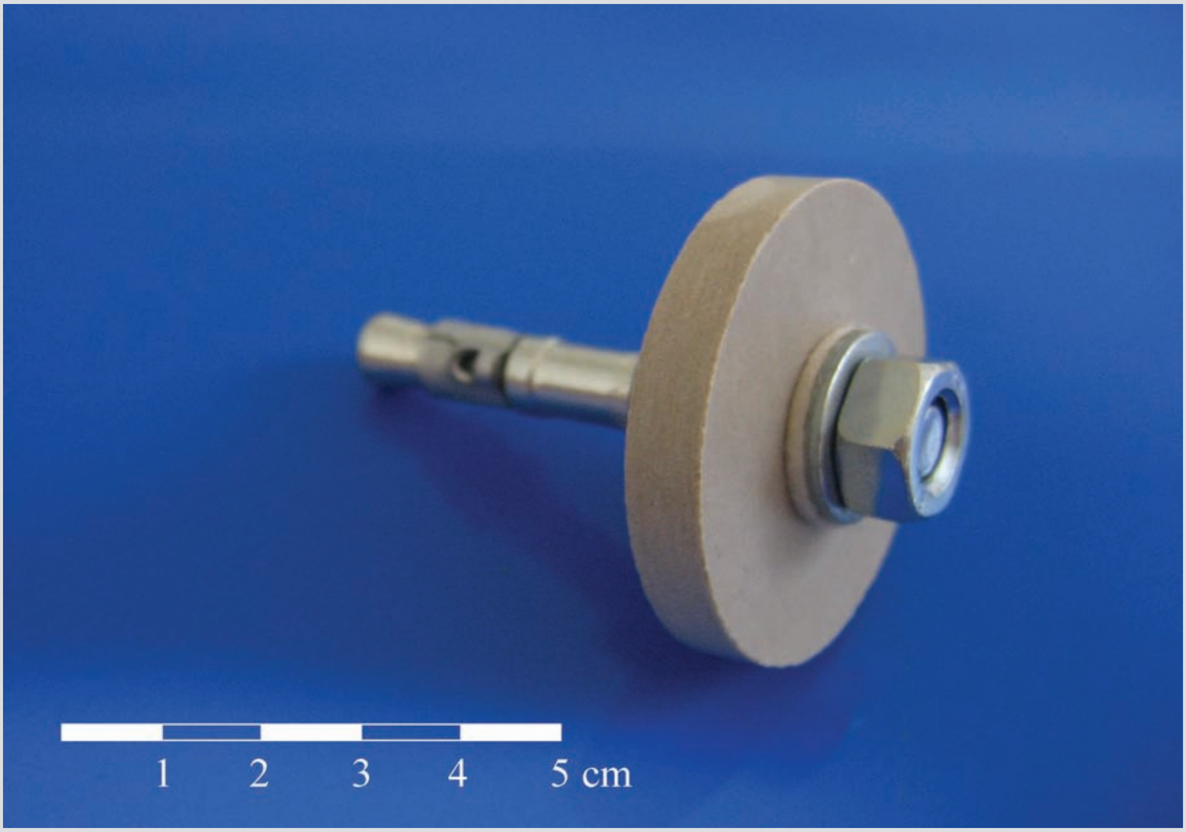

Figure 2.2. *Limestone tablet fixed on iron screw.*

2.2.3 Measurement errors and correction factors

Measurement errors present a deviation from real values. Knowing of errors and using correction factors should substantially improve precision. The latter is appreciated while measuring underground since dissolution and sinter deposition rates are usually in the range of several (tenths of) µm.

Deviation due to changes of relative humidity

Limestone is a porous sediment and therefore easily absorbs water from or emits water into the air until equilibrium with the atmosphere is achieved. This is well known and can be seen from seven limestone tablets that were stored in the Chemical Analytical Laboratory of the Karst Research Institute and weighed 147 times during changeable humidity conditions (Fig. 2.3A). Since we avoided the drying of limestone tablets in an oven and cooling in silica gel[1], as was performed by Gams (1985) and advised by Goudie et al. (1981; 143), and humidity conditions significantly changed through each year in the laboratory, correction of weight relating to relative humidity is crucial to avoid deviation due to changes of relative humidity. This can be done with the equation in Fig. 2.3B, which was derived with linear regression analysis on the basis of a strong and positive Pearson product correlation coefficient (+0.62; N=147) between weight change and relative humidity. Application of the correction factor for relative humidity significantly reduces (up to 5.8 mg) high seasonal variation in the weight of 20-25 g limestone tablets (about 0.7 µm in metric unit) if relative humidity varies between 36 and 67 %. Using this equation, the calculated weight can still deviate from real values on average ±0.3 mg (about ±0.03 µm) and up to ±1.1 mg (about ±0.12 µm), which is most

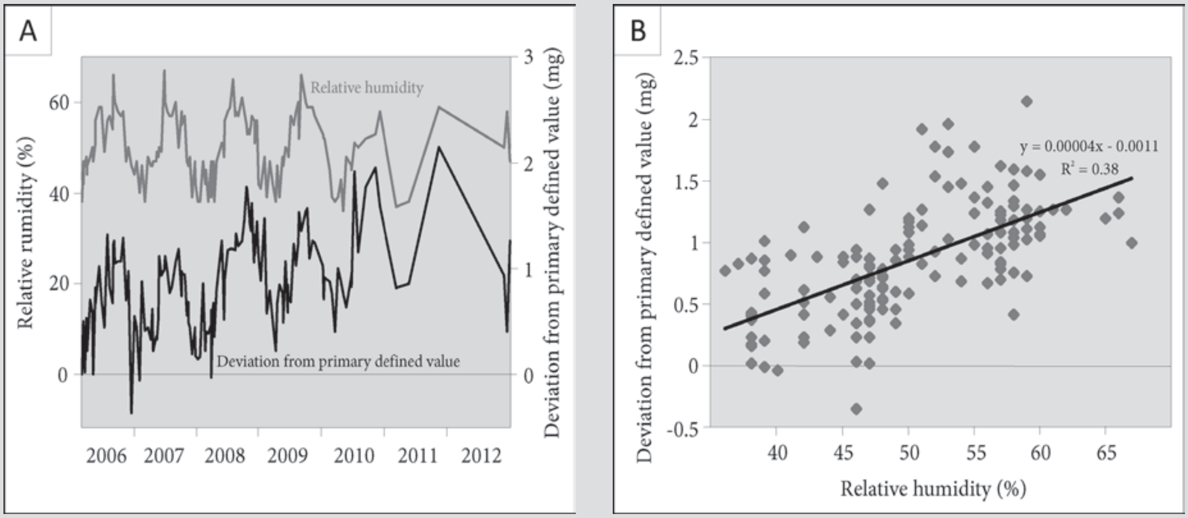

Figure 2.3. *A - Annual and sub annual variation of relative humidity and deviation of weight from primary defined (initial) value of seven limestone tablets (average); B - Relation between relative humidity and deviation of weight from primary defined weight.*

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[1] *This was done to (a) simplify and (b) speed up the procedure and (c) due to multiple cyclic use of two limestone tablets (see Chapter 3), when several times repeated drying of tablets cause intensive migration of saturated water to the surface of limestone tablets and structural modification of limestone tablets (e.g. case hardening).*

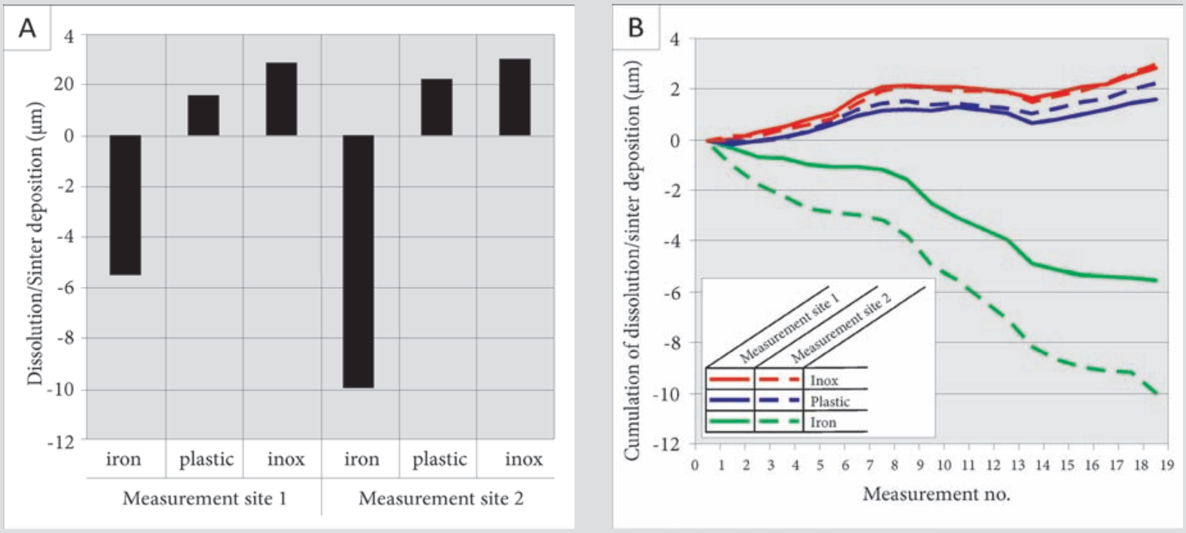


Figure 2.4. *Comparison of dissolution and sinter deposition rates on limestone tablets fixed to the cave wall with different materials at Križna Jama 2 (A-final cumulative values; B-growth of differences in time).*

probably a sum of the balance error, the error of defining relative humidity and the error of some measurements when humidity in the limestone tablets was not well equilibrated with relative humidity in the air. Instead of using the equation in Fig. 2.3B, we can place, but not expose to water, several limestone tablets beside exposed ones, and after exposure treat them as exposed and observe their weight change (initial weight and weight after exposure should be the same).

Deviation due to formation of iron oxide

Limestone tablets used in this study differ significantly from others previously used due to the central hole for fixation. Other researchers, who were measuring dissolution rates in streams, usually used nylon cages (Newson 1971 after Gunn 1986; 383, Trudgill 1975 after Gunn 1986; 383), meshes size 63 µm (Goudie et al. 1981; 143) or plastic wires (Gams 1986) to fix limestone tablets to the cave wall. This can result in higher abrasion rates (at least of weakly attached crystals when cement around them is partly dissolved), which was avoided in our study by firm fixation with screws, nuts and felted washers. At the beginning, the material for fixation was made of iron that resulted in rusting and accelerated weight loss (Fig. 2.4).

The rusting of iron screws, washers or nuts and the contact of rust with limestone can represent a significant problem for reliable dissolution and sinter deposition rate measurements. Contact of rust with limestone probably forms siderite (FeCO3), which enhances acidity (Ford &Williams 2007; 58) and accelerates dissolution. If the sinter deposition rates are very weak, rusting sometimes turns weak sinter deposition rates into misleading dissolution rates. Accelerated dissolution, as a result of rust, can be seen under a magnifier as a circular entrenchment at the surface of a limestone tablet, especially below the edge of washers or as an incomplete solution over all areas of limestone tablets located under the felted washers.

Rusting, and its influence on dissolution rates, is not expressed equally at all measurement points. In Križna Jama and Križna Jama 2, a comparison of tablets fixed on stainless steel screws, nuts and washers shows that calculated rates of misleading dissolution can amount from

-0.1 to -2.4 µm/30 days. The lowest average and the lowest monthly maximum misleading dissolution rate (up to -0.1 µm/30 days) in Križna Jama was detected in Pisani Rov (variegated passage) near Kalvarija and at Brzice (rapids) downstream from the first lake of Križna Jama (for plan see Fig. 3.1.6 on page 40). The highest calculated maximum misleading dissolution rate was detected in the upstream part of Jezerski Rov (lake passage), with amounts up to -2.4 µm/30 ays. In Križna Jama 2, the maximum monthly misleading dissolution rates are smaller in comparison with Križna Jama (up to -1 µm/30 days), but the average through the year can be much stronger (from -0.3 to -0.6 µm/30 days). These values are so high that they show dissolution instead of real sinter deposition, at least in Križna Jama 2.

Since the rusting of iron represented a big problem especially when dissolution or sinter deposition rates were weak, stainless steel or plastic should be used instead of iron. Synchronous measurements with limestone tablets fixed on stainless steel screws and PVC plastic screws, which were used in Križna Jama 2, showed little difference between stainless steel and PVC plastic.

Figure 2.5. *To transport limestone tablets through the harsh underground environment, a special carrier was designed to prevent physical damage (photo: Alojz Troha, DLKJ).*

Deviation due to transportation damages

Damage to limestone tablets was avoided by using a specially designed carrier (Fig. 2.5) in which limestone tablets were arranged in several layers. Each limestone tablet within each layer was separated from other limestone tablets by at least 5 mm to avoid any contact between them. Between layers, limestone tablets were separated with felted washers to prevent damage from abrasion. Plastic foil with the tablets' numbers under each layer of limestone tablets enabled identification of each, since they were not directly designated. No damage during transport was detected during 6 years of use.

Deviation due to freshly cut surface

According to some warnings (Šušteršič-personal comm.) and field experience (Gams 1985, Trudgil et al. 1994), a freshly cut surface has some influence on dissolution rates. Gams (1985; 372) found that dissolution rates may be, due to a fresh cut surface, weaker in the first year and remain constant during a second and third year of measurements. A contradictory phenomenon was observed by Trudgil et al. (1994) – in the first two years dissolution rates were a magnitude higher in comparison with later observations that lasted eight years. The decrease of dissolution rates was interpreted either as a "rapid erosion of exposed crystals at first and the formation of a less soluble weathering crust at a later stage" or as a result of the cleaning process. In addition, it is possible that the drier years in the second period of observation could have decreased dissolution rates.

Our study of dissolution rates carried out in Lekinka showed a weakening of dissolution rates

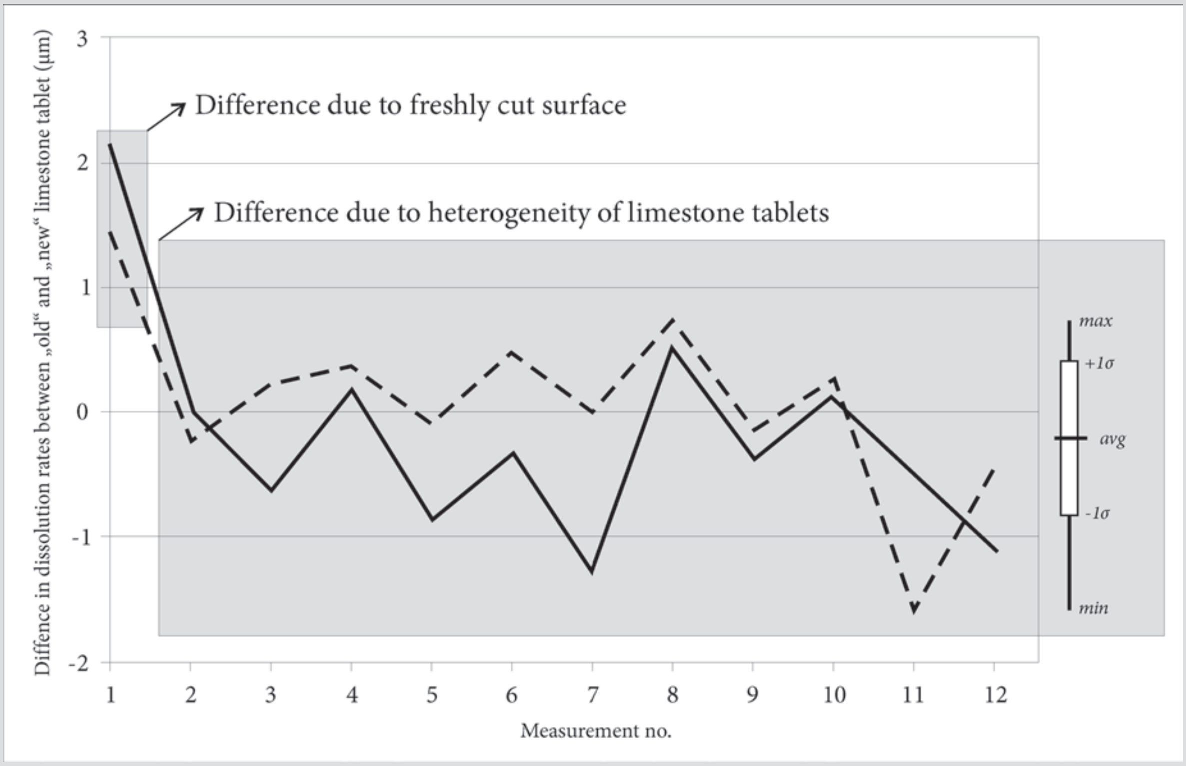


Figure 2.6. *Differences in dissolution rates due to freshly cut surfaces and heterogeneity of limestone tablets (positive deviation shows higher dissolution rates on fresh limestone tablets). Each measurement lasted about 15 days.*

(Fig. 2.6), since the strongest dissolution rates were observed on freshly exposed limestone tablets, while the others had already been exposed for about 540 days (in this period dissolution already removed at least 32 µm of the limestone tablet's surface). The highest difference between limestone tablets was observed at the beginning of measurements (the difference amounted to more than 2 µm/15 days). When dissolution had removed 25 µm of the limestone tablet's surface, the limestone tablets indicated similar dissolution rates. This was a result of changes on the reaction surface, which was modified with a cut into the crystal lattice. After dissolution of many small (probably partly broken) crystals with high specific areas, reliable dissolution rates followed on the undamaged crystal lattice. At the latter surface of crystals, dissolution "passes from one atomic layer to the next, much like unravelling successive rows of knitting" (Ford & Williams 2007; 66). This is a slower process in comparison with the dissolution of partly broken crystals or calcite cement with a greater reaction surface.

The influence of freshly cut surfaces on sinter deposition rates was studied at the downstream end of Pisani Rov (Križna Jama; Chapter 3.1.5), where deposition rates are among the highest detected in cave streams of Slovenia. Two pairs of old and new limestone tablets were used for measurements. Each measurement lasted 30 days. Before placing new limestone tablets, old ones were exposed for 490 days (during this period 21 µm of sinter was already deposited on old limestone tablets). On-going synchronous measurements point out that differences in sinter deposition rates exist only at the beginning of measurements (up to 3 µm/30 days) until about 3-5 µm of sinter is deposited (Fig. 2.7). Later, sinter deposition rates are nearly equal since the standard deviation amounts to only 0.3 µm and the minimum and maximum are within ±1 µm span.

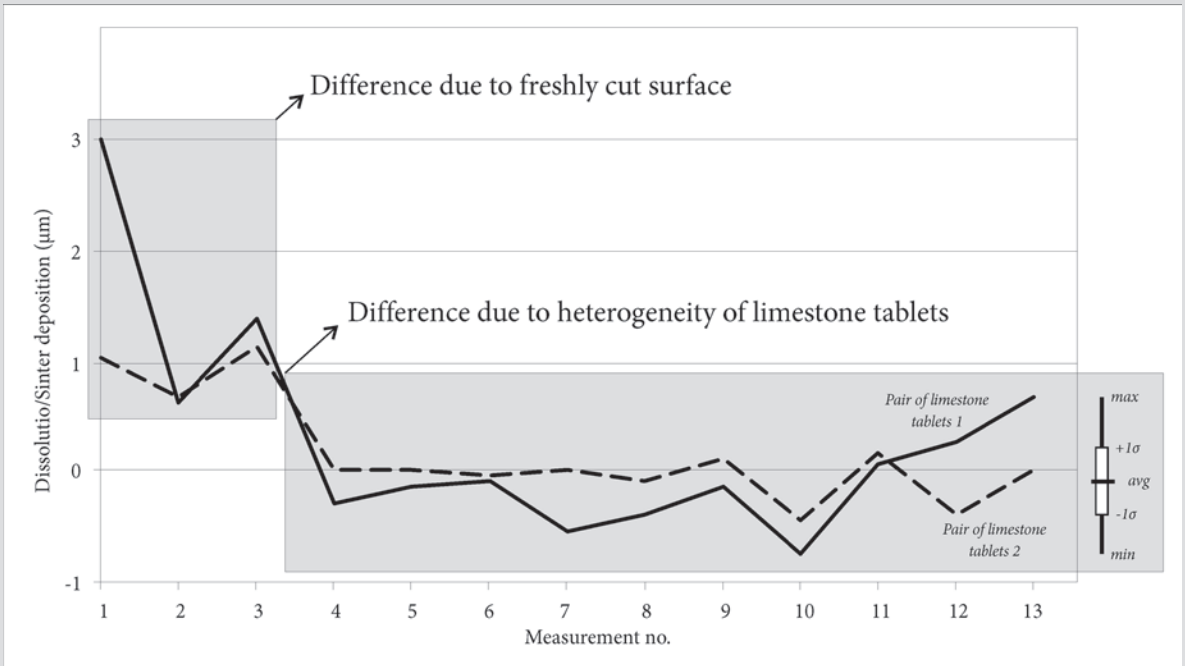


Figure 2.7. *Differences in sinter deposition rates due to freshly cut surfaces and heterogeneity of limestone tablets' surfaces (positive deviation shows higher sinter deposition rates on old limestone tablets). Each measurement lasted about 30 days.*

Deviation due to heterogeneity of limestone tablets

Although limestone tablets are made of the same type of limestone, they display a certain degree of heterogeneity. Gams (1985) did not devote any special attention to this problem although he visually recognized heterogeneity of limestone itself, from which the tablets were prepared. Like Crabtree & Trudgill (1985), he avoided this problem by using similar limestone, if possible from the same stratigraphic horizon. According to our observation, even limestone from the same stratigraphic horizon consists of different portions and compositions of allochems (biogenetic remnants - shells, peloids and intraclasts) and different portions of micrite with different degrees of recrystallization. Since sparites and other coarse grained rocks are less soluble than pure micrite, we should expect different dissolution rates. Many studies have found that micrites and biomicrites show higher dissolution rates and that rates of dissolution weakens substantially where sparite becomes greater than 40-50 % by volume (Sweeting & Sweeting 1969 after Ford & Williams 2007; 28, Maire 1990 after Ford & Williams 2007; 28). Dissolution rates also increase with the heterogeneity of grain size since differences in grain size result in greater roughness (reaction surface) – this is the reason for weaker dissolution rates in pure micrite (Ford & Williams 2007). Although Lipica limestone seems to be quite homogeneous, we should still expect some differences in dissolution rates.

In Fig. 2.6 we can see two pairs of differences between new and old limestone tablets. The first positive deviation (higher dissolution rates on new limestone tablets) is already described as a deviation due to a freshly cut surface. Further on, deviation mostly derives from heterogeneity of limestone tablets and can amount on average to ±0.5 μm/15 days. The maximum observed deviation amounts to -1.6 and 0.7 μm/15 days. Nonetheless, two pairs of limestone tablets indicate over 399 days of measurement similar average dissolution rates (the difference is only -0.1 μm/15 days; Fig. 2.6). Deviation due to heterogeneous surfaces of limestone tablets where sinter deposition prevails are even lower (Fig. 2.7).

Deviation due to different lithology

Use of standard limestone tablets in different caves provides comparable measurements of water aggressiveness and not necessary dissolution rates in that cave. If we apply measured dissolution rates to a cave where measurements took place, we have to take into consideration different lithological characteristics that influence dissolution rates. Therefore, measurements of dissolution rates on different lithology have to be made to apply measurements with tablets made of Lipica limestone to the present-day speleogenesis of that particular cave.

Gams (1966b, 1980) states that the hardness of waters from dolomite does not differ much from that which flows through limestone. This would suggest similar dissolution between dolomite and limestone, as was recognized also by Sweeting (1972; 29), who interpreted similarities with sufficient residence time of water to reach equilibrium (Sweeting 1972; 29) and a higher degree of fracturization in dolomite, which enhances dissolution with greater reaction surface. The amount of dissolved carbonates also reflects the residence time of waters and this significantly increases the difference between the amount of dissolution and dissolution rates. The major role in dissolution rates is played by the kinetics of dissolution, which is without doubt slower in dolomite (Gerstenhauer & Pfeiffer 1966 after Sweeting 1972; 28-29, Chou et al. 1989 after Dreybrodt 2004; 297-298, Dreybrodt 1988; 179) due to bigger crystals and stronger bonds between $MgCO_3$ molecules (Ford & Williams 2007; 71). Differences are evident especially at low saturation (up to 50-60 %), while at higher degrees of saturation differences seem to decrease (Dreybrodt 1988; 179, Dreybrodt & Eisenlohr 2000; 145). Differences in dissolution rates appear also within different types of

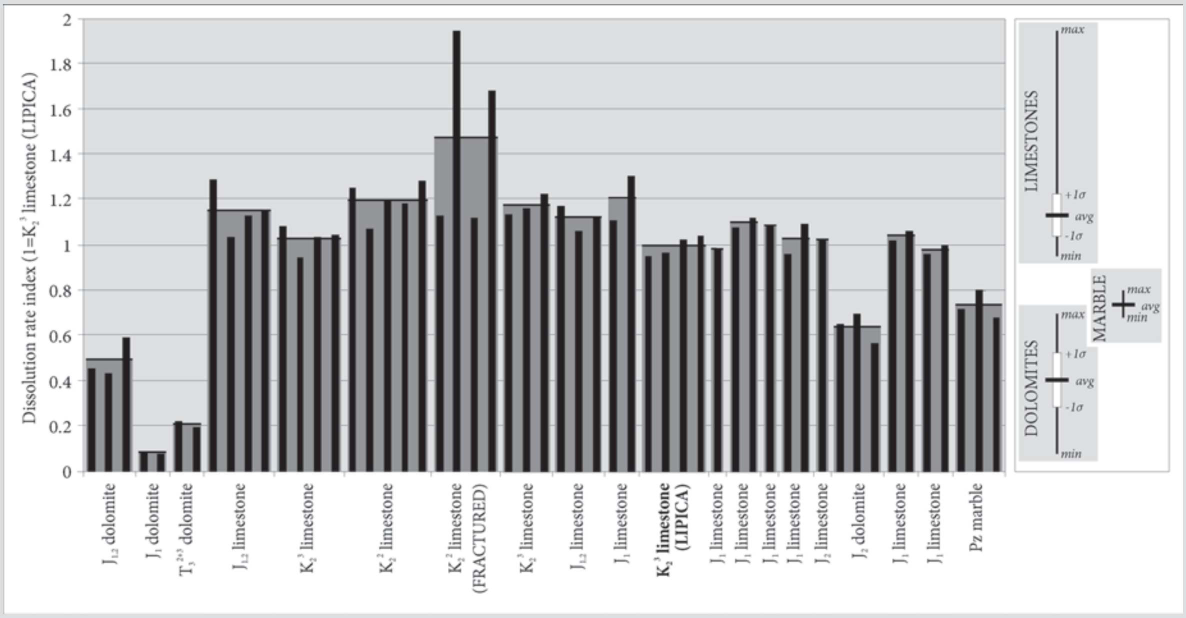


Figure 2.8. *Dissolution rates according to different lithology of tablets.*

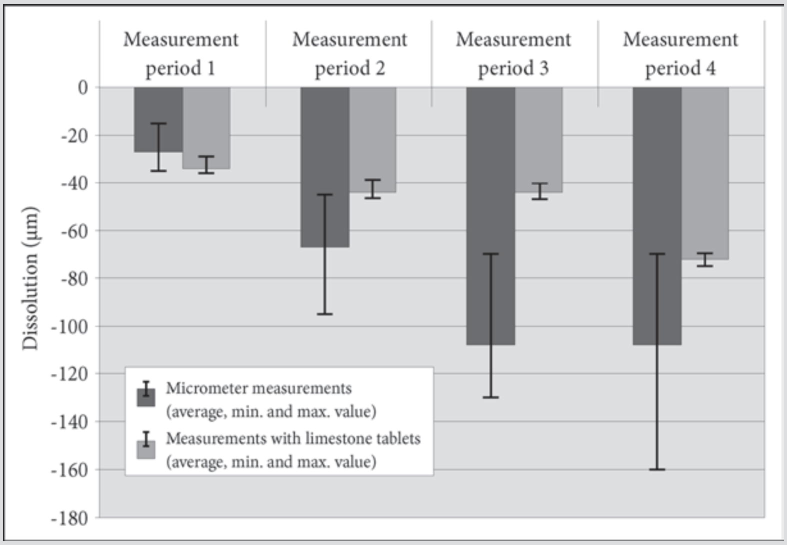
limestone, since they contain different amounts of "impurities", different types and amounts of allochemical grains, different cements (micrite/sparite) and different primary porosity. Regarding some examinations, Sweeting (1968; 229) states that limestone which has a percentage of sparry calcite, may be less soluble than micrites, most probably because of their larger crystals.

To compare dissolution rates of different rocks, observation of dissolution rates between several carbonate rocks was done in Lekinka where saturation of water ranges from low to high. Some carbonates were taken from caves that were chosen as case studies (Chapter 3; Križna Jama, Lekinka cave, Postojna cave system), while some others were taken randomly, usually from Slovenian karst. Results represented in Fig. 2.8 show that all limestone demonstrates similar dissolution rates. Deviation from Lipica limestone (K_2^3) is rather small and amounts to up to 20 %. Lower dissolution rates were observed with marble from Pohorje mountain (P_Z marble), with dolomite from the Dolenjska region (J_2 dolomite) and especially with Middle-Lower Jurassic, Lower Jurasic and Upper Triassic dolomites sampled in or near Križna Jama ($J_{1,2}$, J_1 and T_3^{2+3} dolomite). The latter dissolves up to 90 % slower than Lipica limestone. Higher dissolution rates were observed with fractured limestone (K_2^2 limestone) due to a greater reaction surface. Deviation within each rock sample is relatively small – on average it amounts to 7.7 %.

2.2.4 Absolute precision of measurements with limestone tablets – comparison with MEM measurements

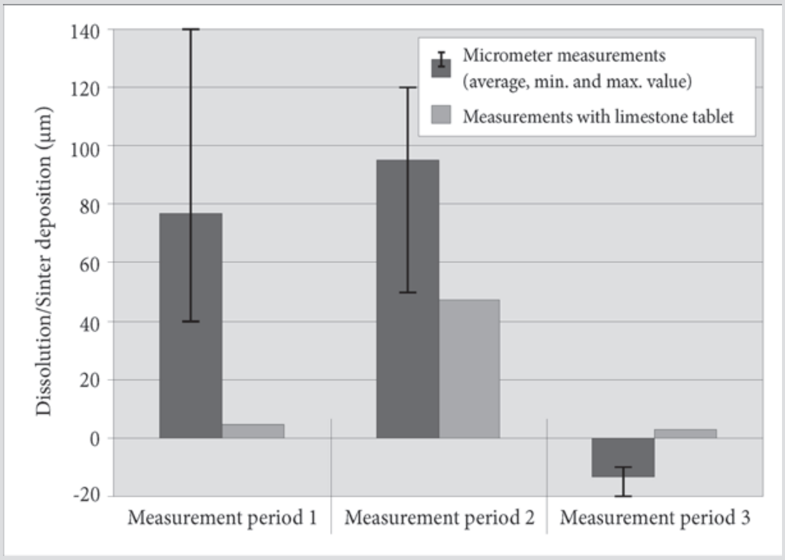
According to Jennings (1981 after Spate et al. 1985), good agreement between limestone tablet experiments (-17 μm/a) and micrometer measurements (-21 μm/a) in absolute terms was achieved. Our comparison of MEM measurements and measurements with limestone tablets took place in Lekinka cave for dissolution rates and in Križna Jama for sinter deposition rates.

Figure 2.9. *Differences in dissolution between MEM measurements and limestone tablets recorded in Lekinka.*



In Lekinka cave, differences of dissolution rates were measured at the same place on the same type of a rock. In each of 4 measurement periods, 9 values per measurement period were defined by MEM and 3 values for limestone tablets (Fig. 2.9). All deviations described and calculated in the previous chapter were taken into account and for that reason avoided to improve the precision of measurements and comparisons. Only during the first measurement period was the dissolution rate stronger with limestone tablets. Later, during all measurement periods stronger dissolution rates were found using MEM. It is important that some minimal values measured with MEM can be equal to average values measured with limestone tablets. The highest discrepancy (1:0.41) was observed during the third measurement period, in which limestone tablets were partly buried under the bed load material. This partly prevented them from dissolution. Nevertheless, the second and the fourth measurement periods indicate that, even when the conditions are equal, the average dissolution rate measured with limestone tablets

Figure 2.10. *Comparison of dissolution/sinter deposition rates between MEM measurements and measurements with limestone tablets recorded at Brzice (Križna jama).*



is by about 33 % lower in comparison with the average dissolution rate measured by MEM. A similar deviation in the same direction was found by Jennings (19 %; 1981 after Spate et al. 1985). On the basis of these results it is very likely that higher values defined by MEM are overestimated and a result of probe erosion, which can result in more than 20 μm higher "dissolution" per reading even on hard limestone (Spate et al. 1985; 431). Since we were measuring on wet surfaces that are relatively softer in comparison with dry ones, higher probe erosion is to be expected.

Fig. 2.9 also provides us good insight into the maximum span of measurements using MEM and limestone tablets. The average standard deviation and maximum span using limestone tablets is at least 5-times smaller in comparison with MEM measurements. This difference arises from microlocal differences in dissolution, which are averaged using limestone tablets, since the dissolution rates are calculated from weight loss and reaction surface. When using MEM, differences reflect real differences in dissolution between several measurement points at the rock surface due to microscopic heterogeneity of the rock.

Differences of sinter deposition rates were measured in Križna Jama. In each of 3 measurement periods, three values per measurement period were defined by MEM and one value for limestone tablets. MEM measurements were done on natural sintered channel bottoms while measurements with limestone tablets were done with limestone tablets already exposed to saturated waters in Križna Jama for 247 days. Fig. 2.10 shows that methodological discrepancies in the case of sinter deposition are much higher than those in regard to dissolution. The highest difference was observed during the first measurement period (using limestone tablets we detected only 8 % of flowstone deposition measured with MEM). Later, differences are lesser (during the second measurement period, using limestone tablets we detected 50 % of flowstone deposition measured with MEM). Differences can arise from already established calcite crystal lattice on natural sintered channels and from roughness of the rock surface, which influences the thickness of the diffusion boundary layer. The latter is thinner on rough natural surfaces and deposition rates are therefore higher.

2.3 HYDROCHEMICAL METHOD

The hydrochemical method was often used to observe chemical denudation rates. The method is based on differences of solute load between input (surface) and output (resurgence) and observation of discharge (White 2000; 151). If an aquifer is recharged by primary infiltration, input solute load is usually neglected and only discharge and solute concentrations are measured at the spring. If we are dealing with at least a portion of allogenic input, consideration of the latter is of crucial importance.

Since measurements of specific electrical conductivity (SEC) are more easily obtained than chemical analysis of water samples and SEC is a relatively good approximation for total hardness (in carbonate waters generally $CaCO_3$ and $CaMg(CO_3)_2$), continuous measurements of discharge and SEC are valuable for chemical denudation rates where SEC<600 μS/cm and where pollution is not problematic (Ford & Williams 2007; 83 & 63, Toran et al. 2006). Nonetheless, to check the reliance of data (especially solute concentration), some laboratory analyses and discharge verifications are essential.

If observations are done at the resurgences, denudation rates are related to the whole catchment area, but such measurements do not provide any information on spatial variability, which can be considerable within the aquifer. In our case studies (Chapter 3), the dissolution rate was calculated using changes of SEC (~change in solute load) between two measurement points, where confluences (and diffluences) are absent. Downstream increase of SEC can be interpreted as dissolution and decrease of SEC as sinter deposition. To define dissolution or sinter deposition rates, reaction surface and transit time are crucial to convert downstream change of SEC into metric rates. Since such measurements were done only occasionally they show momentary rates of processes and not cumulative ones as do limestone tablets or MEM measurements.

2.4 OTHER COMPLEMENTARY METHODS

Concentration of Ca^{2+} and Mg^{2+} in water samples were determined by complexometric titration with 0.01 M EDTA in the chemical analytical laboratory at the Karst Research Institute ZRC SAZU, Postojna. Due to relatively pure Ca-Mg-CO_3 waters, Mg^{2+} concentration was defined as the difference between total hardness (Ca^{2+} and Mg_{2+}) and calcium hardness. Carbonate alkalinity (usually HCO_3^- in our cases) was determined at the same location by potentiometric titration with 0.02 N HCl with an end-point at pH = 4.5. Often, Ca/Mg ratio was determined using Ca^{2+} and Mg^{2+} concentrations.

Specific electrical conductivity (SEC) can provide, in relatively pure carbonate water solutions, a good approximation of dissolved load (Ca^{2+} and Mg^{2+} concentrations; White 2000; 145). Consequently, its change during water course reflects the degree of interaction with soluble rock or the degree of flowstone deposition. For defining spatial and temporal changes of dissolved load we used a WTW Multiline P4 and SEC probe. Resolution was 1 μS/cm, accuracy estimated to be ±2 μS/cm. SEC was always measured in situ.

pH measurements show a concentration of H^+ (or H_3O^+) ions in water. Since the H^+ ions act aggressively to solid $CaCO_3$, pH is one of the most important parameters of water in karst terrains (Roques 1969; 144). Concentration of H^+ ions depends on reaction with rock and air and on reactions within solutions. Since the influence of H^+ concentration to saturation index, which was calculated also using pH value, is high, its accurate measurements are crucial for a proper determination of carbonate balance. If we mistake the correct pH value for 0.1, the saturation index with respect to calcite will be wrong by nearly the same value (Sasowsky & Dalton 2005; 127). pH measurements were done using a WTW Multiline P4 and a plastic body pH probe. In situ measurements were taken in calm or slowly flowing water. Calibration of the pH meter was done in the chemical laboratory with pH = 7 and pH = 10 buffer solutions. Due to the high number of measurements and complicated nature of calibrating in caves we practiced calibration in the laboratory instead of the proposed calibration at each measurement place. The resolution was 0.01 of pH value. Accuracy was estimated to be ±0.05.

Water temperature was determined with a WTW Multiline P4 and an SEC probe, which also supports temperature measurements. Resolution and precision was 0.1 °C, while accuracy is supposed to be ±0.2 °C.

Saturation index with respect to calcite (SI_C) and dolomite (SI_D) indicates aggressiveness of water with respect to calcite or/and dolomite. In the case of SI_C, the saturation index depends on activity concentrations of Ca^{2+} and HCO_3^-, K_2 (which is a constant for decay of HCO_3^- into H^+ and CO_3^{2-}), K_C (which is a constant for decay of $CaCO_3$ into Ca^{2+}), activity of CO_3^{2-}, pH value, temperature and some other ions in the solution (Ford & Williams 2007; 48-49, Meadows 2000; 68). If it is lower than -0.1, water will dissolve calcite but if it is higher than 0.1 water tends to deposit $CaCO_3$. Between -0.1 and 0.1, water is more or less inactive. SI_C and SI_D were calculated using the computer program WATEQ4F (Ball & Nordstrom 1991). Input parameters were SEC, T, pH (determined in situ), concentration of Ca^{2+}, concentration of Mg^{2+} and carbonate alkalinity (defined in the chemical laboratory).

To define the stage-discharge curve, **discharge** was measured at different water levels using the salt-dilution method (Käss 1998). This involves the preparation of solute (usually sodium chloride-NaCl), injecting the solute into the stream and determining its dilution at a downstream measuring point. A time dependant NaCl concentration curve defined with an SEC meter (WTW Multiline P4) and mass of salt at the downstream point, where the solute becomes uniformly mixed with stream water, provides us enough information about discharge. For a given volume or rate of injection, greater stream discharges will result in greater salt dilution and lower concentrations measured at the downstream site and vice versa.

Height of water level was obtained either with periodical visual observations of water gauges (Križna Jama, Lekinka cave), from the Slovene Environmental Agency where data were available (Škocjanske Jame, Postojna cave system) or with digital level loggers where other hydrogeological research was done at the same time (Postojna cave system, Škocjanske Jame).

Between 21 March 2007 and 17 October 2007 Gealog S was used in Križna Jama for determining water level, water temperature and SEC. Resolution for SEC and T was the same as resulted from measurements done by the WTW Multiline P4. Because of questionable long-term stability, estimated accuracy was slightly lower (for SEC ±5 μS/cm and for T ±0.2 °C). Discharges were calculated using continuous water level data and a stage-discharge curve determined using the salt-dilution method.

Air CO_2 concentration was determined using Vaisala's hand-held carbon dioxide meter GM70, which consists of the indicator and GMP222 CO_2 probe. The latter had a resolution of 20 ppm and accuracy of ±1.5 % of range + ±2 % of reading (Vaisala's Technical data 2007). Since the range of a probe was between 0 and 3,000 ppm, accuracy was always better than 105 ppm. Better results were obtained with longer measurements at individual measurement points and the calculation of an average.

3

CASE STUDIES

Results obtained during the 8-month-long test study (Chapter 2.2.2) showed that additional, more frequent and spatially widespread measurement can be done at several places using the limestone tablets where the dissolution or sinter deposition rates are sufficiently strong. More intensive measurements with shorter measurement periods can indicate seasonal differences in rates of karst processes already proposed by Trudgill (1975 after Gunn 2004; 322). Seasonal or even monthly fluctuation of dissolution or sinter deposition rates at several measurement places can lead toward better understanding of spatial and temporal factors that control the present-day genesis of selected caves. Nevertheless, we also took into

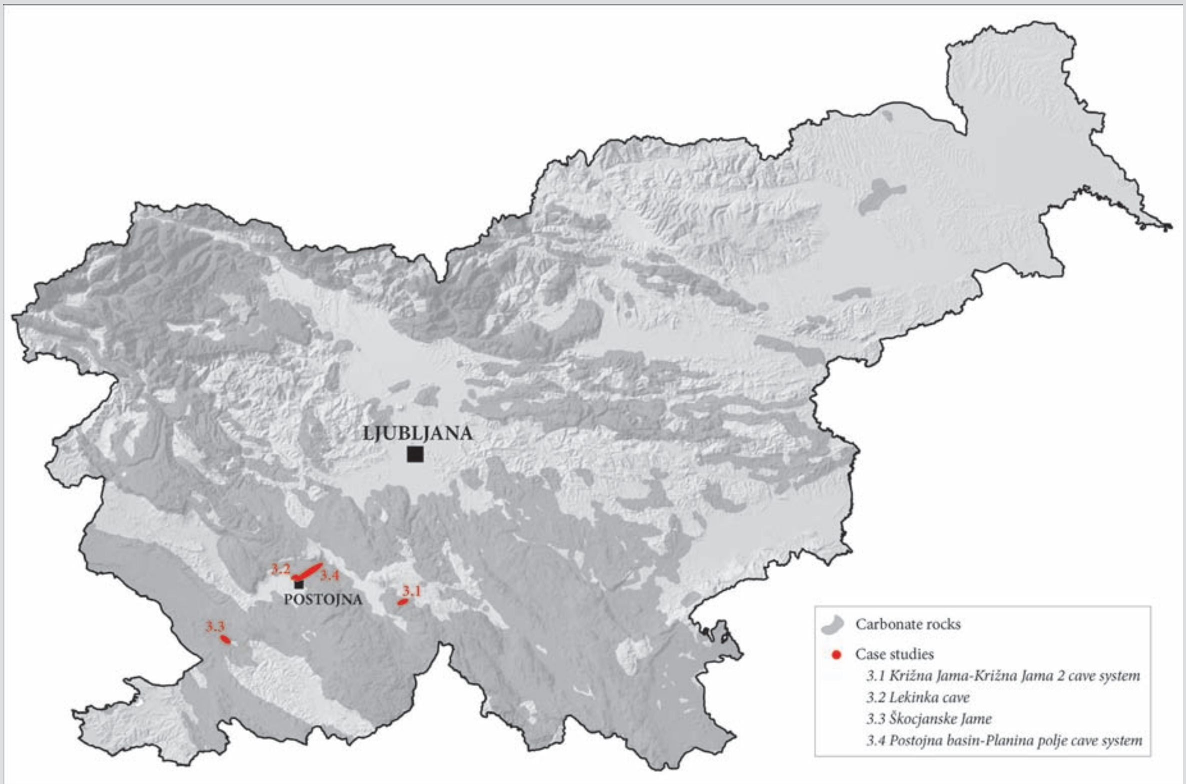


Figure 3.1. *Location of case studies (numbers of sites are equal to chapters).*

consideration some caves which are important due to their (inter)national recognisability or their special geomorphic or hydrologic function. From these points of view the following caves (cave systems) were chosen for more intense research:

3.1 **Križna Jama-Križna Jama 2 cave system** (well ventilated subhorizontal cave system in an epiphreatic zone with high sinter deposition rates; in Križna Jama 2, present-day speleogenetic processes have not yet been studied), pages 33-73;

3.2 **Lekinka cave** (a subhorizontal stream cave with exceptionally strong dissolution rates as a result of allogenic recharge from the Pleistocene accumulation terrace of Nanoščica/Pivka), pages 75-98;

3.3 **Škocjanske Jame** (where there is an excellent example of an underground gorge of the Reka River, which is characterized by extreme power of allogenic recharge at middle-high water levels and extensive flooding at very high water levels), pages 99-112;

3.4 **Postojna basin-Planina polje cave system** (a long and regionally important underground network of dry and hydrologically active subhorizontal passages of Postojna cave system and Planinska Jama), pages 113-126.

3.1 KRIŽNA JAMA-KRIŽNA JAMA 2 CAVE SYSTEM

Križna Jama (cave of the cross; Reg. No. 65) is a cave recognized by its high biodiversity (45 defined troglobionts – 4th place in the world; Culver & Sket 2000) and more than 2,000 excavated *Ursus spelaeus* bones from the end of the 19th century. It is also a recognizable touristic cave due to its several underground lakes along the cave stream. The hydrological continuation of Križna Jama (Križna Jama 2) is, due to fragile rimstone dams, on the list of six highly protected caves in Slovenia and accessible only with special permission from the Ministry of the Environment and Spatial Planning.

Scientific research was first undertaken here by Hochstetter at the end of 1870s. At the same time, the first detailed map of Glavni Rov (main passage) to the first lake was made by the geodesist Szombathy. Hochstetter investigated the cave primarily from the paleontological point of view, but he described the cave in detail and mentioned some geomorphological features: flowstone coating in the water channel near Ponor, the "erosional" cross-section of the same channel, etc. The first to relate the formation of Križna Jama passages to dissolution was F. Kraus (1894). Between the First and Second World Wars, investigations in the cave were primarily dedicated to the exploration and survey of passages upstream from the first lake. Some basic speleogenetic observations were done by cavers of Društvo za raziskovanje jam Ljubljana (Society for Cave Exploration Ljubljana; Planina 1965, Puc 1986). In the 1960s, Novak (1966, 1969, 1990) traced the stream in Križna Jama twice and confirmed its water connection with Šteberščica spring. Later, Gospodarič (1974) was interested in allochthonous sediment in Jezerski Rov (lake passage) and Pisani Rov (variegated passage). In the 1980s, the first dating of *Ursus spelaeus* deposits by U/Th dating was done by Ford and Gospodarič (1989). The last datings of allochthonous sediments in Križna Jama were done by Pohar et al. (14C; 2001) and Zupan Hajna et al. (paleomagnetism; 2008). The morphology of passages was studied scientifically for the first time by Gospodarič (1974) and later by Slabe (1989, 1989, 1992). The first one to measure processes was Mihevc (1997), who measured sinter deposition rates at three places between the first lake and Ponor.

Križna Jama 2 (Reg. No. 6286) has a much shorter history of research since the entrance was dug out successfully only in 1991. Before 1991, the entrance was blocked with boulders at the edge of the collapse doline that separates Križna Jama and Križna Jama 2. The only published work is a brief description provided by Drole (1997), who led the cave survey.

Geological and geomorphological characteristics

Križna Jama and Križna Jama 2 are typical stream caves in an epiphreatic zone. They are located in the centre of a triangle between Bloke plateau (~720 m a.s.l.), Cerknica polje (~550 m a.s.l.) and Lož polje (~570 m a.s.l.). The majority of nearly horizontal water passages are developed between 577 m a.s.l. (the lowest sump in Križna Jama 2) and 630 m a.s.l. (spring under the ending breakdown in the Blata passage in Križna Jama). The main trunk passages (Glavni Rov, Pisani Rov and the Blata passage) are on average 10 m wide and usually more than 5 m high. Where passages cross well fractured rock, several collapse chambers developed (for example Kalvarija (calvary), Križna Gora, Kristalna Gora (chrystal mountain), collapse chambers in the Blata passage, and the Kobe chamber in Križna Jama 2). Where flowing water is absent, the rocky cave floor is covered by allochthonous sediments, breakdown material or speleothems. Water passages are characterized by stagnant water bodies (lakes) and the flowing water between them. Lakes are usually formed behind rimstone dams.

The surface above Križna Jama is highly karstic with (elongated) conical hills and closed depressions without superficial streams. Relative elevation amplitude between hills and depressions can amount to as much as 200 m. The thickness of the vadose zone below the karst surface ranges from 10 to 270 m.

Northeast of this karst surface, is the levelled Bloke plateau. Since the lowest levelled surface of the southern Bloke plateau is occasionally flooded, Bloke plateau can be treated also as a border polje (Gams 2003; 330). It seems that the surface at Bloke plateau was similar to the area above Križna Jama in the past until the area of Bloke plateau reached the piezometric level. At that time, dissolutional lowering stopped at the piezometric level. Due to continued denudation of hills, the area of levelled surface on Bloke plateau progressively expanded. The southern part of Bloke plateau was also influenced by allocththonous material, which was carried from the northern Bloke plateau by Bloščica stream.

West of the Križna Jama-Križna Jama 2 cave system is Cerknica polje. It can be considered a well-developed over flow polje where Bloke plateau and the area nearby Križna Jama-Križna Jama 2 cave system represents its catchment area. The genesis of Cerknica polje is related to the Idrija fault zone, which crosses the polje in a NW-SE direction.

The northern Bloke plateau is made up of Lower, Middle and Upper Triassic rocks. The latter prevail in the southern part of the Bloke plateau. Lower Triassic dolomite is due to thicker layers of impurities usually impermeable for water. The permeability of dolomite rises toward Upper Triassic (Norian and Rhaetian) rocks, but in the latter tectonic deformation plays an important role regarding permeability. If they are strongly tectonized, their permeability is close to Lower Triassic dolomite. Ponors of major superficial streams at Bloke plateau (Bloščica, Farovščica and Studenec pri Ravnah) are in Upper Triassic dolomite (see Fig. 3.1.2). Caves are very rare even in Upper Triassic dolomite, since its low resistance to physical weathering usually produces parallelepipedic gravel (Pleničar 1953) that blocks underground passages especially near the surface. All along superficial streams we can find fluvial deposits.

Lower Jurassic dolomite (and partly limestone) has very similar characteristics to Upper Triassic dolomite. Since they are composed of cemented fine-grained particles, incomplete solution produces fine-grained sand, which is incorporated in the soil matrix. Such residual dolomitic "sand" may inhibit further karstification (Bogli 1980 after Gunn 1986). The upper part of the Blata passage in Križna Jama is already located in Lower Jurassic dolomite.

Lower-Middle Jurassic limestone is the host rock for the majority of Križna Jama's passages (Fig. 3.1.2). According to Folk's classification, this limestone is classified as micrite and oomicrite. Well-developed karstification of this limestone results in a lack of any superficial streams and springs. Due to partial secondary dolomitization, dolomite layers, lenses and nests can be found within Lower-Middle Jurassic limestone. In the Middle Jurassic rocks, dolomite can completely prevail.

The most important tectonic feature in the area of Križna Jama-Križna Jama 2 cave system is the syncline between Bloke plateau and Notranjsko podolje (Notranjska lowland) and the Idrija fault zone (Fig. 3.1.1). The entrance of Križna Jama lies only 1 km NE from the syncline's axis. In the longitudinal section (NW-SE), the syncline begins near Cerknica and continues through Križna Jama toward the syncline between Lož polje and the closed depression of Loški Potok (Gospodarič 1974).

Although Križna Jama and Križna Jama 2 lie several kilometres from the Idrija fault zone, the carbonate massif between Bloke plateau, Cerknica polje and Lož polje did not suffer any important fault deformation. There is some evidence of minor tectonic movement near Križna Jama, for example the fault-junction of Upper Jurassic dolomite which borders Middle Jurassic limestone in the axis of the syncline (Fig. 3.1.1; Gospodarič 1974). Relatively slight tectonic deformations are also observed in Križna Jama.

Hydrological characteristics

From a hydrological point of view, the Križna Jama-Križna Jama 2 cave system lies between three differently elevated and occasionally flooded levelled surfaces (two poljes and a plateau). Between them, the well karstified area spreads without superficial streams of water (Fig. 3.1.2). Therefore the aquifer between the levelled surfaces is fed by allogenic and autogenic recharge.

Because of its high elevation, Bloke plateau was considered by Gams (2003) to be a roof of the Notranjska karst – the water flows to Cerknica polje, Lož polje, Ribnica polje and the Ljubljana marsh. Superficial streams on the Bloke plateau receive water from many small springs. Since water collects in well-fractured dolomite, the average hardness of water is high (13.9 °N) (Gams 1966, 2003; 73). A minor portion of water is derived from surface runoff which is also, due to thin carbonate soils, quite hard. The majority of water is collected in the Bloščica and Farovščica streams. According to Gospodarič & Habič's (1976; 49) measurements, the minimal discharge of Bloščica between 1972 and 1975 amounted to 0.02 m^3/s, the average discharge 0.42 m^3/s and the maximal discharge was 15.9 m^3/s. Due to similar characteristics but a much smaller catchment area, the average discharge of Farovščica should be about 0.09 m^3/s. At low-middle water levels the ponors of Bloščica lie near Velike Bloke. At high water levels Bloščica continues as a superficial stream toward Nova Vas, where it joins Farovščica stream and they sink together near the Fara settlement.

On the basis of past tracer tests (Fig. 3.1.2; Šerko 1946; 126, Novak 1966, 1969, 1990, Kogovšek et al. 2008), it is known that Bloščica and Farovščica appear on the surface again at the eastern edge of Cerknica polje (in Štebrščica and Žerovniščica springs). A minority of water flows toward two springs at Podlož but not toward the spring in Lož at Lož polje (Kogovšek et al. 2008). The mean Štebrščica (1.30 m^3/s) and Žerovniščica discharges (0.21 m^3/s; Gospodarič & Habič 1976; 49) are much higher than those of Bloščica and

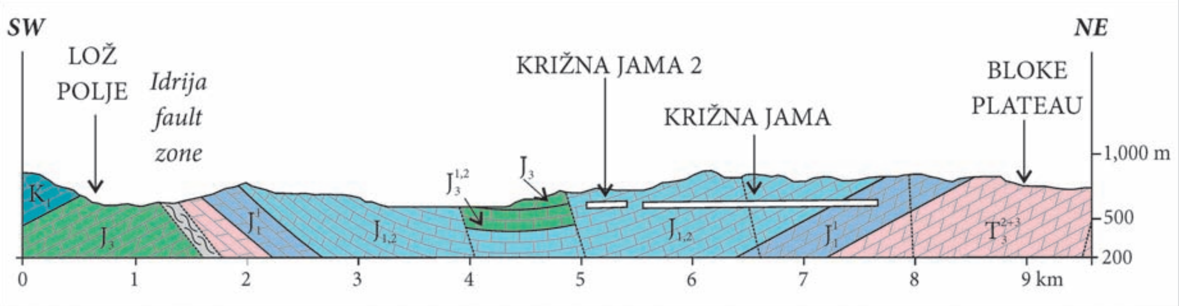


Figure 3.1.1. *Schematic geological cross-section perpendicular to the syncline's axis (modified after Gospodarič 1974).*

Farovščica. The comparison of mean discharges of superficial input to the aquifer between Bloke plateau, Cerknica polje and Lož polje (Bloščica and Farovščica) on one side and outflows from the aquifer (Štebrščica and Žerovniščica) on another side shows that about 66 % of the water derives from autogenic recharge. The contribution of Bloščica and Farovščica to the aquifer was assessed at about 34 %.

Underground water flow downward from Križna Jama was never in question after the tracing test conducted by Novak (1966, 1969) which in Križna Jama confirmed the water connection with Štebrščica spring. Križna Jama 2 seems to be on the way of this water course but since the tracing test was done before the discovery of Križna Jama 2 (1991), the connection between Križna Jama and Križna Jama 2 was never confirmed by a tracing test. Similar physical characteristics of the water, the short distance (242 m), charcoal findings, Ursus spelaeus bones found in Križna Jama 2 and a similar quantity of water suggest the continuation of the water flow from Križna Jama through Križna Jama 2. Since we know that the water temperature in Križna Jama 2 deviates slightly from that in Križna Jama (positively during summer and negatively during winter) there must be a minor tributary between the two caves. This was confirmed through a tracer test in 2007 (Kogovšek et al. 2008).

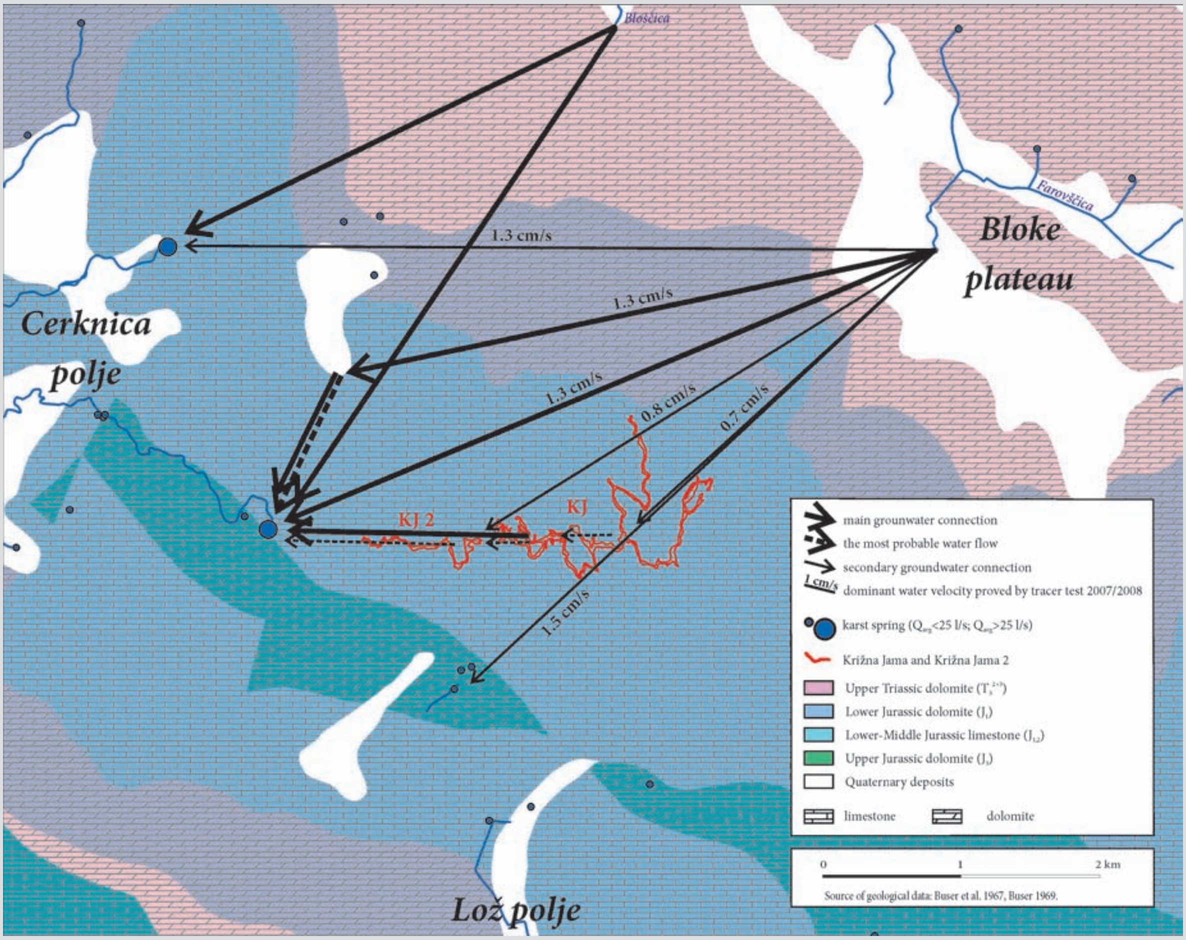


Figure 3.1.2. *Hydrogeological map of the area between Bloke plateau, Cerknica polje and Lož polje with an emphasis on tracing tests (Šerko 1946, Novak 1966, Novak 1969, Novak 1990, Kogovšek et al. 2008).*

Despite several tracing tests in the aquifer, the origin of the water in the Križna Jama – Križna Jama 2 cave system was unclear for a long time due to a lack of sampling in Križna Jama during the only tracing test in the hinterland of the caves before 2007 (Šerko 1949; 128). Springs which feed the main water courses at Bloke plateau have a very low Ca^{2+}/Mg^{2+} ratio, mainly very close to 1 (Kogovšek 1998). Such a low ratio is a result of infiltration entirely through Upper Triassic dolomite, which covers the catchment area of these springs. Water in Križna Jama and Križna Jama 2 have a higher Ca^{2+}/Mg^{2+} ratio (1.59-2.34 at the first lake), which indicates the important portion of inflow through limestone. Such an inflow is possible only through autogenic recharge in the neighbourhood of the cave system. If we also take into account primary infiltration through Lower Jurassic dolomite in the upstream part of the cave system, the portion of allogenic water should be very low in the Križna Jama – Križna Jama 2 cave system. This was confirmed with a tracer test in 2007 at middle water levels from Farovščica ponor – recovery of tracer was very low in Križna Jama (1.3 %, which is 3 g of 226 g injected uranin) and probably slightly higher in Križna Jama 2 (Kogovšek et al. 2008). A very slight annual temperature variation in Križna Jama at the first lake (about 1 °C) and much higher in a nearby cave (Mrzla Jama pri Bločicah; more than 5 °C; for the location of this cave see the broken main groundwater connection between Bloke plateau and Cerknica polje in Fig. 3.1.2) also shows that at least at low-middle water levels allogenic water flows north and not through Križna Jama.

The spine of the hydrological system in Križna Jama – Križna Jama 2 cave system are two streams from Pisani Rov and the Blata passage which join together at Kalvarija and flow together through Jezerski Rov in Križna Jama and most probably all along Križna Jama 2 (Fig. 3.1.3). In Pisani Rov and the Blata passage, water appears under the ending breakdowns. Along the Blata passage, at least six tributaries were detected with SEC, T and pH measurements. They contribute various quantities of water depending on the water levels; for instance the tributary from Tršanov Rov (Tršan's passage) contributes 92 % of all the water in the Blata passage at middle water levels and less than 43 % at low water levels. It is important for water chemistry that nearly all tributaries end as sumps or the water flows from narrow, very poorly ventilated passages.

Streams from Pisani Rov and the Blata passage join at Kalvarija. Regarding the six measurements of SEC and temperatures at different water levels (from $H_{\text{First lake}} = -4$ cm to $H_{\text{First lake}} = 8$ cm), discharge from Pisani Rov and Blata is in the ratio

Figure 3.1.3. *Hydrological network of the cave system Križna Jama – Križna Jama 2 regarding visual observations and SEC, temperature and pH measurements at low and middle water levels.*

from 1:4.3 to 1:0.69. Although we are dealing with relatively small numbers of measurements, a quite high Pearson product moment correlation coefficient (0.68) suggests that with higher water levels contribution from the Blata passage increases.

In Križna Jama, water finally disappears in the 70 m deep sump Kittlova Brezna (Kittl's shafts). This connection was proven by a tracing test (Novak 1966). In Križna Jama 2, water appears after 242 m of underground flow from a more than 124 m deep sump and flows mainly as free surface flow toward the ending sump Sifon Upanja (sump of hope). Along this water course, the stream receives two tributaries, one from Kaplanov Rov (curate's passage) that is according to discharge very weak (at low-middle water levels it contributes about 1 l/s, which is less than 5 %). A few tens of metres upstream from the ending sump, Sifon Upanja, we detected an underwater tributary which slightly changes the physicochemical characteristics of the water. Its contribution is, due to lack of discharge measurements before and after confluence, unknown. The most important tributary lies between Križna Jama and Križna Jama 2. At middle water levels it was recognized as at least part of the underground Farovščica stream (Kogovšek 2007). A portion of this tributary is unknown.

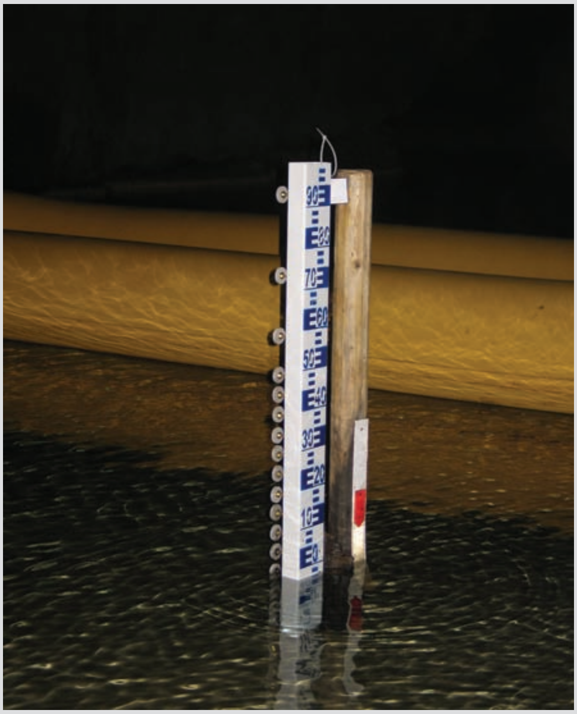


Figure 3.1.4. *Gauging station in the first lake. A gauging station was also used for measurement location KJ-2 where dissolution/sinter deposition was measured with 21 limestone tablets.*

Height of water and discharge was observed in the first lake of Križna Jama (Fig. 3.1.4) at measurement location KJ-2. At medium water levels ($H_{\text{First lake}} \approx 0$ cm) discharge is about 0.1 m^3/s. At $H_{\text{First lake}} = -7$ cm outflow from the first lake ceases. According to extrapolation of the stage-discharge curve, the highest observed discharge between 2004 and 2008 amounted to about 7 m^3/s. Low discharge is characteristic for winter, when we observe retention due to snow, and for summer, when low amounts of precipitation are accompanied by high evapotranspiration. High discharge appear in autumn and spring.

Meteorological characteristics

The meteorological conditions in Križna Jama – Križna Jama 2 cave system are influenced mainly by outside temperatures and number of entrances. Air temperature is quite stable, in some part due to the temperature of water that is generally equilibrated with the temperature of the massif and amounts to 8.5 °C.

Since Križna Jama has at least two openings, air flow occurs as a result of a chimney effect. Intensity and direction of air flow in the cave is based on differences between outside and cave temperatures. Air flow is directed from the main entrance (Fig. 3.1.5) toward the Blata passage and Pisani Rov in winter and the opposite in summer. In winter, the flow of air into the cave significantly reduces temperatures in the entrance part of Križna Jama and cave CO_2 concentration.

The entrance to Križna Jama 2 is much smaller and artificially enlarged to a diameter of about 0.5 m (Fig. 3.1.5). In winter the air flow is directed from the cave and vice versa in summer. If temperature differences are small, direction of air flow alternates in less than one minute. Cross-sections of passages in Križna Jama 2 are bigger than in Križna Jama and this is the reason air flow cannot be observed along the main water passage.

Figure 3.1.5. *Entrance to Križna Jama (left) and Križna Jama 2 (right).*

3.1.1 Measurement location KJ-1 – temporal variability of processes at Brzice

A widely accepted belief in speleology is that the intensity of dissolution strongly corresponds to discharge. During higher discharge the dissolution rates should be greater and at lower discharge less intensive (Palmer 2007). This is related to the kinetics of limestone/dolomite dissolution, which is at the first contact with soluble rock very fast (exhibits high dissolution rates) and later slows down while reaching equilibrium (Dreybrodt 1988, Gabrovšek 2005). Therefore, during high discharge, flow is faster and aggressive water can deeply affect a carbonate massif. Non-linear kinetics of dissolution when the water approaches equilibrium should keep (in theory) the water aggressive all the way from the first contact with carbonate rock to the spring (Palmer 2000; 78). In practice it is not as simple since equilibrium is strongly influenced by CO_2 concentration, which varies in the aquifer and can lead at ventilated places to CO_2 outgassing and consequentially to oversaturation – especially during low discharge. This phenomenon was observed by Palmer (2002, 2007) in McFaill's Cave (New York, USA), where the calcite saturation index (SI_C) falls below 0 at high water levels and rises above 0 at low water levels. At such water levels sinter deposition was observed.

According to general theoretical knowledge, rain-snow flow regime, and sinter deposition rate measurements done by Mihevc (1997), we would expect the highest deposition rates in summer/winter (during the lowest discharge) and the highest dissolution rates in autumn/spring (during the highest discharge).

Temporal variation of chemical processes in the main water stream was observed at measurement location KJ-1 (Fig. 3.1.6) located at Brzice (rapids) 10 m downstream from the first lake. Measurement started on 14 February 2006 and finished on 5 April 2009. Water flow here is considered to be fully developed turbulent flow with mean water velocities of more than 0.5 m/s. Water flow at the measurement location was absent when the water level in the first lake fell below -7 cm (on average several weeks per year). We used two limestone tablets – one was exposed at the measurement location and the second was at the same time dried in the chemical laboratory at the Karst Research Institute ZRC SAZU. Tablets were switched after 15 days of exposure. Limestone tablets were fixed on iron screws with iron nuts and two felted inox washers 2 cm above the channel bed. Although we noticed a little iron oxide on the limestone tablets we estimated its influence as negligible (less than -0.1 μm/15 days).

By far the highest sinter deposition rates occur in winter, when the water level is usually lower (Fig. 3.1.7). But lower water levels occur also in summer, when higher sinter deposition rates are absent. Further, in some summer months weak dissolution was detected. Dissolution rates are extremely weak and are not stronger than -0.3 μm/15 days. Dissolution usually occurs in the late summer or early autumn months and is usually absent in spring months when discharge is also high. Even at exceptionally high water level on 30 May 2006 ($H_{\text{First lake}}$ = 120 cm) the dissolution rate was very weak, at only -0.1 μm/15 days.

Weak correlation between discharge and dissolution or sinter deposition can also be seen in Fig. 3.1.8, where dissolution/sinter deposition rates are plotted together with the height of water and specific electrical conductivity measured at the first lake. If we consider specific electrical conductivity as a rough approximation of dissolved limestone/dolomite, since water is

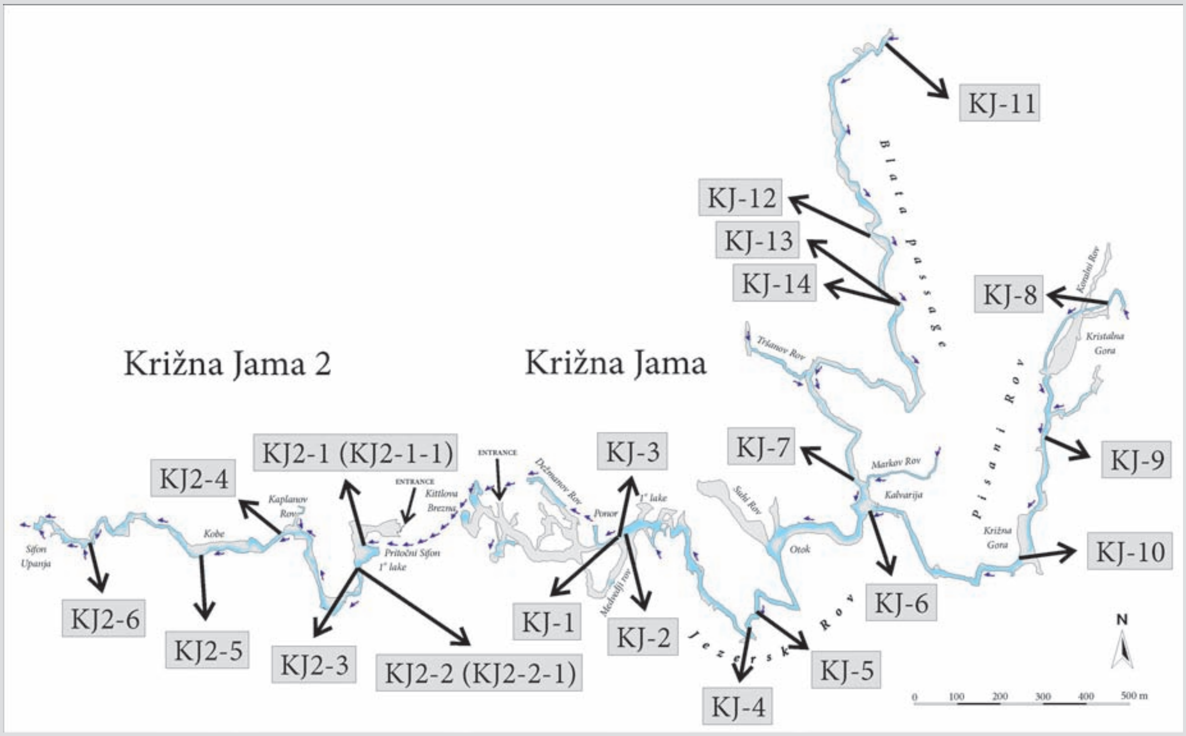


Figure 3.1.6. *Ground plan of the Križna Jama – Križna Jama 2 cave system with measurement locations.*

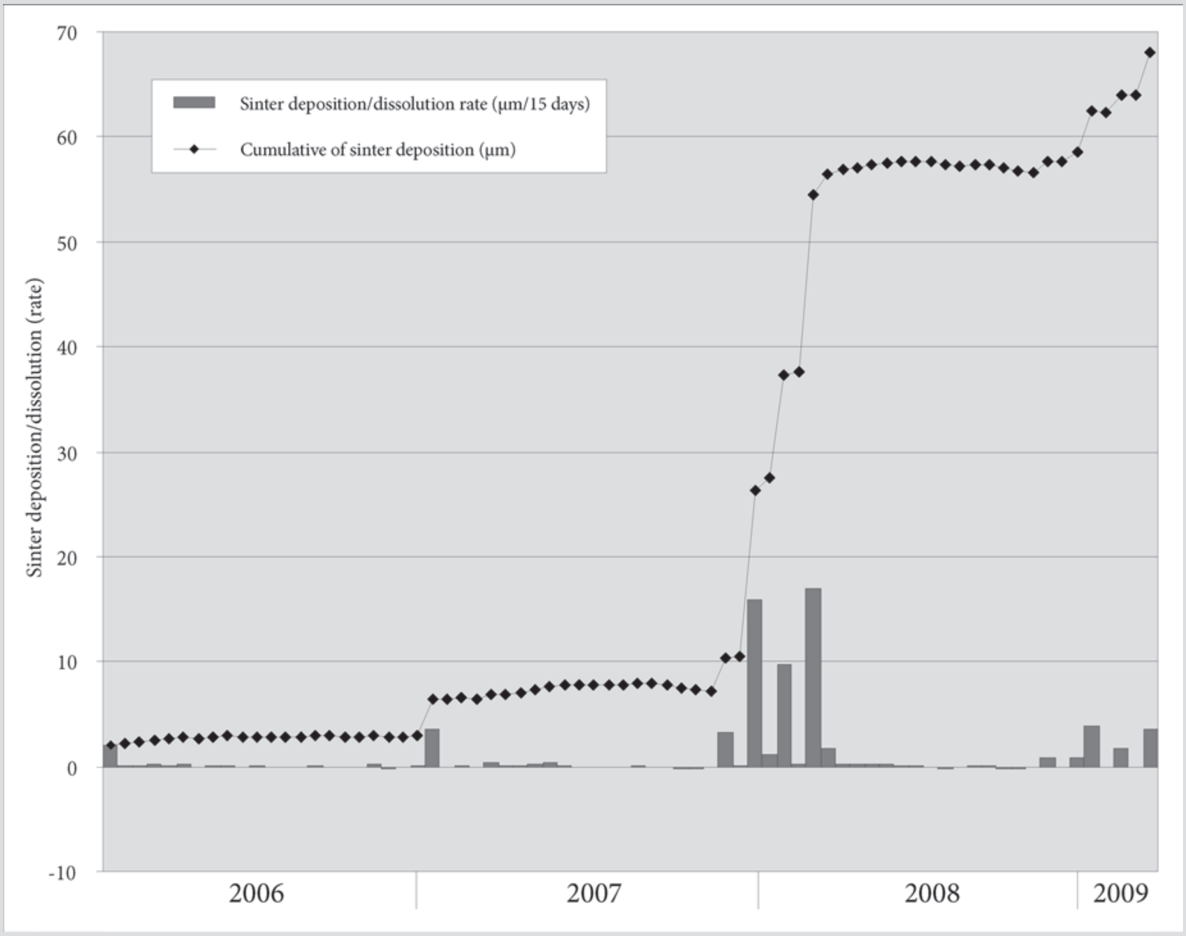


Figure 3.1.7. *Dissolution and sinter deposition rates between 14 February 2006 and 5 April 2009 at measurement location KJ-1 in Križna Jama.*

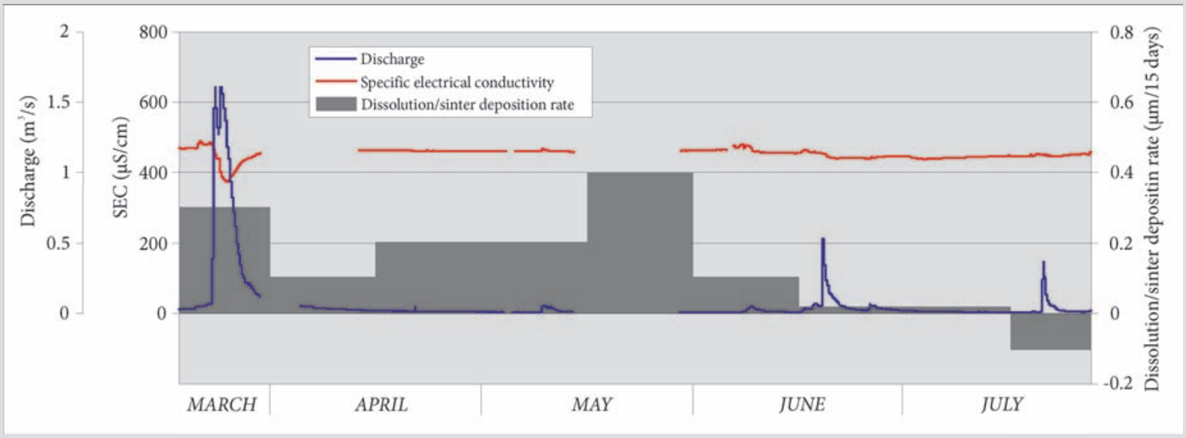


Figure 3.1.8. *Dissolution/sinter deposition rates during spring-summer 2007 at measurement location KJ-1. Discharge and specific electrical conductivity (SEC) were measured at the first lake.*

clean, we see practically no correlation between height of water and dissolution/sinter deposition rates. During high water levels in March 2007 ($H_{\text{First lake}}$ = 52 cm) slight sinter deposition was recorded.

The acquired data are far from what was expected and we can be sure that discharge is not the most important factor that controls the strongest chemical processes. Since the strongest sinter deposition rates seem to correspond to the strong ventilation of Križna Jama in winter months, high sinter deposition rates can be related to outgassing of CO_2 from the water that is stimulated in winter by the inflow of outside air poor in CO_2. The precipitation of calcium from the water solution is a final result of several chemical reactions (Fig. 3.1.9) that are driven by the outgassing of CO_2 from the water and ends with the chemical deposition of $CaCO_3$ (Dreybrodt 1988). The cause for this flux of CO_2 from the water is lower CO_2 concentration in the air. At least four conditions have to be fulfilled for sinter deposition:

I. water has to contain a high amount of dissolved limestone/dolomite and has to be at or close to equilibrium with respect to calcite,
II. concentration of CO_2 in the air has to be sufficiently low to support outgassing of CO_2 from the water,
III. interface between the water body and air has to be high enough for satisfactory flux of CO_2 from the water, and
IV. some nuclei (e.g. calcite crystals) have to be available for deposition, especially at low oversaturation (Roques 1969; 155).

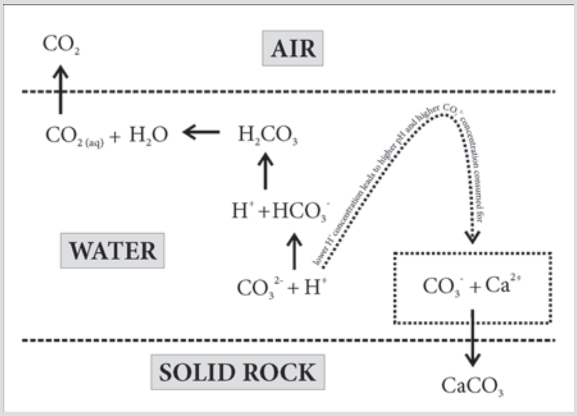


Figure 3.1.9. *Schematic presentation of reaction sequence due to outgassing of CO_2 from the water.*

Periodic measurements of specific electrical conductivity (SEC) and several chemical analyses show relatively high SEC (generally from 445 and 490 µS/cm, on 27 March 2007 366 µS/cm ($H_{\text{First lake}}$ = 52 cm)) and high calcium hardness of water (4.0-4.5 meqv/l). When the water level is very high (for example on 30 May 2006; $H_{\text{First lake}}$ = 120 cm), the concentration of Ca^{2+} falls to 2.85 meqv/l and the water should become slightly aggressive (SI_C = -0.1). Therefore, the first condition is not problematic for sinter deposition at measurement location KJ-1. Only at higher and very high water levels ($H_{\text{First lake}}$ ≈> 10 cm) does the concentration of Ca^{2+} seem to be too low for detectable sinter deposition.

The third condition is not problematic since measurement location KJ-1 is located at rapids. At such places turbulent water flow (very high Reynolds number) is common and the ratio between water volume/interface water-air is the highest. Interface between water body and interface water-air is enlarged also because of air bubbles which pass into the water at steep rapids. The flux of CO_2 from the water is much more reduced at poorly turbulent water flow (medium-high Reynolds number), which appears in lakes upstream from Brzice.

The fourth condition (nucleation) can be a problem in the first lake, where the water flow is deep and wide, but not at Brzice, where the contact with the surface of crystals is sufficient. Therefore, deposition of calcite on already established crystal lattice is not a limiting factor.

According to the highest rates of sinter deposition in winter (Fig. 3.1.7) and occasional measurement of air CO_2 concentration, the strongest control can be cave air CO_2 concentration. At measurement location KJ-1, measurements of CO_2 concentration (Fig. 3.1.10) show that short-term variations of CO_2 concentration are strongly influenced by the direction of air flow in the cave. During winter months, outside air is entering the cave intensively through the main entrance and reduces cave air CO_2 concentration at KJ-1 to about 350 ppm. Usually during summer months, the air flow is the opposite and the cave air CO_2 concentration is much higher (up to 3,880 ppm). Although the latter values can also be appropriate for CO_2 outgassing, the best conditions for outgassing of CO_2 from the water are during winter months.

But in several cases even when the water level and cave air CO_2 are low, high deposition rates are absent (e.g. second part of September and October 2008). In Fig. 3.1.11 we can see that high sinter deposition rates are strongly related to intensive and/or long winter ventilation of the cave and that minor autumn and spring ventilation is not sufficient for high sinter deposition rates (the only exceptions are the last values in 2009). Therefore, substantial sinter deposition rates at KJ-1 can be observed only if ventilation is strong and long enough to ventilate all of Glavni Rov, the big collapse chambers Križna Gora and Kristalna Gora, known and unknown passages behind them and maybe also the poorly ventilated Blata passage. In such meteorological conditions outgassing of CO_2 takes place all along the water course and can reach substantially high SI_C at KJ-1 for high sinter deposition rates. Generally speaking, substantially high sinter deposition rates occur only during the days when the maximum daily temperature remains below -2 °C. From the first condition we know that high sinter deposition rates are also influenced by discharge, which should be lower than 0.2 m^3/s ($H_{First\ lake} \approx 10$ cm). During favourable conditions, SI_C should be higher than 0.7 (at such SI_C sinter deposition rates do not exceed 0.5 μm/15 days), which is in accordance with Usdowski (after Dreybrodt 1988; 269), according to whom SI_C should be higher than +1, but not with Palmer (2007), according to whom SI_C should be higher than +0.2. Some other authors (Jacobson & Udowski 1975 after Dreybrodt 1988; 256) did not recognize calcite precipitation even at $SI_C = +1$, which is probably related to the presence of other ions.

Fig. 3.1.11 also demonstrates how important long-lasting low temperatures are in winter for the total amount of sinter deposited at

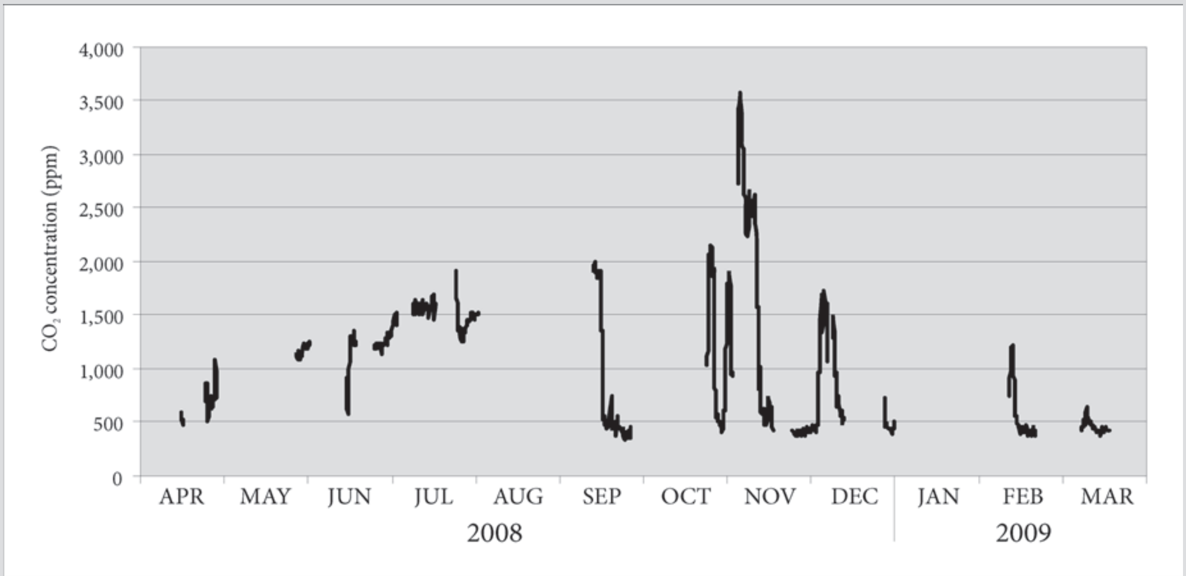


Figure 3.1.10. *Cave air CO_2 concentration at KJ-1 during the year.*

measurement location KJ-1. Although minimal average daily temperatures were similar during the winters of 2006/2007 and 2007/2008, intrusions of atmospheric air into the entrance part of Križna Jama were much longer during the winter 2007/2008. Such long-lasting events highly ventilated passages in Križna Jama and caused much high sinter deposition that winter. During the relatively warm winter of 2006/2007 only 7.3 % of sinter was deposited in comparison with the much colder and longer winter of 2007/2008. Direction, duration and intensity of air flow in winter therefore strongly influences the amount of sinter deposited at KJ-1.

Observations at several springs (Pitty 1968 after White 2006, Shuster & White 1971 after White 2006; 145) showed two types of fluctuations regarding hardness, SI_C and CO_2 concentration in water that can influence dissolution/sinter deposition rates:

- seasonal fluctuation due to CO_2 production in the soil and
- erratic discharge-dependent fluctuation caused by increased discharges.

Erratic and seasonal variations in dissolution/sinter deposition rates can be observed in Križna Jama (Fig. 3.1.7). Erratic rates were already described as a result of intensive winter ventilation. If we exclude such events from analysis (sinter deposition rates higher than 0.5 µm/15 days), a seasonal pattern can be seen clearly in all years. This seasonal pattern can be seen as low sinter deposition rates during winter and spring that turn into weak dissolution rates during summer and autumn. Seasonal fluctuation can be related to seasonal variation of CO_2 in the cave air and in the karst massif (Fig. 3.1.10) or seasonal fluctuation of CO_2 in the soil and consequently in autogenic recharge. To find the proper answer, further study on water chemistry is necessary.

Gospodarič (1974; 332), Gospodarič & Habič (1979; 59) and Slabe (1989; 91, 1992; 217) all state that dissolution takes place in Križna Jama at high water levels, when scallops are formed. At high water levels erosion should also take place (Gospodarič 1974; 332), since some potholes are developed in the present-day water channel. Such statements are based exclusively on the study of the morphology of the water passages of Križna Jama, which should correspond to present-day processes. Contrary to these statements we were not able to observe any important erosional damage at measurement location KJ-1, although the limestone tablet was placed in the middle of the water flow and high water definitely transports particles with diameters of up to 2 mm. Dissolution rates are also surprisingly low. The highest dissolution rate (-0.4 µm/15 days; October 2007 and October-November 2008) was detected out of very high water levels. Even when intensive and long-lasting floods occurred at Bloke plateau (from 2 to 15 April 2008) and water levels in Križna Jama did not fall below $H_{\text{First lake}}$ = 20 cm for 13 days, we detected sinter deposition (0.8 µm/30 days). All these data demonstrate that dissolution rates are extremely low and not related to the high water levels.

Since the dissolution rates are so low in Križna Jama, even the smallest 3 mm deep scallops could hardly have been formed even during the Holocene. Since the scalloped walls of the first lake do not correspond to present-day slow-flowing water (even at high water levels, water flow is too slow for the formation of 3 cm long scallops), such dissolutional features are inherited from the more distant past. Decantation flutings, which can be observed on the wall of the first lake, are nowadays always under the water level and covered with flowstone coating. Location (under the water level) and the flowstone coating are proofs that they are not developing with present-day processes and that they are inherited from the past.

Factors which would cause higher dissolution rates are connected with ventilation (reduced winter ventilation) or hydrology (lower total hardness). Closure or opening of entrances occurs quite often (Brodar 1949, Brodar 1966, Brodar 1970, Spötl et al. 2005; 2467) and would lead

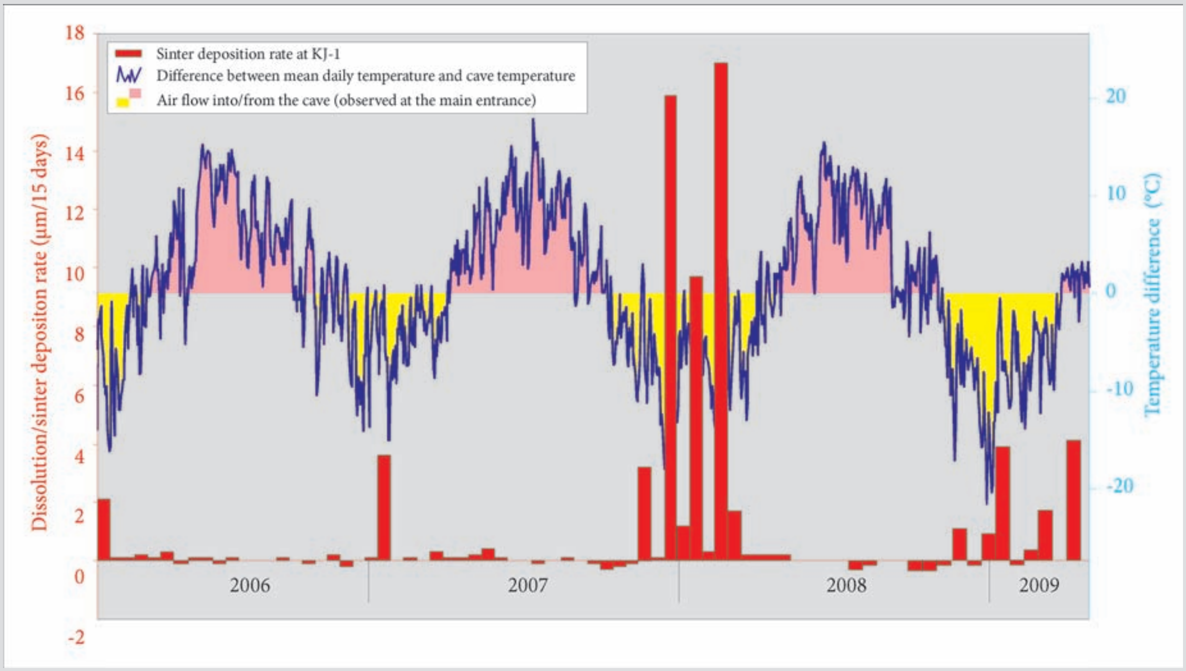


Figure 3.1.11. *Difference between average daily outside temperature and cave temperature (~8 °C), wind direction and dissolution/sinter deposition rates between 14 February 2006 and 5 April 2009.*

to weaker ventilation, higher CO_2 concentration in the massif and probably higher dissolution rates. Lower hardness could be achieved with lower CO_2 concentration in the soil and in the vadose zone. The latter characteristic occurred during Ice Ages since the present-day forest above Križna Jama then consisted of grassland with clumps of trees (Šercelj 1974) due to lower temperatures.

Nowadays the prevailing process at Brzice is sinter deposition; according to Mihevc's MEM measurements (1997), a sinter deposition rate amount of 100 µm/a. Our value is 4.8 times lower (20.7 µm/a), which is a result of the difference between methodologies (Fig. 2.10 in Chapter 2.2) where MEM measurements are more reliable in absolute terms. Over 12,000 years, the sinter deposition rate observed by Mihevc (1997) would result in a 1.2 m high rimstone dam which roughly corresponds to the actual estimated height of the rimstone dam at Brzice downstream from the first lake.

3.1.2 Measurement location KJ-2 – temporal and spatial variability of processes in the first lake

Strictly speaking, it is impossible to delineate dissolution rates from sinter deposition rates at measurement location KJ-1, where the processes overlap at the bed of a channel even within 15 days. Therefore we started to measure in the first lake with a vertical set of limestone tablets. Such type of measurement also provides us variation of dissolution and sinter deposition rates according to depth and makes possible comparison between measurement locations KJ-1 and KJ-2 (Chapter 3.1.3). According to the actual morphology of the passage we should expect net sinter deposition below $H_{\text{First lake}}$ = 0 cm and slight (net) dissolution above this limit. Results represented in Fig. 3.1.12 partly confirm this presumption.

Measurements at KJ-2 (Fig. 3.1.4 and 3.1.6) started on 17 June 2006 and finished on 5 April 2009. A vertical set of 21 limestone tablets was installed on a water gauge. The vertical distance between limestone tablets was usually 5 cm. Water flow was much slower in comparison with KJ-1 because though the discharge is equal the cross-sectional area is much larger. During low and medium discharge water flow can be defined as low turbulent and subcritical. During high discharge water flow was more turbulent but not supercritical. Limestone tablets were replaced in the same way and at the same time as at measurement location KJ-1. They were fixed with brass screws, nuts and washers. We observed no colour or dissolutional changes on limestone tablets under the brass screws and washers.

The results can be summarized in three vertical zones: 1 – zone of gradual lowering of sinter deposition rates downward (below $H_{\text{First lake}}$ = 0 cm), 2 – zone of gradual lowering of sinter deposition rates upward (between $H_{\text{First lake}}$ = 0 cm and $H_{\text{First lake}}$ = 20 cm) and 3 – zone without changes or with slight dissolution (above $H_{\text{First lake}}$ = 20 cm).

Periods of high sinter deposition rates in zone 1 correspond to those at measurement location KJ-1, within a few days in winter when the passage is well ventilated (Fig. 3.1.13). Since the outgassing of CO_2 occurs at the water surface the highest SIC close to the water surface of low-medium water levels is expected. Below low-medium water levels sinter deposition rates are lower. At $H_{\text{First lake}}$ = -37.5 cm the sinter deposition rate drops to only half of the one at $H_{\text{First lake}}$ = -2.5 cm. This zone of sinter deposition can be observed on cave walls as up to 3 cm thick subaqueously deposited flowstone coating.

Sinter deposition was observed also in zone 2 but the rates are much lower in comparison with zone 1 and are not related to periods of very intensive ventilation (Pearson product moment correlation coefficient between sinter deposition at KJ-1 and sinter deposition on limestone tablets at $H_{\text{First lake}}$ = 2.5 cm amounts to 0.19 and decreases with height). In zone 2 sinter deposition takes place exclusively in late autumn, winter and spring (November-April) during periods of medium-high water levels (up to $H_{\text{First lake}}$ = 20 cm). Quite low sinter deposition rates result in a thin layer of flowstone coating, which can be visible on cave walls just in the lowest section. Higher, the coating is too thin to be visible to the naked eye.

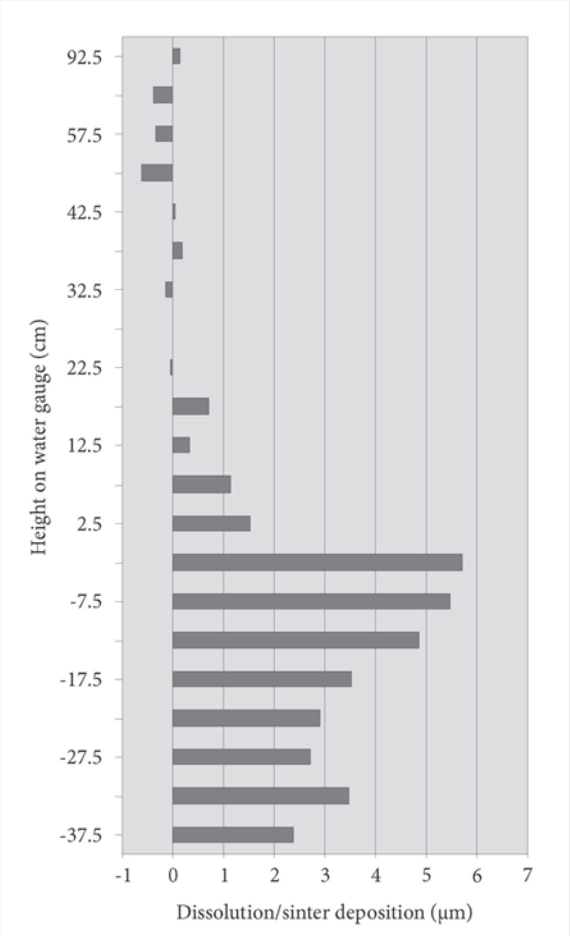


Figure 3.1.12. *Dissolution and sinter deposition at KJ-2 between 17 June 2006 and 5 April 2009. Results represent the sum of 69 usually 15-day measurements.*

Zone 3 indicates almost equal weights of limestone tablets before and after exposure and no gradual transition can be observed. The sum of all results for the whole measurement period in zone 3 is -0.2 µm, which indicates slight dissolution. Extremely weak dissolution rates in zone 3 is beside slow water flow in this area even during high discharge, another proof that the scalloped wall of the first lake, where the length of scallops is unbalanced with present-day hydrodynamic conditions, is inherited from the past when at least the channel was narrower. The latter explanation is possible since we know that Križna Jama was intensively filled with allochthonous material, which was later washed away (Gospodarič 1974).

3.1.3 Comparison of measurement locations KJ-1 and KJ-2 – important differences in sinter deposition rates between rapids and lakes

Comparison between measurement locations KJ-1 and KJ-2 shows some differences in sinter deposition rates which are the result of equal water but different velocity of water flow that influences the diffusion boundary layer (Dreybrodt & Gabrovšek 2009). Such differences in sinter deposition rates produce well-known rimstone dams underground and similar travertine dams in superficial streams. This is also the case in Križna Jama, where more than 40 lakes have been formed beyond rimstone dams. A comparison between rapids (KJ-1) and lake (KJ-2) are represented in Fig. 3.1.13.

If we take into account only very low sinter

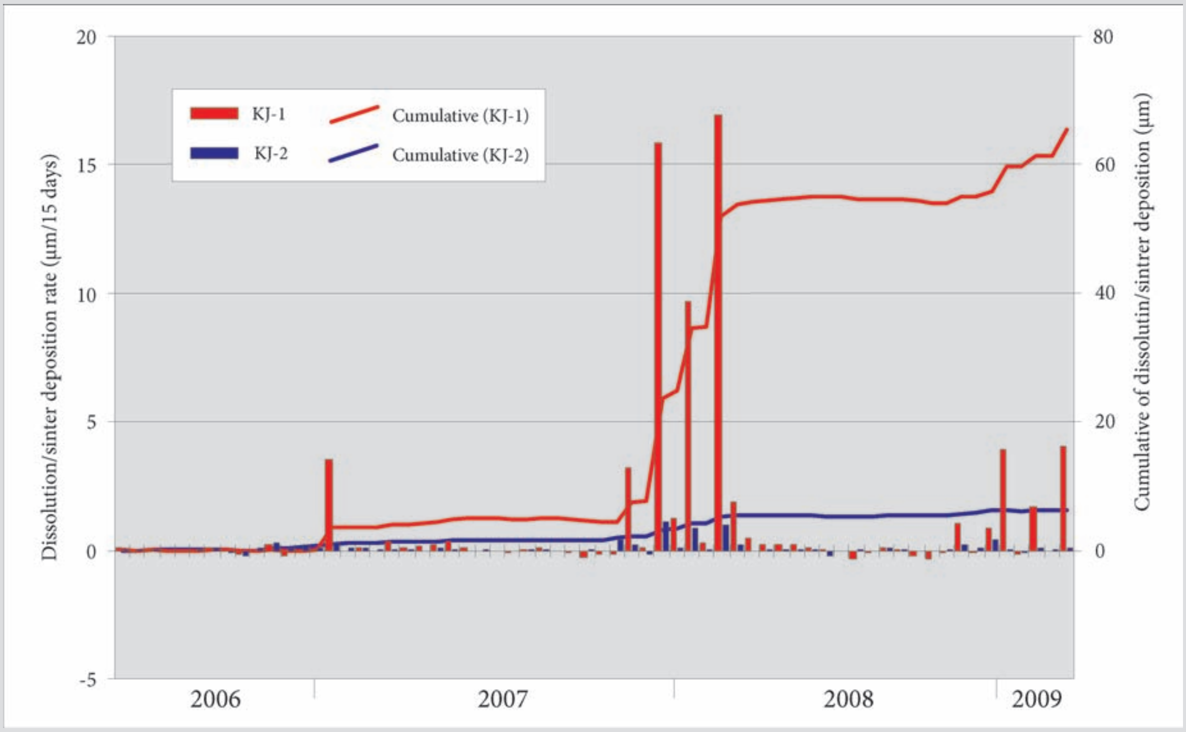


Figure 3.1.13. *Dissolution/sinter deposition rates and their cumulative values at measurement locations KJ-1 (rapids) and KJ-2 (lake) between 17 June 2006 and 5 April 2009.*

deposition rates (below 0.2 μm/15 days) we notice that sinter deposition rates at KJ-1 and KJ-2 are equal or even KJ-2 slightly prevails. Differences appear only at higher sinter deposition rates, when sinter deposition rates at KJ-1 are generally up to 17-times higher in comparison with KJ-2 and as a result rimstone dams and lakes behind them are formed. Without intensive ventilation in winter time differences between KJ-1 and KJ-2 would be negligible and rimstone dams could not be formed. The mechanism for differential rate is still unclear (Hammer et al. 2007; 259) since it can be related to (a) enhanced precipitation under higher flow velocity because of the thinning of a diffusion-limiting boundary layer (Liu 1996, Dreybrodt 2004; 187) or (b) accelerated degassing of CO_2 due to agitation, pressure drop and shallowing.

Tab. 3.1.1 shows portions of sinter deposited at different depths at KJ-2 in comparison with KJ-1. The decrease of sinter deposition rates is evident with depth. For all data a high Pearson product moment correlation coefficient is characteristic but falls with depth. The latter phenomenon is probably a result of higher measurement errors, which increase with lower rates.

Regarding the values presented in Tab. 3.1.1, we can describe decreasing sinter deposition rates with Eq. 3.1.1.

$$\Delta d_{(-37.5--2.5cm)} = \Delta D \times 0.1168 \times e^{0.0283 \times H}$$

(Equation 3.1.1),

where Δd*(-37.5--2.5 cm) is the amount of sinter deposited in depth between* $H_{First\ lake}$ *= -37.5 cm and* $H_{First\ lake}$ *= -2.5 cm at measurement location KJ-2,* ΔD *is the amount of sinter deposited at KJ-1 and H is the depth at measurement location KJ-2.*

Between $H_{First\ lake}$ = -2.5 cm and $H_{First\ lake}$ = 20 cm sinter deposition rates decrease can be described with Eq. 3.1.2.

$$\Delta d_{(-2.5-20cm)} = \Delta D \times (-0.0013 \times H + 0.0277)$$

(Equation 3.1.2),

where Δd*(-2.5—20 cm) is the amount of sinter deposited in depth between* $H_{First\ lake}$ *= -2.5 cm and* $H_{First\ lake}$ *= 20 cm at measurement location KJ-2,* ΔD *is the amount of sinter deposited at KJ-1 and H is depth at measurement location KJ-2.*

Regarding Eq. 3.1.2, Eq. 3.1.2 and the average deposition rate 100 μm/a near KJ-1 (Mihevc 1997), we can model sinter deposition during the Holocene (over the last 12,000 years). If sinter deposition rates were similar in this period to present-day values, rimstone dams would be 120 cm high, the thickest flowstone coating at the wall of the first lake would be about 3.2 cm thick and would decrease under $H_{First\ lake}$ = -77 cm (Fig. 3.1.14). The highest real thickness of flowstone coating (up to 3.5 cm) and decreasing thickness with depth is in agreement with field observations and additional confirmation that rimstone dams and flowstone coating were formed during the Holocene. Nevertheless, the thickness of flowstone coating between $H_{First\ lake}$ = 0 cm and $H_{First\ lake}$ = 25 cm does not correspond to present-day morphology (flowstone coating is up to

Table 3.1.1. *Portion of deposited sinter at different depths at KJ-2 in comparison with KJ-1 based on data obtained between 17 June 2006 and 3 May 2008.*

Depth at KJ-2 (cm)	**-7.5**	**-17.5**	**-27.5**	**-37.5**
Portion of deposited sinter at KJ-2 regarding to KJ-1	10.0 %	6.8 %	5.1 %	4.3 %
Pearson product moment correlation coefficient between rates at KJ-1 and KJ-2	0.88	0.81	0.74	0.72

several millimetres thick and not up to 17.5 mm as modelled), which can be a result of higher present-day sinter deposition rates several cm above $H_{\text{First lake}} = 0$ cm.

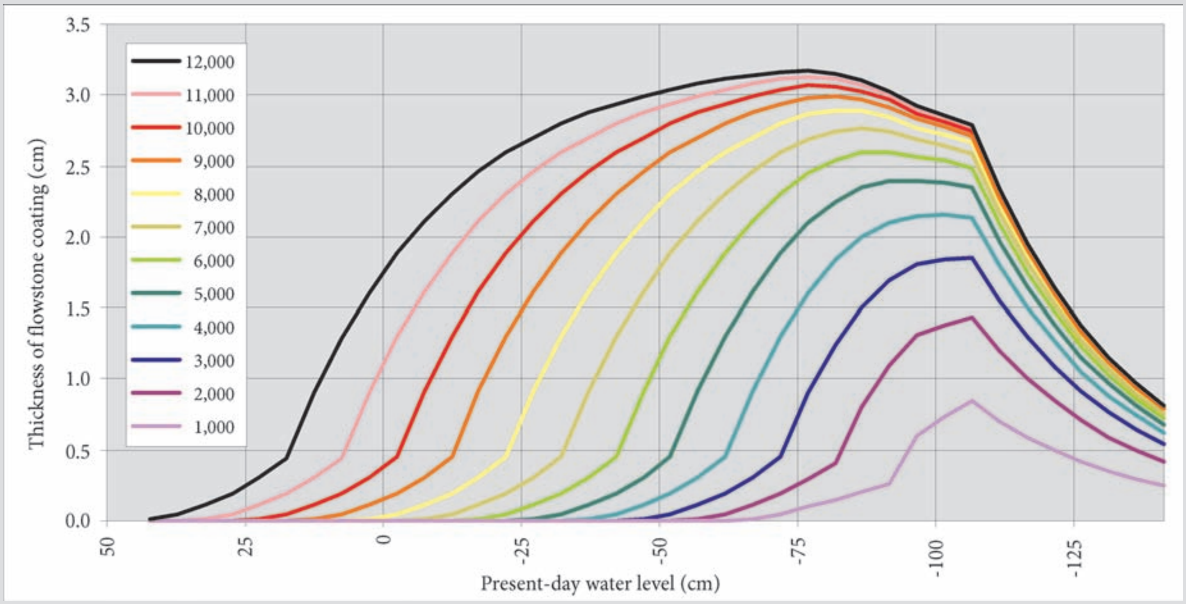


Figure 3.1.14. *Modelled flowstone coating growth regarding Eq. 3.1.1, Eq. 3.1.2 and sinter deposition rate 100 µm/a near measurement location KJ-1 (Mihevc 1997) for the last 12,000 years.*

3.1.4 Measurement locations KJ-3, KJ-4 and KJ-5 – spatial variability of processes in the water course between Kalvarija and Ponor

The water course between Kalvarija and Ponor is characterized by 13 lakes formed behind rimstone dams. The positions of the rimstone dams indicate that they started to grow at places with initially highly turbulent water flow, such as inclined passage floors and breakdowns. At such places higher sinter deposition rates are characteristic in comparison with lakes, as previously described. With measurements at different places between Ponor and Kalvarija we observed spatial dynamics of sinter deposition rates downstream from the confluence at Kalvarija and endeavour to recognize basic factors that influence the variability of rates.

Geomorphic processes between Kalvarija and Ponor were measured with a micrometer (MEM), limestone tablets and measurements of the physicochemical properties of water. MEM measurements were taken at three locations between the first lake and Ponor. Some of them were already set by Mihevc in 1994. At each place we obtained three values. On 20 November 2006 we extended measurements to three upstream locations, where we could get six values per measurement location. All places are laying on rimstone dams in similar water flow conditions, except for the measurement location between the seventh and eighth lakes, where the rimstone dam is partly flooded. Therefore we could expect much lower sinter deposition rates due to slower and less turbulent water flows.

Measurements with limestone tablets began on 16 August 2006 at KJ-4 and KJ-5. Later, on 13 January 2007, they were extended to KJ-3, which lies 4 m upstream from KJ-1 (Fig. 3.1.6). Due to difficulties with fixing the tablets and environmental limitations they were fixed in deeper *water than where the MEM measurements were taken. Due to the development of iron oxide on iron screws at KJ-4 and KJ-5 that caused misleading dissolution (Chapter 2.2), we started with contemporary measurements with limestone tablets fixed on stainless steel parts several centimetres beside the older measurement locations on 18 December 2007. At measurement location KJ-3 we used inox screws, washers and nuts from the beginning of taking measurements. Limestone tablets were usually changed after 30 days of exposure.*

Spatial measurements of physicochemical properties of water (SEC, T and pH) were made with a WTW Multiline P4 at different hydrological and climatic conditions between 15 October 2006 and 8 January 2009.

Rates and spatial variability of dissolution/sinter deposition are best seen in Fig. 3.1.15 and in Fig. 3.1.16, which represent the results of measurements taken with a MEM. It is clear that sinter deposition rates decrease from Ponor toward Kalvarija. Only at the measurement location between the seventh and eighth lake was the sinter deposition rate significantly lower. This decrease in sinter deposition rates is characteristic for the winters 2006/2007 and 2007/2008. The Pearson product moment correlation coefficient between the sinter deposition rate and the distance from the entrance is significantly high even if we take into account the measurement location between the seventh and eighth lake, 0.92. Without the measurement between the seventh and eighth lake, the Pearson product moment correlation coefficient is very close to perfect correlation (-0.96). Between the ninth and tenth lake only 54 % of sinter is deposited in comparison with measurement locations between the first lake and Ponor.

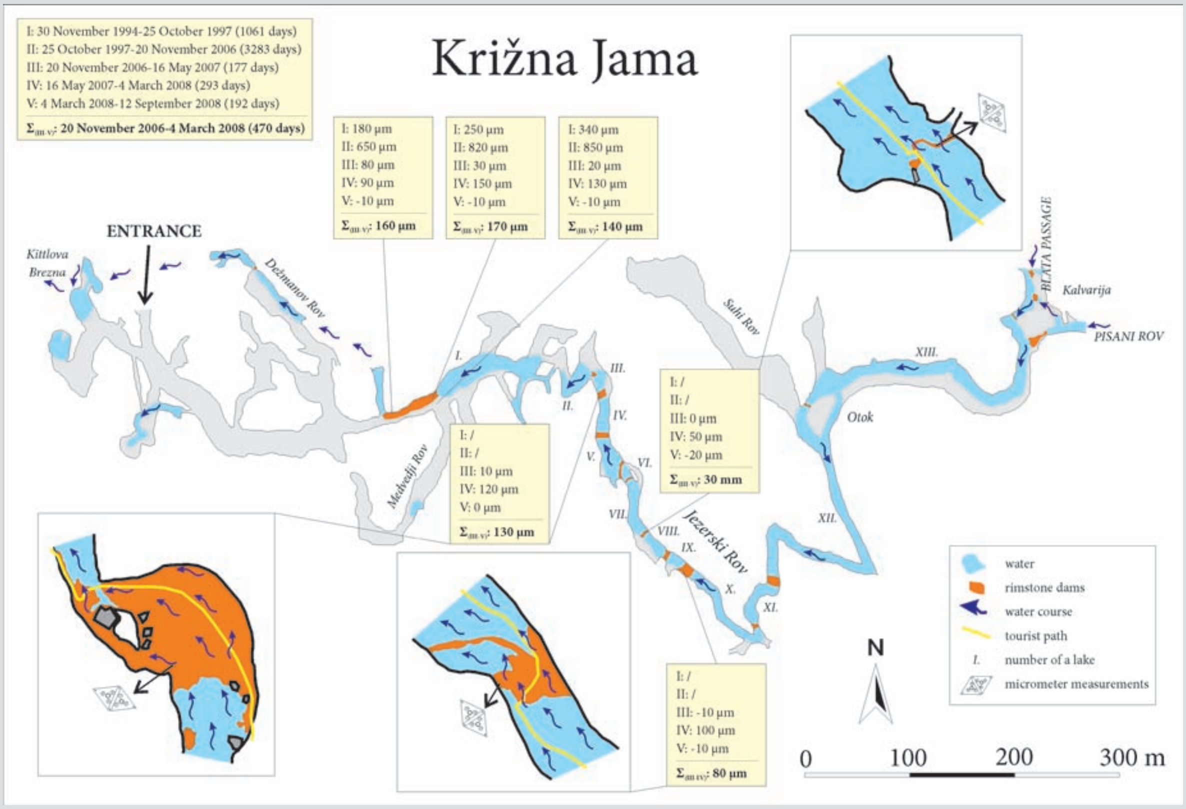


Figure 3.1.15. *Locations and results of MEM measurements between Kalvarija and Ponor from 30 November 1994 to 12 September 2008 (data from 1994-1997 were measured and published by Mihevc 1997).*

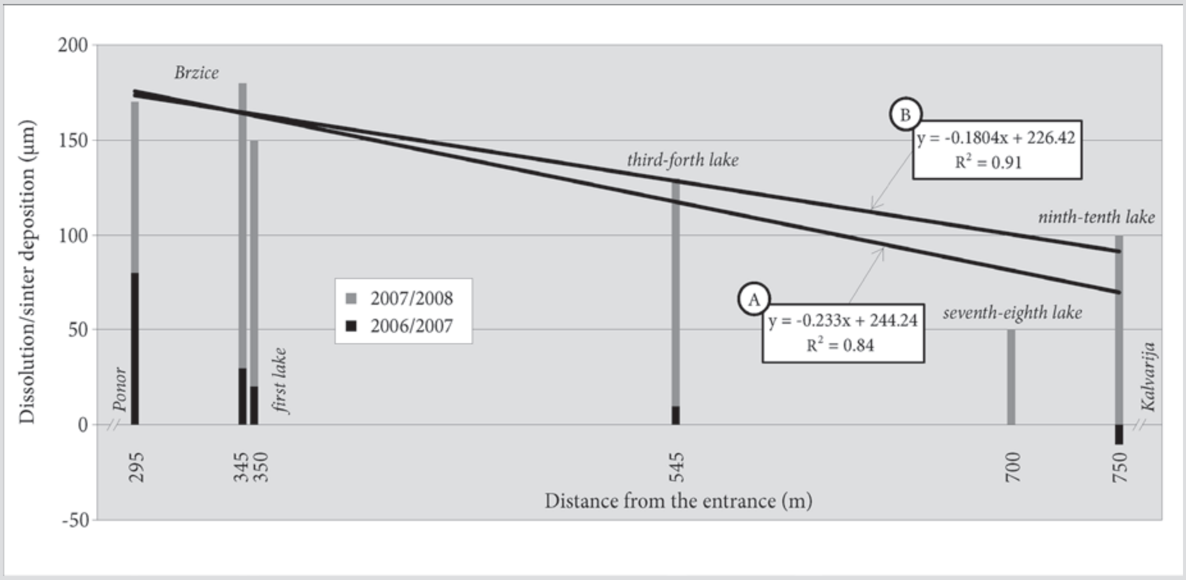


Figure 3.1.16. *Decrease in sinter deposition rates from Ponor toward Kalvarija. In equation A, we take into account the sinter deposition at the rimstone dam between the seventh and eighth lake; in equation B values from this measurement location are excluded.*

Another very obvious phenomenon is the connection between sinter deposition rates and winter ventilation, already known from measurement location KJ-1 at Brzice (Chapter 3.1.1). Since the winter of 2007/2008 was significantly colder than the winter of 2006/2007, a much thicker flowstone coating was deposited in 2007/2008 at the majority of measurement locations. Differences are the largest farther from the entrance. In winter 2006/2007 Križna Jama was so poorly ventilated that sinter deposition between the third and fourth lake was slightly above zero but at the rimstone dam between the ninth and the tenth lake we detected even slight dissolution (-10 µm), caused most probably during the previous summer and early autumn months.

Absolute rates defined through the use of limestone tablets do not reflect absolute rates of sinter deposition on rimstone dams but rather the relative difference between measurement periods and measurement locations due to (a) freshly cut surfaces of limestone tablets (Chapter 2.2), (b) lower rates due to deeper water at KJ-4 and KJ-5 and (c) usage of iron parts for fixation that caused misleading dissolution (at the end of 2007, parallel measurements also started with limestone tablets fixed with inox parts). In spite of these problems, it is clear that at all places sinter deposition rates are influenced by strong ventilation of the cave during winter (Fig. 3.1.17). If we take into account limestone tablets fixed with inox, the Pearson product moment correlation coefficients are higher than 0.96 between KJ-3 and KJ-4 or KJ-3 and KJ-5. The greatest differences occur at high sinter deposition rates, when by far the highest rates are observed at KJ-3. Toward Kalvarija, sinter deposition rate strongly decrease. At KJ-4 it falls to 12.6 % and at KJ-5 it falls to 7.1 % of that recorded at KJ-3. This decrease is much greater than that observed with MEM measurements due to the much faster water flow at KJ-3 in comparison with KJ-4 and KJ-5.

Insight into the speleogenetic processes between Ponor and Kalvarija is also possible through spatial measurements of SEC and pH, but, due to aspects of physical access and a lack of data loggers, only at low and medium water levels. Such measurements are easy to take and

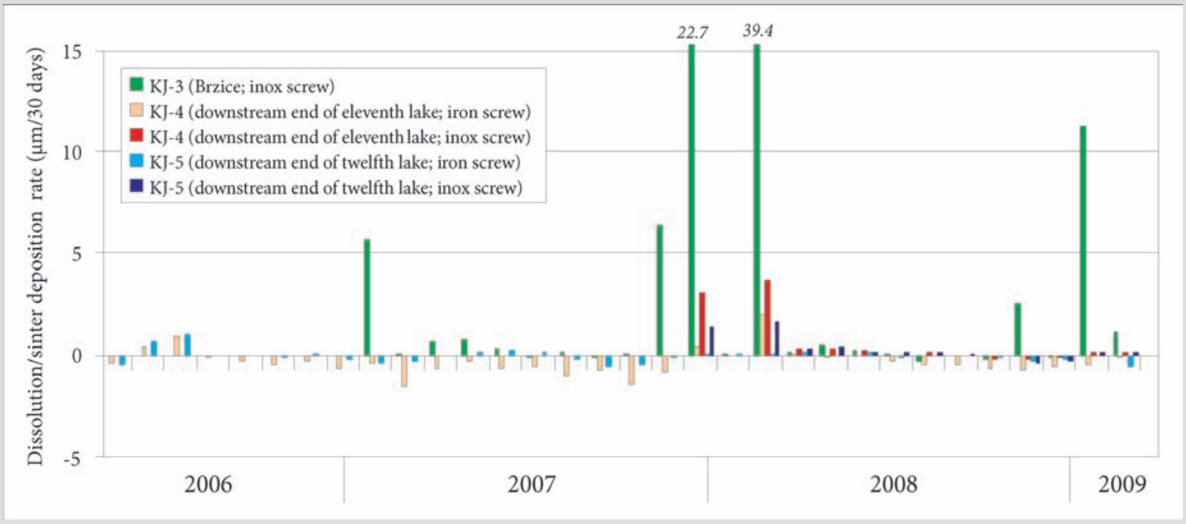


Figure 3.1.17. *Comparison of sinter deposition and dissolution rates between KJ-3, KJ-4 and KJ-5 from 13 January 2007 to 19 March 2009. After 18 December 2007 measurements were also done with limestone tablets fixed with inox.*

reliable especially in this case where we have no tributaries that can change physicochemical properties of the water along the water course (Fig. 3.1.3).

Measurements show that pH is increasing (up to +0.31) and SEC is slightly decreasing (Tab. 3.1.2) from Kalvarija toward Ponor throughout the year at low and medium discharges. The increase in pH indicates a decrease in H^+ concentration and since we observe a downstream decrease of SEC, the downstream increase of pH can only be caused by outgassing of CO_2 from the water and not by dissolution. Outgassing of CO_2 from the water increases SIC and leads to sinter deposition that was recorded with downstream lowering of SEC. Due to continuous outgassing of CO_2 from the water downstream, an increase of SI_C is expected downstream that results also in higher sinter deposition rates.

A downstream decrease of SEC makes possible the calculation of sinter deposition rates along the cave stream. To convert the decrease of SEC to a decrease of the total hardness of water in mg/l, Eq. 3.1.3 obtained by Krawczyk & Ford (2006 after Ford & Williams 2007; 63) that was established from >2300 field analyses was used.

Table 3.1.2. *Amount of deposited calcite (Δm $CaCO_3$), average thickness of deposited flowstone coating (Δd $CaCO_3$) and average weight change of average limestone tablet (Δm) regarding discharge and spatial SEC measurements between Kalvarija and Ponor.*

	Discharge (l/s)	**$SEC_{Kalvarija}$**	**SEC_{Ponor}**	**ΔSEC (μS/cm)**	**Δm $CaCO_3$ (kg)**	**Δd $CaCO_3$ (μm)**	**Δm (mg; 3.000 mm^2)**
12 February 2007	140	456	446	10	1951	0.025	0.20
15 October 2006	9	461	452	9	113	0.001	0.01
11 October 2007	72	476	459	17	1706	0.022	0.18
18 July 2008	4	462	457	5	28	0.000	0.00

$$TH = \frac{SEC - 31.5}{1.86}$$ **(Equation 3.1.3),**

where TH is total hardness in mg/L and SEC is specific electrical conductivity in µS/cm.

Discharge was calculated using a stage-discharge curve for a water gauge in the first lake (Fig. 3.1.4). The surface of the water channel was calculated using estimated width of passage (~7 m), average depth of water measured at 127 locations between the first lake and Otok (Planina 1985) and the length of the passage with Eq. 3.1.4.

$$A = \frac{\pi \times W \times D}{2} \times L$$ **(Equation 3.1.4),**

where A is cross-sectional area of water flow, W is the average width of passage, D the average depth of passage/lake and L length of a passage.

Thickness of the flowstone coating can be calculated using Eq. 3.1.5.

$$\Delta_d = \frac{\left(\frac{SEC_{Kalvarija} - 31.5}{1.86} - \frac{SEC_{Ponor} - 31.5}{1.86}\right) \times 1{,}000 \times Q \times t}{A}$$

(Equation 3.1.5),

where Δd is the average thickness of flowstone coating between Kalvarija and Ponor, Q is discharge in l/s and t time in seconds.

Results represented in Tab. 3.1.2 are calculations for 30 days, the time used for measurements with limestone tablets. Although the quantity of deposited sinter at discharge of 140 l/s amounts to 1,951 kg, the cross-sectional area of water flow is so big (29,080 m^2) that the average thickness of flowstone coating amounts to only 0.025 µm/30 days. This is too thin a layer to be detected with limestone tablets, but if we take into consideration that 17-times higher sinter deposition rates are characteristic for rimstone dams in comparison with lakes (Chapter 3.1.3), the thickness of the flowstone coating up to 0.425 µm/30 days can be detectable at these rimstone dams. Although such values can be reduced during higher water levels during measurement periods, the data (Fig. 3.1.17) at least suggest that rates were very low during measurement periods in Tab. 3.1.2. None of the dates in Tab. 3.1.2 corresponds to the highest sinter deposition rates since the latter are quite unpredictable (they occur only several days per year). During such events, which are also accompanied by the appearance of floating rafts between Kalvarija and Ponor composed mainly of calcite (calcite-96.9 %, dolomite-2.8 %, other-0.4 %), the highest differences in SEC can probably be recorded.

The increase of sinter deposition rates from Kalvarija toward Ponor has clear morphological evidence. Change is best seen in the thickness of flowstone coatings in lakes – it increases from less than 0.1 cm at Kalvarija to about 3.2 cm in the first lake. Similar changes downstream from confluences were also noticed in Pisani Rov and the Blata passage (Chapters 3.1.6 and 3.1.7).

The second consequence is the decreasing length of lakes from Kalvarija toward Ponor due to the downstream increase of growth rate of rimstone dams. The initiation of rimstone dam growth is definitely related to micro-location factors (for example, inclined parts of passages with open surface flows, position of breakdowns that partly block the water passage (Chapter 3.1.3)); but further growth is controlled by distance from Kalvarija. Since the growth of rimstone dams near Ponor is the most favoured, the rise of the water level behind them progressively floods the upper rimstone dams, especially lower ones. At such places the sinter deposition rate progressively turns from the one at the rimstone dam toward the one in the lakes (finally, it can be 17-times lower) and the growth of rimstone dams almost ceases. This phenomenon can be observed at many places above the third lake and

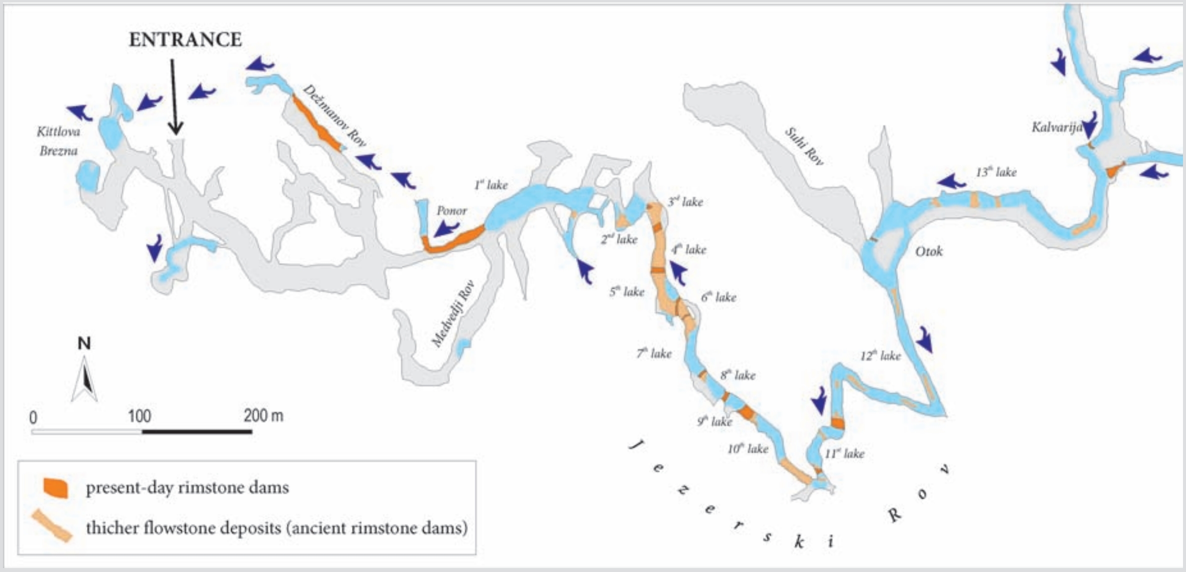


Figure 3.1.18. *Active and ancient rimstone dams between Kalvarija and Ponor.*

was detected with a MEM at the rimstone dam between the seventh and eighth lake. Even more widespread are places with thicker flowstone coating on the floors, which are actually remnants of currently shallowly flooded rimstone dams (Fig. 3.1.18). These indicate that rimstone dams were wider in the past and were later narrowed to strips perpendicular to water channels where sinter deposition rates were the highest. Such flooded sinter-covered floors are now, due to their softness, partly eroded by corrasion. As a consequence, at least 12 rimstone dams and lakes behind them have already disappeared in the past between Kalvarija and Ponor, especially in today's twelfth and thirteenth lake.

The growth of rimstone dams decreases the ventilation in Križna Jama because of the reduction of the cross-sectional profile above the lakes. This phenomenon forms a negative feedback loop. It is especially the case above the second lake, where the roof is only about 1 m above medium water level, and in the downstream part of Pisani Rov, where the roof is less than 0.5 m above medium water level. At both places the sinter growth rate is one of the highest. We can expect that sinter deposition rates will decrease and will be rarer in the future even without climatic changes (i.e. warmer winters). The growth rate of water levels due to the growth of rimstone dams will decrease exponentially. As a result, middle water levels will never reach the cave ceiling, something that can now be observed at Nizka Pasaža (low passage) in the upstream part of the Blata passage.

3.1.5 Measurement locations KJ-5, KJ-6 and KJ-7 – mixing of streams from Pisani Rov and from the Blata passage at Kalvarija

Kalvarija is a place of confluence of two underground streams. One comes from the Blata passage and is characterized by water flow in a muddy channel formed in a horizontal and weakly ventilated passage. The second stream comes from Pisani Rov. This passage is also horizontal but much better ventilated, especially in winter and summer in comparison with the Blata passage.

The discharge ratio between the two streams varies in time and amounts from 1:4.3 to 1:0.69. The portion of discharge from the Blata passage is usually higher at higher water levels. The physicochemical properties of water at Kalvarija differ slightly with respect to measured T, SEC, pH and Ca^{2+}/Mg^{2+} ratio. Temperatures in Pisani Rov are quite stable at 8.4 ± 0.1 °C at low-middle water levels throughout the year. At very high water levels, the overflow of waters from Bloke plateau (combined Bloščica and Farovščica streams) can be identified (in winter with substantially lower temperatures). In the Blata passage, the average water temperature is similar but varies more with respect to season (8.4 ± 0.5 °C). The highest temperatures are recorded in autumn and the lowest at the end of winter.

Specific electrical conductivity (SEC) of water from both passages ranges from 432 to 504 µS/cm at low-middle water levels. Average SEC is nearly the same (461 µS/cm for the Blata passage and 463 µS/cm for Pisani Rov). The correlation between SEC and the water level is weak. Much better correlation was found between SEC and season (Fig. 3.1.19). The highest SEC was found in early summer months and in early winter months. Between these peaks two periods with low values appear. Nearly the same oscillation with almost perfect correlation was also observed in pH, that is, on the other hand, on average 0.27 higher in Pisani Rov constantly through the year. Similar oscillation of physicochemical parameters in the Blata and Pisani Rov indicates similar interaction between rock, water and at least soil atmosphere.

Despite many similarities, higher Ca/Mg ratio (3.52) in the Blata passage indicates a higher portion of limestone aquifer than in Pisani Rov (1.91). In the Blata passage, we should also

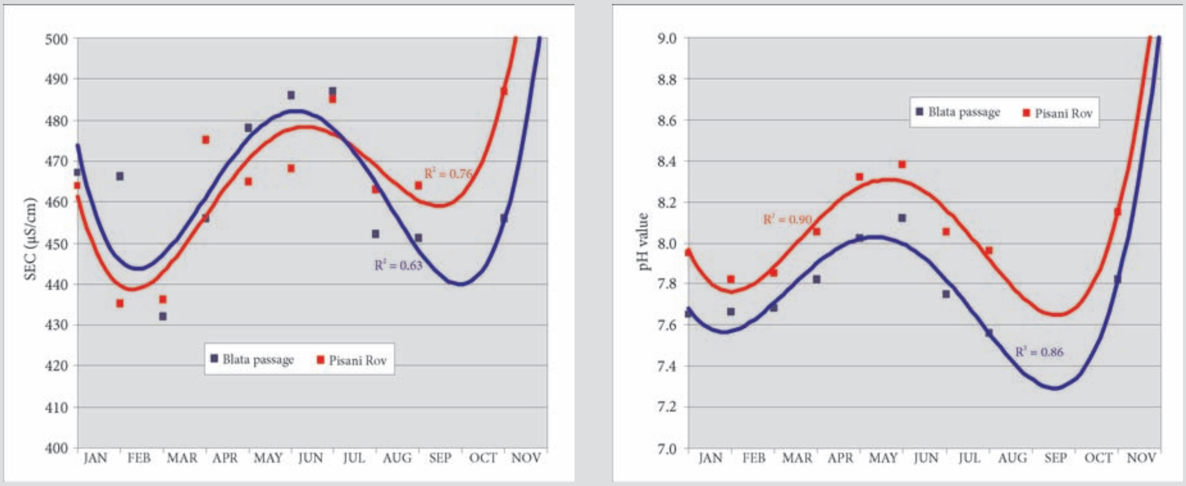


Figure 3.1.19. *Year-round oscillation of SEC and pH in Pisani Rov and in the Blata passage at Kalvarija.*

take into account the minor contribution of the underground Farovščica watercourse, which was proven by a tracing test (Kogovšek et al. 2008). In both cases, occasional measurements at low-middle water levels indicate an always positive SI_C (from +0.29 to +0.76) and therefore slightly oversaturated waters. Nevertheless, SI_C is usually higher in Pisani Rov than in the Blata passage, a result of lower pH in the Blata passage (Fig. 3.1.19).

Measurement locations KJ-5, KJ-6 and KJ-7 were established to observe differences in speleogenetic processes in Pisani Rov and the Blata passage and the influence of the confluence downstream from Kalvarija.

The speleogenetic processes of the stream from Pisani Rov, the stream from the Blata passage and the combined stream (all at Kalvarija) were studied using limestone tablets at measurement locations KJ-5, KJ-6 and KJ-7 (Fig. 3.1.6). Measurements at KJ-5 (combined water flow downstream from Kalvarija) and KJ-6 (Pisani Rov) began on 16 August 2006. Limestone tablets were fixed on iron screws which caused misleading dissolution especially at KJ-5, much less so at KJ-6. On 18 December 2007, iron parts were replaced with stainless steel. Measurements at KJ-7 (Blata passage) began on 15 July 2007. Limestone tablets there were fixed on stainless steel from the beginning of measurements. The measurement interval was usually 30 days.

Fig. 3.1.20 shows that the sinter deposition and dissolution rates at KJ-6 are nearly the same as the sinter deposition rates at KJ-7 in spring, summer and autumn, which is the result of similar origins of water. If we exclude the sinter deposition rates higher than 1 μm/30 days that occur in winter, results from KJ-6 and KJ-7 (and also downstream) show gradual transition from the sinter deposition during winter and spring months to slight dissolution during summer and autumn months. It is interesting how closely KJ-6 fits with KJ-7 between 18 April 2008 and 5 November 2008 – the rates are just 0.1-0.2 μm/30 days higher at KJ-6 (Pisani Rov) in comparison with KJ-7 (Blata passage).

The biggest differences between measurement locations appear during winter months, when the highest sinter deposition rates amount to 0.4 μm/30 days in the Blata passage (KJ-7) while in Pisani Rov the sinter deposition rates amount to over 10 μm/30 days. In Pisani Rov (KJ-6), the response to winter ventilation is similar to KJ-3, although the sinter deposition rates at KJ-3 are more closely related to extreme winter ventilation, while at KJ-6 the rates are more constant. The similar response of KJ-3 and KJ-6 is a result of the intensive winter ventilation of Jezerski Rov (the passage between Ponor and Kalvarija) and Pisani Rov, which strongly decreases cave air CO_2 concentration and enhances the outgassing of CO_2 from the water. The Blata passage is much less ventilated and therefore has higher CO_2 concentration that results in lower sinter deposition rates. Nevertheless, winter differences in CO_2 concentration between the upstream end of the Blata passage and Pisani Rov are too small (~150 ppm) to produce a much different rate of outgassing of CO_2 from the water. The main reason for different sinter deposition rates in winter months has to be in differential ventilation of the whole karst massif upstream from both passages, which are inaccessible for research due to upstream breakdowns. However, ventilation through the breakdowns and high CO_2 concentration of air coming from the breakdowns in summer indicate that the passages continue further into the karst massif. Without the intensive ventilation of Pisani Rov, the sinter deposition rates at KJ-6 would be similar to the sinter deposition rates in the Blata passage or to the sinter deposition rates several hundreds of metres downstream from Kalvarija. Partly different catchment areas of streams from Pisani Rov and the Blata passage that are evident from different variations of the annual temperature of water, pH, Ca/Mg ratio and a tracing test (Kogovšek et al. 2008) are of minor importance.

The sinter deposition rates downstream from the confluence (KJ-5) are under the influence

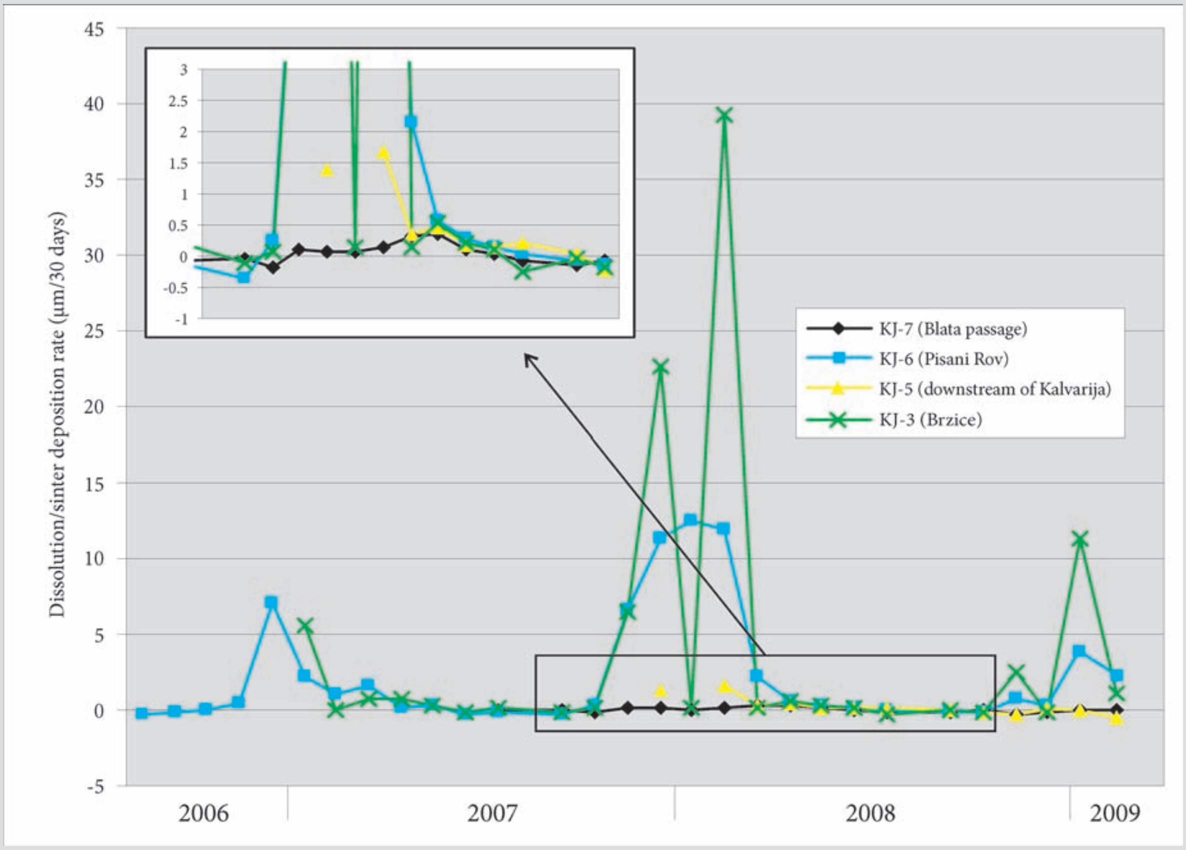


Figure 3.1.20. *Results of measurements at KJ-5, KJ-6, KJ-7 and at KJ-3 for comparison from 13 January 2007 to 27 February 2009. Presented are just results of measurements which were not significantly affected by dissolution at the contact with rusted iron screws.*

of mixed physicochemical properties of water from Pisani Rov and from the Blata passage. In such conditions, we could expect some mixing dissolution (Bögli 1964 after Gunn 1986) in cases when waters are different with regard to CO_2 and calcium concentration and are close to saturation. Occasional chemical analyses during low and middle discharges show that water from Pisani Rov and the Blata passage is usually slightly oversaturated; they have different CO_2 concentration as is seen from different pH and different Ca^{2+} concentrations as a result of similar SEC (total hardness) and a different Ca/Mg ratio. Consequently, the combined stream could theoretically show sinter deposition rates somewhere between those detected in both passages or even slight dissolution rates. During high discharge it can be slightly undersaturated, which could together with different CO_2 and Ca^{2+} concentrations lead to higher dissolution downstream from the confluence. Results of measurements (Fig. 3.1.20) show that when higher sinter deposition rates prevail at KJ-6 and KJ-7, the sinter deposition rates at KJ-5 are usually between those of KJ-6 and KJ-7 but during slightly aggressive water at least from the Blata passage (KJ-7) dissolution rates at KJ-5 are higher, which is in accordance with theoretical expectations. Nevertheless, autumn downstream increases of dissolution rates are not high and close to the error of measurement. The limited potential of mixing dissolution was already warned of by Gunn (1986; 378), who states that mixing dissolution can be responsible for up to 20 % additional dissolution, but 1-2 % is more usual in normal waters. The average yearly rate at KJ-5 is, as well as at KJ-6 and KJ-7, still in favour of sinter deposition. Another important conclusion is that the tributary from the Blata passage significantly reduces sinter deposition rates along the Pisani Rov-Jezerski Rov water course downstream from Kalvarija.

3.1.6 Measurement locations KJ-8, KJ-9 and KJ-10 – speleogenetic processes in Pisani Rov

The explored water course in Pisani Rov begins under the breakdown at the end of the trunk passage. Along its underground course toward Kalvarija, the main stream is fed by at least 5 springs/tributaries. Since the uppermost four tributaries are very similar in SEC and temperature we suppose that Kristalna Gora (crystal mountain) acts as a restriction for a stream flowing through an unexplored passage upstream of Kristalna Gora, which diffluences uniform water course.

Along the water course in Pisani Rov, we observe similar geomorphic phenomena as in Jezerski Rov between Kalvarija and Brzice – a scalloped wall above middle water level, flowstone coating on the wall under the middle water level and, in a longitudinal cross-section, rimstone dams with lakes behind them. Flowstone coating is absent just at the lowest tributary in Pisani Rov. Free surface flow of this tributary is not longer than 10 m and ends in a sump. Tributary water has up to 21 μS/cm higher SEC and up to 0.60 lower pH in comparison with the main water course, a result of the lack of ventilation. This tributary is characterized also by a generally 0.5-0.7 °C lower temperature. The influence of this tributary on the main stream is supposed to be relatively slight since it contributes only about 16 % of water to the main stream during low-middle discharges.

Present-day processes in Pisani Rov were studied at three measurement locations: KJ-8, KJ-9 and KJ-10 (Fig. 3.1.6) from 15 July 2007 to 27 December 2008. At each measurement location we used three limestone tablets at the same time for higher precision. Limestone tablets were fixed with inox from the beginning of measurement. The limestone tablets were always under the water level. Due to the remoteness of the end part of Pisani Rov, limestone tablets were replaced after several months of exposure. Consequently, results for the three measurement periods are available.

The results of measurements in Pisani Rov are presented in Fig. 3.1.21 and Tab. 3.1.3. Two phenomena can be identified: (a) sinter deposition rates are significantly higher in the colder part of the year (Tab. 3.1.3) and (b) sinter deposition rates increase from the terminal breakdown toward Kalvarija (Fig. 3.1.21). High sinter deposition rates in winter and low sinter deposition rates in summer are similar to a phenomenon already known from Jezerski Rov (Chapter 3.1.4). They are related to the winter ventilation of Križna Jama, which significantly decreases cave air CO_2 concentration in the karst massif. It is somehow surprising that summer ventilation does not reduce CO_2 concentration in the upstream part of Pisani Rov so much that high or even medium sinter deposition rates would appear. Since the highest cave air CO_2 concentration in summer was detected at the most NE part and the lowest at the end of Matjažev Rov (Matjaž's passage), this data suggests that the air which is coming from the passages behind the terminal breakdown is substantially enriched by CO_2 from the epikarst and the vadose zone and CO_2 concentration in the massif is still high at least during vegetation season. Of great interest is a decrease in sinter deposition rates downstream from the terminal breakdown, which was recorded in summer-autumn during the first measurement period.

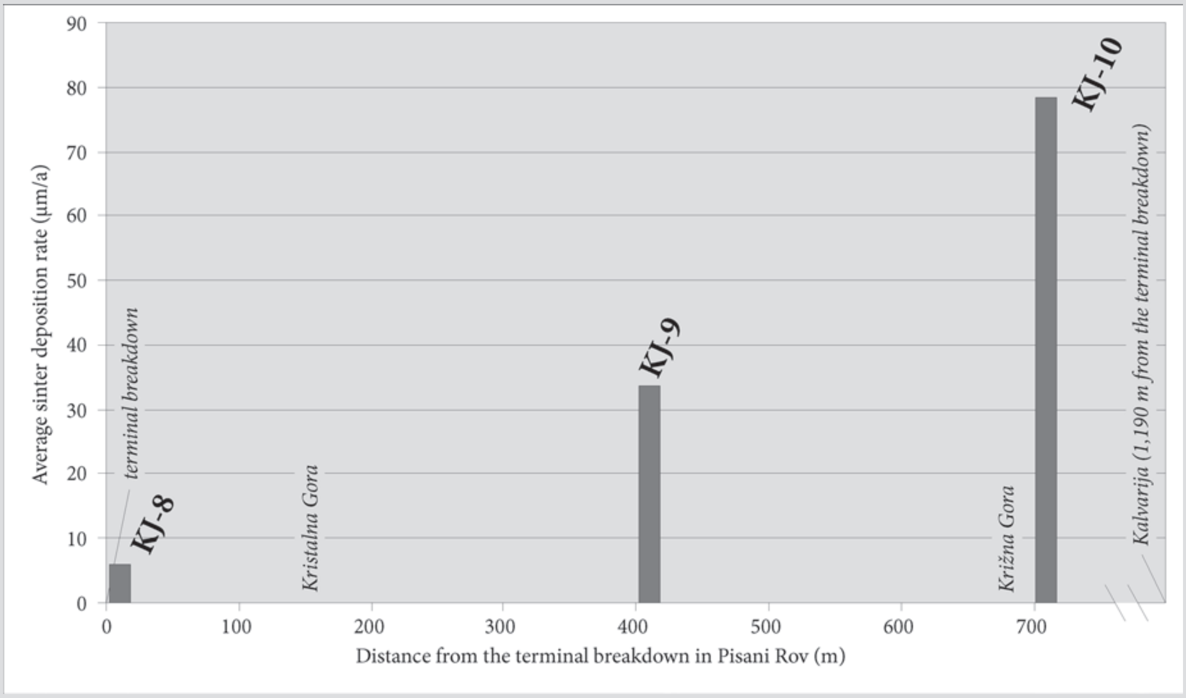


Figure 3.1.21. *Sinter deposition rates in Pisani Rov (at KJ-8, KJ-9 and KJ-10) from 15 July 2007 to 27 December 2008.*

Table 3.1.3. *Sinter deposition rates in Pisani Rov during three measurement periods from 15 July 2007 to 27 December 2008.*

	KJ-8			KJ-9			KJ-10		
15 July 2007-11 October 2007 (mm)	0.2	0.4	0. 2	0.3	0.3	0.2	0.0	0.1	0.0
15 July 2007-11 October 2007 (mm/a)	1.0	1.7	0.7	1.3	1.2	0.7	-0.1	0.2	-0.1
AVG (mm/a)	**1.1**			**1.0**			**0.0**		
11 October 2007-24 April 2008 (mm)	8.4	8.5	7.7	49.8	47.7	47.7	113.5	111.4	111.5
11 October 2007-24 April 2008 (mm/a)	14.2	14.4	13.0	84.2	80.6	80.6	191.8	188.3	188.3
AVG (mm/a)	**13.9**			**81.8**			**189.9**		
24 April 2008-27 December 2008 (mm)	0.5	0.4	0.4	0.5	0.4	0.3	1.9	1.8	2.2
24 April 2008-27 December 2008 (mm/a)	0.8	0.7	0.6	0.8	0.7	0.5	3.1	2.9	3.5
AVG (mm/a)	**0.7**			**0.7**			**3.2**		

Downstream increase of the sinter deposition rate in Pisani Rov (10.2 μm/a along 100 m of stream) is similar to that in Jezerski Rov (8.5 μm/a along 100 m of stream; Chapter 3.1.4) – as a result, between KJ-8 and KJ-10 the sinter deposition rate increases by 12.8 times. Nevertheless, this increase in rate is not linear but rather curved, with a smaller increase of sinter deposition rate close to the terminal breakdown. Further downstream the sinter deposition rate downstream from measurement location KJ-10 is lower due to the left tributary being located about 20 m downstream from KJ-10. This was observed especially during the second measurement period, when the average thickness of sinter at KJ-10 (112.1 μm) was 39.2 % higher in comparison with KJ-6 (44.6 μm).

The influence of the lowest tributary in Pisani Rov toward Kalvarija can also be seen from the spatial measurements of SEC, pH and T. From springs under Kristalna Gora toward Križna Gora, the SEC constantly lowers due to sinter deposition. The only significant rise in SEC is observed below the confluence with the left tributary downstream of Križna Gora. The pH value usually rises because of outgassing of CO_2 from the water. The only significant fall in pH is observed at the confluence with the left tributary downstream of Križna Gora. Downstream toward Kalvarija, pH is rising again. Since the water is close to equilibrium at springs below Kristalna Gora, outgassing of CO_2 causes the rising of SI_C, which leads to sinter deposition. Due to higher SI_C downstream, the highest

Figure 3.1.22. *Flowstone coating slightly above and under the water level, located about 20 m downstream from KJ-8 (photo: Alojz Troha, DLKJ).*

sinter deposition rates are characteristic for the downstream part of Pisani Rov before the confluence with the left tributary.

The prevailing sinter deposition below middle water level is in agreement with morphological observation. All along the water course, features like rimstone dams and flowstone coating as a result of net sinter deposition can be observed. The thickness of flowstone coating is least near the ending breakdown and increases downstream – as observed from limestone tablets. Net sinter deposition rates are most probably absent above middle water level since scallops without flowstone coating are developed there (Fig. 3.1.22). The wall above middle water level is covered by scallops, but since the measurements were done below medium water level and all measurement locations show net sinter deposition rates, dissolution during higher water level is probable but not confirmed by measurements. Very interesting features in the upstream part of Pisani Rov include horizontal stripes, which are composed of two more than 1 mm thick flowstone coatings (Fig. 3.1.22). They are developed about 10 cm above middle water level. It seems that they were formed at the water level in the time higher water level and in the time of the strongest winter ventilation that was followed by dissolution.

3.1.7 Measurement locations KJ-11, KJ-12, KJ-13 and KJ-14 – the influence of tributaries in the Blata passage

The Blata passage is more complex from a hydrological point of view since the main water course is fed by several different tributaries (Fig. 3.1.3), both left and right, that influence speleogenetic processes. The Blata passage is significantly less ventilated than Jezerski Rov and Pisani Rov. Therefore, CO_2 concentration is higher in comparison with Jezerski Rov and Pisani Rov during winter and summer ventilation regimes by more than 500 ppm. The direction of air flow depends on outer temperature and is similar to Pisani Rov – below 8 °C air flows upstream from Kalvarija and above 8 °C in the opposite direction.

Because of changeable micromorphology and (most probably) also changeable rates of present-day processes and relevant factors, dissolution and sinter deposition rates were measured only at four typical locations. Results do not provide us full insight into the geomorphological activity in the Blata passage, but, nonetheless, they do give us some information about the intensity and temporal variation of geomorphic processes at typical locations, such as, in this case, confluences. Measurements were taken at KJ-11 (the spring of the longest known water course under the terminal breakdown), at KJ-12 (a periodic tributary which is thought to be the underground Bloščica course according to rare observations), at KJ-13 (above the siphonal tributary at a rimstone dam) and at KJ-14 (below a siphonal tributary; Fig. 3.1.6). Measurements started on 15 July 2007 and ended on 27 December 2008. Due to the remoteness of the end part of the Blata passage, limestone tablets were replaced once or twice per year, at the same times as in Pisani Rov. Therefore, results for three measurement periods are available for this timespan. At all measurement locations we used three limestone tablets, which were fixed on inox screws.

As in all measurement locations in Križna Jama, the highest sinter deposition rate at KJ-11 was recorded during winter months (Tab. 3.1.4). This proves that although the Blata passage is much less ventilated in comparison with Jezerski Rov and Pisani Rov the ventilation regime does influence less ventilated passages. Nevertheless, due to weaker ventilation, the sinter deposition rate at KJ-11 is about 3.2-times lower than the sinter deposition at the terminal breakdown in Pisani Rov (KJ-8; Chapter 3.1.6). In summer, a slight sinter deposition rate close to the error of measurement was recorded. The prevailing sinter deposition corresponds to actual morphology, since all terminal breakdown material under the medium water level is covered with flowstone coating. The thickness of flowstone coatings is hard to estimate but certainly exceeds several cm. Where the passage is slightly inclined, rimstone dams have been forming.

At KJ-12, where the measurements were done in the side passage, the clear dolomite wall without flowstone coating suggests that we can expect dissolution. Micro-dissolutional features are absent since the Lower Jurassic dolomite is heavily fractured and grained. Results (Tab. 3.1.4) suggest that sinter deposition in winter months is turned to dissolution in summer months. Detection of the highest dissolution rates at this place in Križna Jama suggests that the water can be different in origin and could be at least part of the underground Farovščica or Bloščica flow already confirmed for the Blata passage with a tracing test (Kogovšek et al. 2008). The recorded average dissolution rate (-0.03 µm/a) is within measurement error but shows that chemical processes are very close to equilibrium and that low rates cannot lead to observable flowstone coating, if such at all exists, even within the Holocene. During the time of dissolution, the real dissolution rate in the passage is up to 10 times weaker since the Lower Jurassic dolomite is much more slowly dissoluted in comparison with standard limestone tablets (Fig. 2.8 in Chapter 2.2.3).

Measurement locations KJ-13 and KJ-14 are separated by only about 7 meters (Fig. 3.1.6 and 3.1.23). Their location is interesting since an underwater tributary, detected with SEC, T and pH measurements seems to have a strong influence on the micro-morphology of the present-day water channel. The upstream part of the water course, characterized by several cm thick flowstone coating, ends with about a 1 m high rimstone dam, where measurement location KJ-13 was located. Beneath the rimstone dam, a pool with a pipe flow tributary is located. Several hundreds of metres downstream, the water

Table 3.1.4. *Sinter deposition and dissolution rates in the Blata passage measured between 15 July 2007 and 27 December 2008 during three measurement periods.*

	KJ-11			KJ-12			KJ-13			KJ-14		
15 July 2007-11 October 2007 (mm)	0.1	0.1	0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15 July 2007-11 October 2007 (mm/a)	0.3	0.5	0.7	-0.5	-0.4	0.1	-0.2	0.2	-0.2	-0.1	-0.1	0.0
AVG (mm/a)	**0.5**			**-0.3**			**-0.1**			**-0.1**		
11 October 2007-24 April 2008 (mm)	2.3	2.2	2.6	0.5	0.6	0.6	11.7	11.5	11.0	0.3	1.2	0.4
11 October 2007-24 April 2008 (mm/a)	4.3	4.1	4.8	1.0	1.2	1.2	21.7	21.4	20.5	0.6	2.2	0.8
AVG (mm/a)	**4.4**			**1.1**			**21.2**			**1.2**		
24 April 2008-27 December 2008 (mm)	0.5	0.3	0.2	-0.7	-0.6	-0.4	0.9	0.8	0.2	0.0	0.0	-0.1
24 April 2008-27 December 2008 (mm/a)	0.8	0.4	0.3	-1.0	-0.9	-0.6	1.3	1.2	0.3	0.0	0.1	-0.1
AVG (mm/a)	**0.5**			**-0.8**			**0.9**			**0.0**		

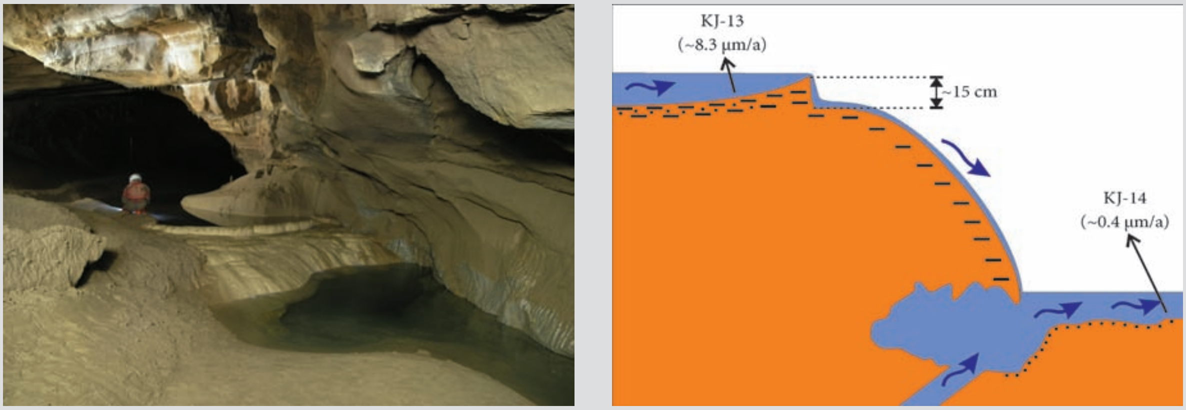


Figure 3.1.23. *Rimstone dam between measurement locations KJ-13 and KJ-14 during low water level (photo: Alojz Troha, DLKJ).*

course is characterized by a scalloped wall with an absence of flowstone coating but close to the confluence with Tršanov Rov (Tršan's passage; see Fig. 3.1.6) flowstone coating and rimstone dams gradually appear again due to constant downstream outgassing of CO_2 (seen as rising pH) and a consequential increase of SI_C.

Once again, sinter deposition was detected only during winter or early spring (the second measurement period; Tab. 3.1.4), while during summer and autumn (the first and third measurement periods) chemical processes are close to equilibrium. An important difference between KJ-13 and KJ-14 occurs only during winter and early spring months, when sinter deposition rates are 20.5-times higher at the rimstone dam in comparison with the pool, but is not turned to dissolution due to mixing. Although the difference in rates can be caused by the already discussed difference between rimstone dams and pools/lakes (Chapter 3.1.3), the absence of flowstone coating several metres downstream of the confluence indicates that the difference is caused by the tributary with pipe flow, which with relatively low pH and high SEC lowers SI_C. Besides slight sinter deposition rates at KJ-14 that should result in thin flowstone coating, present-day morphology of the water channel corresponds to present-day processes. Similar confluences of the main water stream with tributaries that spring from sumps and downstream outgassing of CO_2 from the water with decrease of SEC are characteristic all along the main Blata passage. Regarding morphology, due to gradual outgassing of CO_2 from the water along the water stream and sudden interruption of sinter deposition at the confluence, sinter deposition rates are the highest just before the confluence with the tributaries.

From a morphological point of view, the rimstone dam between KJ-13 and KJ-14 has a two-stage shape (Fig. 3.1.23). The lower part of the dam is formed as a convex massive rimstone dam while on the top of this massive rimstone dam, about a 15 cm high almost vertical rimstone dam has been developed. If we take into consideration that real sinter deposition rates can be from 2 to 12.5-times higher than rates measured by limestone tablets (8.3 µm/a; Fig. 2.10 in Chapter 2.2), a 15 cm high rimstone dam can be formed during or at the beginning of Holocene. Pre-Holocene genesis of the massive part of the rimstone dam is less probable but it would be very interesting if confirmed by dating.

3.1.8 Measurement locations KJ-3 and KJ2-2 (KJ-2-1) – temporal variation of speleogenetic processes in the entrance part of Križna Jama 2

Križna Jama 2 (Fig. 3.1.2 and 3.1.3) is supposed to be a hydrological and geomorphic continuation of Križna Jama. This presumption is supported by very similar physicochemical characteristics of the water, the short distance between them and the similar morphology of trunk passages. Although the caves are separated by more than 242 m with a deep sump of over 124 m below the collapse doline, the hydraulic gradient is extremely low at low-middle water levels (~10 cm of vertical difference between water levels in connecting sumps; Drole 1997). According to periodic measurements of SEC, T, pH, Ca^{2+} concentration, Mg^{2+} concentration and a tracing test done in 2007/2008 (Kogovšek et al. 2008), at least one tributary is known between the caves that is changing the physicochemical properties of the water and probably also the present-day speleogenetic activity of the water.

Chemical processes at the beginning of the water stream of Križna Jama 2 were studied at KJ2-1 and at KJ2-2. Measurement location KJ2-1 was located 100 m upstream from measurement location KJ2-2. Hydraulic conditions at measurement locations were influenced by a relatively large cross-sectional wetted area that caused slower and therefore less turbulent subcritical water flow at middle water levels. Usually, tablets were replaced every 30 days. Measurements started on 16 August 2006 and were substantially influenced by iron oxide (Chapter 2.2.3). Results at measurement locations KJ2-1 and KJ2-2 were substantially improved on 18 November 2007 when synchronous measurements with limestone tablets fixed with inox 3 cm away from the already established measurement locations started (KJ2-1-1 and KJ2-2-1).

The results of measurements at measurement locations KJ2-2, KJ2-2-1 and at KJ-3 and KJ-7 (Križna Jama) for comparison are presented in Fig. 3.1.24. The highest sinter deposition rates amount to 0.6 µm/30 days while the strongest dissolution rates amount to -0.3 µm/30 days. Annually, the sinter deposition rate prevails over dissolution rates at KJ2-2-1 with a net sinter deposition rate of ~1.4 µm/a. During the spring, summer and autumn months in 2008, the course of sinter deposition rates and transition to dissolution rates is similar at all compared measurement locations. Nevertheless, a slight increase of sinter deposition rates is characteristic from the Blata passage (Križna Jama) to Križna Jama 2 in spring months. Since the difference between KJ2-2 and KJ2-2-1 amounts constantly to 0.5 µm/30 days in 2008, we can suppose that the annual course of sinter deposition rates and dissolution rates was very similar in 2006 and 2007. Such a seasonal course as was already observed in Križna Jama is in Križna Jama 2 not significantly influenced by a tributary (at least part of the superficial Farovščica stream) between Križna Jama and Križna Jama 2, confirmed by a tracing test (Kogovšek et al. 2008).

The most evident difference between measurement locations KJ-3 and KJ2-2 (KJ2-2-1) is the absence of high winter sinter deposition rates in Križna Jama 2. At KJ2-2-1, the highest sinter deposition rate amounts to 0.6 µm/30 days, while at KJ-3 it amounts to 39.9 µm/30 days. A huge winter difference in sinter deposition rates results in annual sinter deposition rates that are at KJ-3 more than 20-times higher in comparison with KJ2-2-1. This high difference in winter deposition rates is caused by differences in the morphology of passages and ventilation. Probably the most important factor is the length of free surface flow from the confluence to the measurement location: outgassing of CO_2 from the water that influences the sinter deposition rates at KJ-3 takes place in Križna Jama all the way from Kalvarija, while at KJ2-2 (and KJ2-2-1) in Križna Jama 2, upstream outgassing of CO_2 from the confluence is limited to only 100 m. If we compare measurement locations KJ2-1-1, located in Pritočni Sifon (inflow sump)

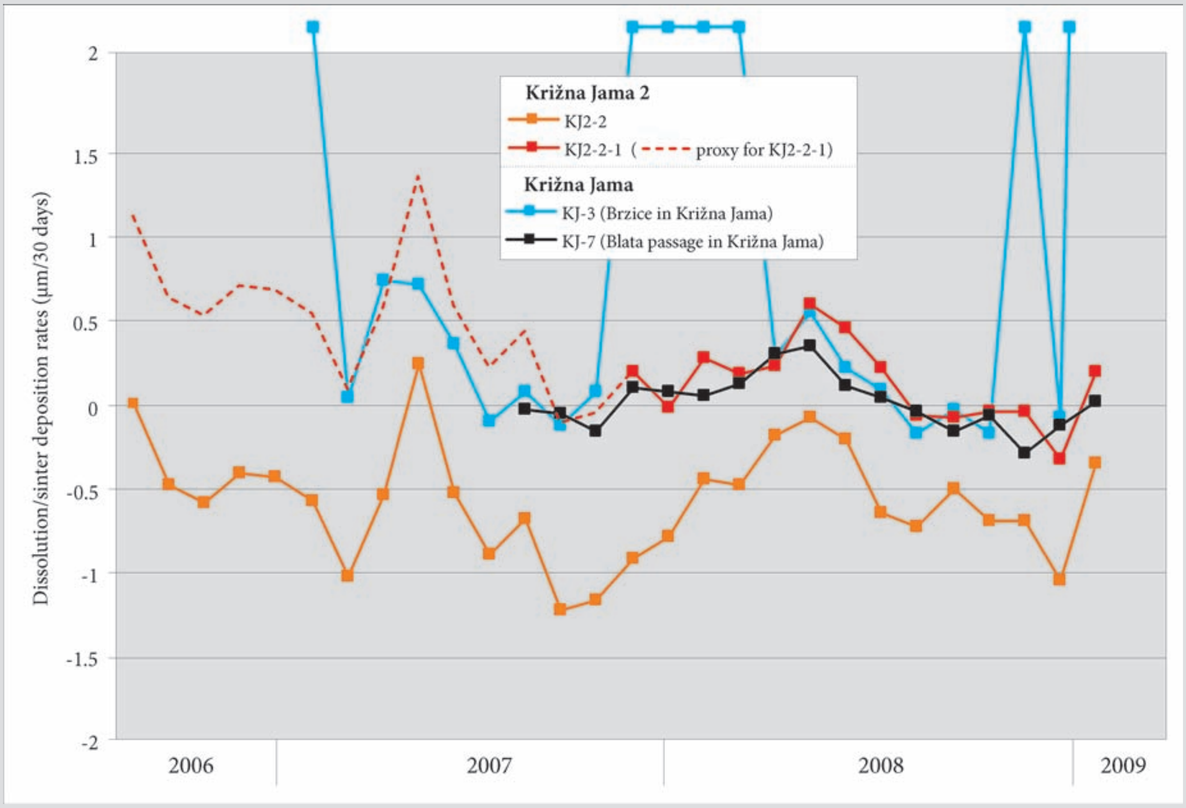


Figure 3.1.24. *Dissolution and sinter deposition rates at measurement locations KJ2-2 and KJ2-2-1 from 16 August 2006 (18 November 2007) to 17 February 2009 . Data from KJ-3 and KJ-7 (Križna Jama) are for purposes of comparison.*

and KJ2-2-1, 100 m downstream, the rates are practically equal (Fig. 3.1.25). Equal rates are the result of the strength and regime of ventilation: at KJ2-1-1 and KJ2-2-1 in Križna Jama 2, the highest CO_2 concentration is reached in winter months (~3,700 ppm) due to the air flow directed upstream (from the cave at the entrance) while the lowest are characteristic for summer months (~900 ppm). Additionally, air flow velocity is much higher in Križna Jama at several places due to several low passages, while in Križna Jama 2 water passages are always wider and higher than 5 metres. Both factors strongly decrease the outgassing of CO_2 from the water and consequently lower the sinter deposition rates in Križna Jama 2. This is also one of the reasons that lower summer cave air CO_2 concentration in Križna Jama 2 does not result in higher sinter deposition rates during summer months.

As in Križna Jama, the scalloped wall prevails above and, all through Križna Jama 2, also under the medium water level without any flowstone coating. Since net sinter deposition rate is characteristic for water channels in depths of KJ2-1-1 and KJ2-2-1, flowstone coating is expected in the present-day situation.

On the contrary, flowstone coating is completely absent at the Pritočni Sifon and 100 m downstream in Križna Jama 2. The latter discrepancy between actual morphology and measured processes is similar to KJ-14 (0.4 μm/a) in the Blata passage and to some extent the upstream part of Jezerski Rov in Križna Jama (~0.8 μm/a at KJ-5), where flowstone coating is missing or thinner than expected. The reasons can be as follows:

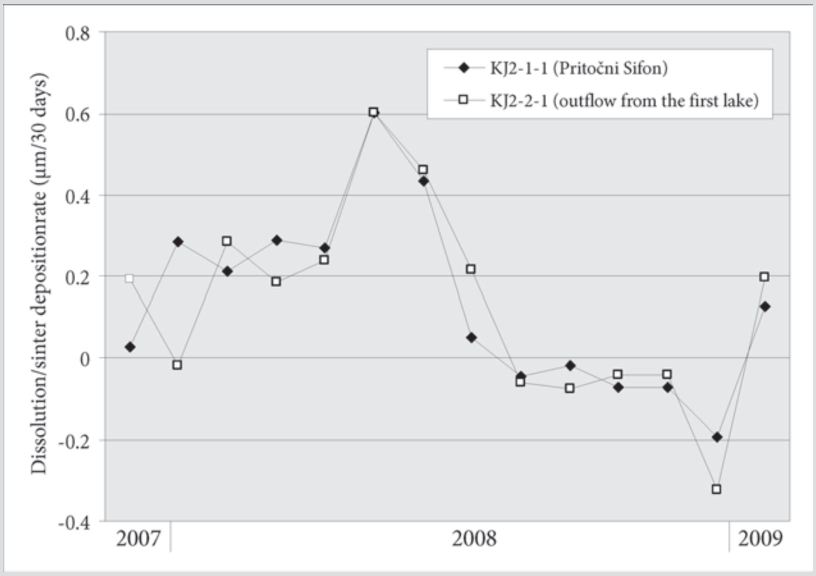
- corrasion,
- dissolution under the thin loamy sediment and/or by biofilm,
- discrepancy between present-day rates and long-term (i.e. millennial) rates and/or
- artificial widening of entrances.

Corrasion definitely takes place in Križna Jama and Križna Jama 2, since the underground stream transports allochthonous sediments and even produces potholes at rimstone dams upstream of the third lake in Križna Jama where sinter deposition rates are lower. Corrasion rates were not measured, but since corrasion should appear also at limestone tablets and is therefore already calculated in the rates, only the difference in corrasion rates could cause any differences. However, flowstone coating was not observed at any remote locations away from corrasion and therefore the latter should not be the reason for the absence of flowstone coating in Križna Jama 2.

The second possibility is feasible since we lack flowstone coating at many loamy banks. Enhanced dissolution under the organic sediment was suggested by Gams (1967; 51) and is certainly responsible for some superficial and speleogenetic features (i.e. dissolution pan/kamenitze, below-sediment bevels/decantation flutings, below-sediment floor pits; Slabe 1995; 71, Ford & Williams 2007; 329). Film of loamy sediment also inhibits direct calcite precipitation. Since we observed a thin flowstone coating on the rocky wall but it is absent on the nearby loamy sediment, dissolution under the sediment seems to be important. After 30 days of exposure, limestone tablets were gently cleaned and dried (see Chapter 2.2.1). With this procedure, we avoided weighing sediment deposited on limestone tablets but we might also break or slow down dissolution, which can be caused by biofilm or long-term decay of organics under the sediment especially over long periods of low discharge when limestone tablets were clean.

Since the annual rates strongly depend on meteorological conditions during winter (see Chapter 3.1.1), long-term measurement could reveal lower annual net sinter deposition rates in comparison with that taken into account (2008-2009). Severe floods that did not happen during the measurement period could also decrease net sinter deposition rates. The relevance of this potential reason will be clearer in coming years since the measurements at some places continue.

Figure 3.1.25. *Comparison of dissolution/sinter deposition rates between KJ2-1-1 and KJ2-2-1.*



Insight into the Holocene sinter deposition rate at rimstone dams with dating can also be helpful.

Before Križna Jama 2 was dug out, ventilation was observed at the entrance but it was weaker than in the present-day situation. Yet since we observe no direct relation of ventilation and sinter deposition rates in the entrance part of Križna Jama 2, a slightly increased ventilation does not seem to be an appropriate reason for (potentially) higher sinter deposition rates. A more probable reason is the widening of the entrance to Križna Jama in the 1940s, which could have led to increased moderate sinter deposition rates in Križna Jama and consequently also in Križna Jama 2.

3.1.9 Measurement locations KJ2-3, KJ2-4, KJ2-5 and KJ2-6 – spatial variability of processes along the main water course in Križna Jama 2

Downstream from the Pritočni Sifon (inflow sump) in Križna Jama 2, on average 10 m wide and 20 m high the water passage continues 1,300 m onward to the terminal sump called Sifon Upanja (sump of hope). This trunk passage is characterized by many rimstone dams that developed on more resistant dolomite layers or on breakdowns. Since we were measuring sinter deposition at KJ2-1 (KJ2-1-1) and KJ2-2 (KJ2-2-1), we were interested also in sinter deposition rates downstream of KJ2-2. Between KJ2-3 and KJ2-6, only one tributary from Kaplanov Rov was detected (Fig. 3.1.3). Since it is relatively small in comparison with the main water course at low and middle water levels (few l/s – up to 5 % of the main water course), it seems to be quite insignificant for present-day speleogenetic processes along the water course.

Sinter deposition and dissolution rates were measured at four measurement locations (KJ2-3, KJ2-4, KJ2-5 and KJ2-6; Fig. 3.1.6). Measurement location KJ2-3 was located 10 cm beside KJ2-2 (KJ2-2-1). At all four locations, three limestone tablets on each location were fixed with inox screws, nuts and felted washers. All measurement locations lie in nearly equal hydraulic conditions – in turbulent and supercritical water flow. Even at low water levels, all limestone tablets stayed under the water. Measurements started on 11 April 2007 and finished on 18 February 2009. Due to the remoteness of measurement locations and fragile rimstone dams along the main water course, limestone tablets were replaced only three times and data for three measurement periods are available.

At all measurement locations, sinter deposition prevails over dissolution (Fig. 3.1.26). On average and during all three measurement periods, sinter deposition rates increased from Pritočni Sifon to Sifon Upanja (on average from 0.6 μm/a to 2.0 μm/a). The value at Pritočni Sifon corresponds to the annual sinter deposition rate downstream from the first lake in Križna Jama if we exclude the high sinter deposition rates caused by intensive ventilation in winter months. Therefore a deposition rate of 0.6 μm/a seems to be the background seasonal rate of net sinter deposition without very intensive winter ventilation. The increase of sinter deposition rates downstream is best described with a polynomial of degree two where R^2 amounts to 0.99. Similar sinter deposition rates at KJ2-4 and at KJ2-4 are at KJ2-4 probably influenced by the tributary from Kaplanov Rov. Very similar but a much faster increase of sinter deposition was measured in Pisani Rov (Chapter 3.1.6) and to some extent in Jezerski Rov between Kalvarija and Brzice in Križna Jama (Chapter 3.1.4). If we simplify the downstream increase of sinter deposition rates with a linear function, sinter deposition rates increase by about 10.2 μm/100 m in Pisani Rov, 8.5 μm/100 m in Jezerski Rov and only 0.2 μm/100 m in Križna Jama 2. The downstream level of increase is definitely not caused by the length of water flow or total hardness but rather by the huge difference in outgassing of CO_2 from the water due to higher CO_2 concentration in Križna Jama 2, although much better conditions exist for outgassing in Križna Jama 2 due to its higher gradient of water flow.

Deviation within each measurement location grows from Pritočni Sifon to Sifon Upanja. This is another hint that different rates of increase within each measurement period is a result of water flow through Križna Jama 2 and a result of temporary changeable conditions along the main water course. Results from the second measurement period are interesting since we detected a decrease of sinter deposition rates between KJ2-5 and KJ2-6 that is not related to measurement error. Another case of downstream decrease of sinter deposition rates was between KJ2-3 and KJ2-4 in the third measurement period. The reason is unknown.

Lower sinter deposition rates and outgassing of CO_2 from the water along the water stream were also measured with the spatial measurement of SEC and pH (Fig. 3.1.27). A typical change in SEC due to deposition over the 1,300 m long water course is 2-4 µS/cm in Križna Jama 2, which is a much smaller value in comparison with the change of 5-17 µS/cm along the 1,165 m long water course between Kalvarija and Ponor in Križna Jama (Tab. 3.1.2 in Chapter 3.1.4). The downstream change of pH value is much more complex in Križna Jama 2 in comparison with Križna Jama since pH is decreased by sinter deposition and at the same time increased by weaker outgassing of CO_2 from the water. Especially in the middle part of Križna Jama 2, pH is very stable.

Two longitudinal cave air CO_2 measurements downstream in Križna Jama 2 during spring and winter (Fig. 3.1.28) show that the CO_2 concentration significantly fluctuates only near the entrance due to the intrusion of outside air while at Sifon Upanja cave air CO_2 concentration is nearly constant at about 2,000-2,300 ppm. Such high CO_2 concentrations were rarely detected in Križna Jama.

The morphological result of sinter deposition recorded with limestone tablets should

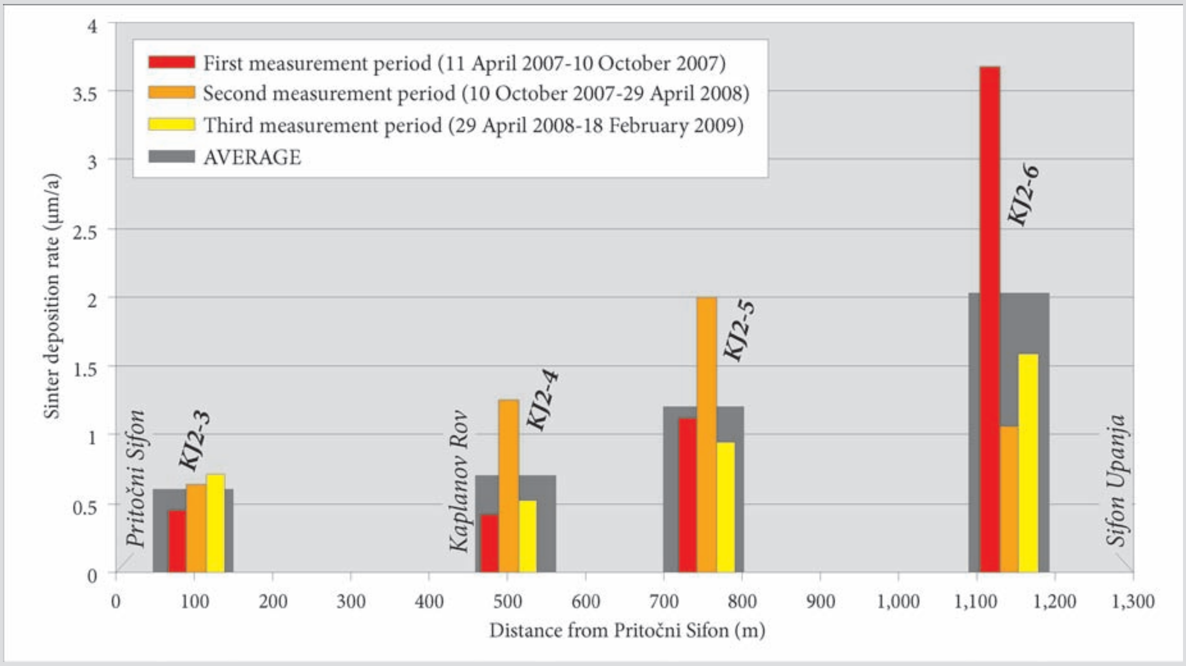


Figure 3.1.26. *Sinter deposition rates in Križna Jama 2 from Pritočni Sifon to Sifon Upanja during three measurement periods and on average.*

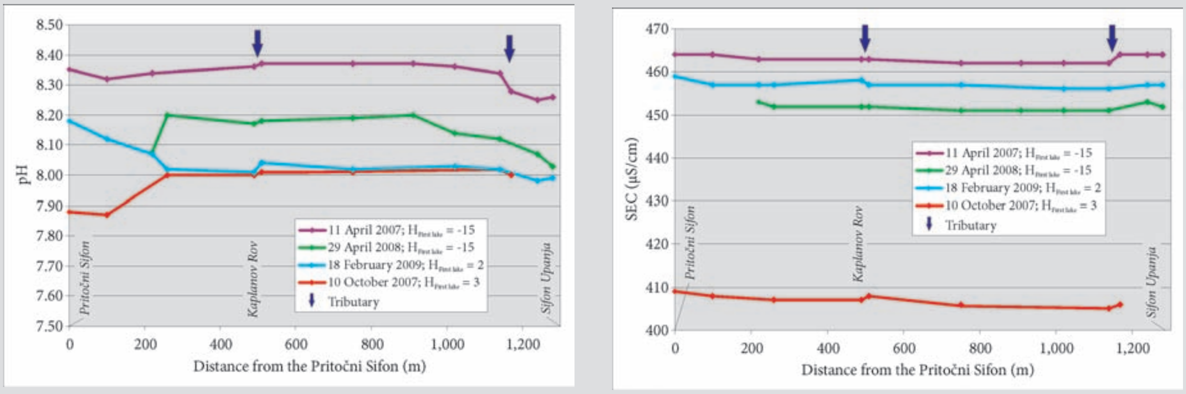
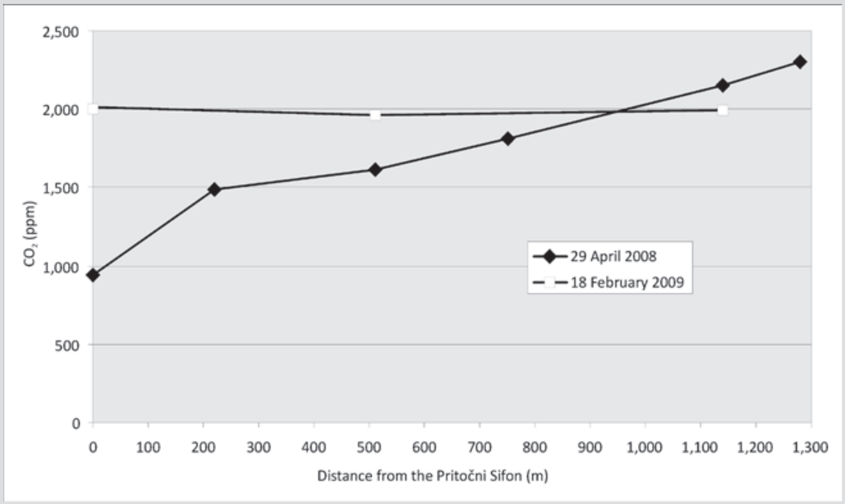


Figure 3.1.27. *Change of pH and SEC from Pritočni Sifon to Sifon Upanja in Križna Jama 2 at different water levels.*

be flowstone coating and rimstone dams. During the Holocene according to sinter deposition rates from 7 to 25 mm thick flowstone coating should be deposited. In spite of this, flowstone coating is absent all along the water stream. The walls are scalloped all along the water course, which, on the contrary with our measurements, indicates dissolution or inherited dissolutional morphology together with an absence of a prevailing process in present-day conditions. Reasons for this were already discussed in Chapter 3.1.8 and the most appropriate seems to be the dissolution under the loamy sediment that covers the water channel in lakes but not at rimstone dams and cascades where measurements with limestone tablets took place.

At waterfalls and rapids (Fig. 3.1.29) we can observe the development of rimstone dams that are due to lower rates much more fragile (and seem also to be thinner) in comparison with Križna Jama. Their fragility decreases from Pritočni Sifon toward Sifon Upanja, which corresponds to the measured downstream increase of sinter deposition rates (Fig. 3.1.26).

Figure 3.1.28. *Change of CO_2 from Pritočni Sifon to Sifon Upanja in Križna Jama 2.*



Recent morphology of many candle-like stalagmites close to the medium water level indicates dissolution after initiation of stalagmite growth, especially close to the Sifon Upanja (Fig. 3.1.30). For such morphology of stalagmites, a uniform supply of fed water with uniform solute concentration is characteristic (Ford & Williams 2007; 285). Growth was probably constant from the beginning and stalagmites are also growing in present-day conditions. It is interesting that they are partly dissolved in the lower part where growth rates are much lower or absent in comparison with the top of stalagmites, which results in a club-like stalagmite morphology. Some such stalagmites are growing at the ~1 cm high rocky pedestal surrounded by the scalloped surface which indicates parallel growth of stalagmites and dissolution by water flow that already removed 1 cm of limestone. This recent morphology suggests that during higher discharge water can be slightly aggressive, especially in the downstream passages of Križna Jama 2, but such dissolution rates are overwhelmed by sinter deposition rates below middle water levels where measurements with limestone tablets are situated.

Figure 3.1.29. *Rimstone dam and cascades covered by several cm thick sinter deposits between KJ2-5 and KJ2-6 during middle discharge (photo: Matej Kržič, DLKJ).*

Figure 3.1.30. *Partly dissoluted club-like stalagmites with up to 1 cm high limestone rocky base 0.3 m above medium water level close to Sifon Upanja. Rocky bases formed in dolomite (black coating) are smaller due to slower solubility of Lower-Middle Jurassic dolomite (photo: Alojz Troha, DLKJ).*

3.1.10 Conclusion

The Križna Jama-Križna Jama 2 cave system is one of the best examples of a horizontal cave speleogenesis in the epiphreatic zone. Although the system was at least partly under the influence of the allogenic recharge of Bloščica and Farovščica, which have catchment areas on the Bloke plateau, nowadays tracing tests and physicochemical characteristics of the water indicate the dominance of diffuse autogenic recharge from the area above and near the cave system. Consequently, stream water has high total hardness and is in equilibrium with higher CO_2 pressure than is characteristic for the outside atmosphere. When such water enters a well ventilated cave system, outgassing of CO_2 from the water leads to oversaturation with respect to calcite and calcite precipitation occurs. From the morphological point of view, formation of flowstone coating in nearly stagnant and rimstone dams in fast flowing water is possible.

The most evident pattern in chemical processes is seasonally driven transition of sinter deposition in winter and spring months and dissolution in summer and autumn months, which was observed in the main trunk passages of Križna Jama under the medium water level. The seasonal peak of sinter deposition rates amounts to more than 0.6 µm/30 days, while the strongest dissolution rates amounts to up to as much as -0.3 µm/30 days (Fig. 3.1.24). Spatial differences from upstream terminal breakdown in Križna Jama to Pritočni Sifon (inflow sump) in Križna Jama 2 are insignificant. Differences between lakes and rapids are also negligible. Over the year, sinter deposition rate prevails over dissolution. Over the year, slight dissolution prevails only at places reached by high water levels and at some tributaries that emerge from passages with pipe flow and are therefore not ventilated. Seasonal variations can be driven by intensive winter ventilation of Križna Jama or by vegetation and consequential seasonal variation in soil CO_2 production.

Along the water course, outgassing of CO_2 from the water occurs that raises SI_C and therefore increases sinter deposition rates downstream during middle and low discharge. Downstream increase is the highest during the coldest winter days (daily temperature remains below ~-2 °C) when air flow is the strongest and long-lasting. Downstream increase is characteristic for lakes and for rapids but it is more expressed at rapids. High downstream increase of sinter deposition rates is terminated by tributaries. The highest deposition rates are therefore characteristic for the downstream part of Pisani Rov (Križna Gora and Kalvarija) and the downstream end of Jezerski Rov (between the first lake and Ponor) and can amount to over 75 µm/a. In shorter periods, sinter deposition rates can amount to 17 µm/15 days. Daily rates are thought to be much higher but they were not measured since intensive deposition rates are highly unpredictable. Where ventilation is weaker (the Blata passage and Križna Jama 2) ventilation-driven winter sinter deposition rates are much lower or absent. The morphological result of intensive winter ventilation is the faster growth of rimstone dams in comparison with flowstone coating in the lakes (17:1), and the faster growth of downstream rimstone dams that causes flooding of upper ones, a vast decrease of sinter deposition rates at flooded rimstone dams and the lengthening of lakes. The gradual rise of water level reduces the aerated cross-sectional profile of passages and consequently results in a negative feedback loop since less intensive ventilation reduces sinter deposition rates. Since gradually weaker sinter deposition rates are expected the roof will never be reached by medium or at least low water levels.

Present-day climatic changes indicate higher temperatures, especially during winter time. If the same trend continues, we can expect lower sinter deposition rates, as was already recorded in the winter of 2006/2007 (contrary to the much colder winter of 2007/2008; Prelovšek 2007). From 1994 (Mihevc 1997) to 2009, the variation of rates during several winters do not show any important trend of sinter deposition decrease but longer observation of sinter deposition rates will be helpful to evaluate the influence of climatic changes and the necessary response from Križna Jama's tourist management (Prelovšek 2012).

Along the main water courses in the Križna Jama-Križna Jama 2 cave system, dissolutional and depositional features can be observed. Rimstone dams and flowstone coating on the cave wall suit present-day processes at least in Križna Jama. The thickness of rimstone dams and flowstone coating equals measured sinter deposition rates over ten thousand years, which limits sinter deposition to the Holocene . In Križna Jama, the discrepancy between measured present-day sinter deposition rates (from 0.6 to 2 µm/a), which should result in 7-25 mm thick flowstone coating during the Holocene, and the absence of flowstone coating is surprising and requires additional study. The sinter deposition rate at one measurement location in the Blata passage (KJ-13) indicates that (low) sinter deposition rates could also be related to the pre-Holocene, although this is less probable. The main proof for important changes at the Holocene-Pleistocene transition are scallops and other dissolutional features, which are numerous on the walls of the Križna Jama-Križna Jama 2 cave system but at some places (e.g. in the first lake) do not correspond at least to present-day hydrodynamic conditions. They could have been formed during the last (Würmian) Ice Age, when the snow line at nearby Mt. Snežnik was between 1,200 and 1,300 m a.s.l. (Šifrer 1959). The reason for stronger dissolution rates during Ice Ages are related to lower annual temperatures that reduced the supply of CO_2 from the soil (instead of the present-day forest above the cave system Križna jama-Križna jama 2 we can expect microtermic vegetation (grassland with clumps of trees; Šercelj 1974), for which lower production of CO_2 is expected.), lowers total hardness of water, lowers the possibility for outgassing of CO_2 from the water due to lower water CO_2 concentration and consequently at least strongly reduced possibility for sinter deposition. Nevertheless, closure of the main entrance to Križna Jama due to breakdown (which is common in such climatic conditions) or changes in the catchment area (which already occurred in the cave system) would have similar results; that is, lower sinter deposition rates or even dissolution.

3.2 LEKINKA CAVE

Lekinka cave (Reg. No. 1867) is a 1,032 m long subhorizontal cave situated at the NE edge of the Postojna basin about 1 km NW of the Pivka ponor. It is one of the several stream caves (e.g. Postojnska Jama (Postojna cave), Predjama, Osojca, Markov Spodmol) at the contact karst (Mihevc 1991) that developed at the transition of Eocene siliciclastic flysch rocks to Cretaceous limestone. The speleogenesis of big cave systems like that of Postojna (Chapter 3.4) is generally complex, involving many long-lasting phases, but in the case of Lekinka cave it seems to be more simple and easier to study in short measurement intervals (Chapter 2.2.2).

Contrary to the Postojna cave system that has a long and rich research history, Lekinka cave has rarely been the focus of speleological research. The first description of Lekinka is from the time of A. Martel (1894; 442 after Gospodarič & Habič 1966; 13). Although the cave is easily accessible even during middle water levels, relatively simple for exploration and close to the touristic Postojna cave, the first survey was done by the cave club Anthron at the end of 19th century. At that time, 350 m of entrance passages were mapped. A more detailed and longer survey was done around 1926, when 387 m of underground passages were explored by Italian cavers. Finally, the entire currently known cave was surveyed by Gospodarič, Habič and Kenda to the Končni Sifon (terminal sump) around 1966.

The speleological research into Lekinka cave is even sparser than the survey of the cave. Gams (1966a), Michler & Hribar (1959) and Melik (1955) did not pay any attention to Lekinka, although they were concerned a great deal with karstological and speleological research in the Postojna basin and its surroundings. Lekinka cave is the subject of only one comprehensive study, by Gospodarič & Habič (1966), in which basic geological, geomorphological and hydrological observations were made. Recently, the influence of water CO_2 on longitudinal decrease of dissolution rates and morphology was made by Covington et al. (2012).

Geological and geomorphological characteristics

The catchment area of Črni Potok (black stream), which sinks into Lekinka cave, extends on the Pleistocene accumulation terrace of Pivka and Nanoščica. Fluvial deposits of weathered siliciclastic Eocene flysch are several metres thick and Črni Potok cuts part of its channel into underlying flysch rocks for several tens of meters before contact with limestone (Fig. 3.2.1). Contact between Eocene flysch and limestone is located 50 m before Črni Potok disappears into Lekinka cave. This 50 m long watercourse lies at the regionally important thrust fault which is responsible for steep contact of Eocene flysch with Cretaceous limestone.

All known passages of Lekinka cave are developed in Senonian limestone, which is generally inclined 70-90° SW. Toward the northeast, the inclination of strata decreases toward the Postojna anticline, which has its axis in a NW-SE line and extends over the Postojna cave system. The thickness of strata depends on age – lower (older) Senonian limestone is thick-bedded or even non-stratified while the upper (younger) is developed as stratified limestone with a thickness of strata about 1 m (Gospodarič & Habič 1966). All Senonian limestone contains very small amounts of impurities. Due to the vicinity of thrusting, Senonian limestone is well fractured but not severely crushed in the Lekinka cave. Interbed movements at bedding planes are numerous (Gospodarič & Habič 1966).

All these geological characteristics are expressed in general cave morphology. Since the limestone is not crushed, breakdown chambers are absent. In the entrance part of a cave with well-expressed bedding planes, passages developed along tectonically deformed bedding planes. This is reflected in the roughly rectangular plan of Lekinka cave (see Fig. 4.2.5). Deeper into the cave, the absence of bedding planes forced passage development along faults and cracks with a less expressive geometric pattern. Unknown water-filled passages between Končni Sifon in Lekinka and Otoška Jama are formed in Turonian strata, which are developed as thick-bedded limestone with rare bedding planes (Šebela 1998). Rare bedding planes can result in a lower possibility of the development of free surface flow, and, therefore, the development of sumps.

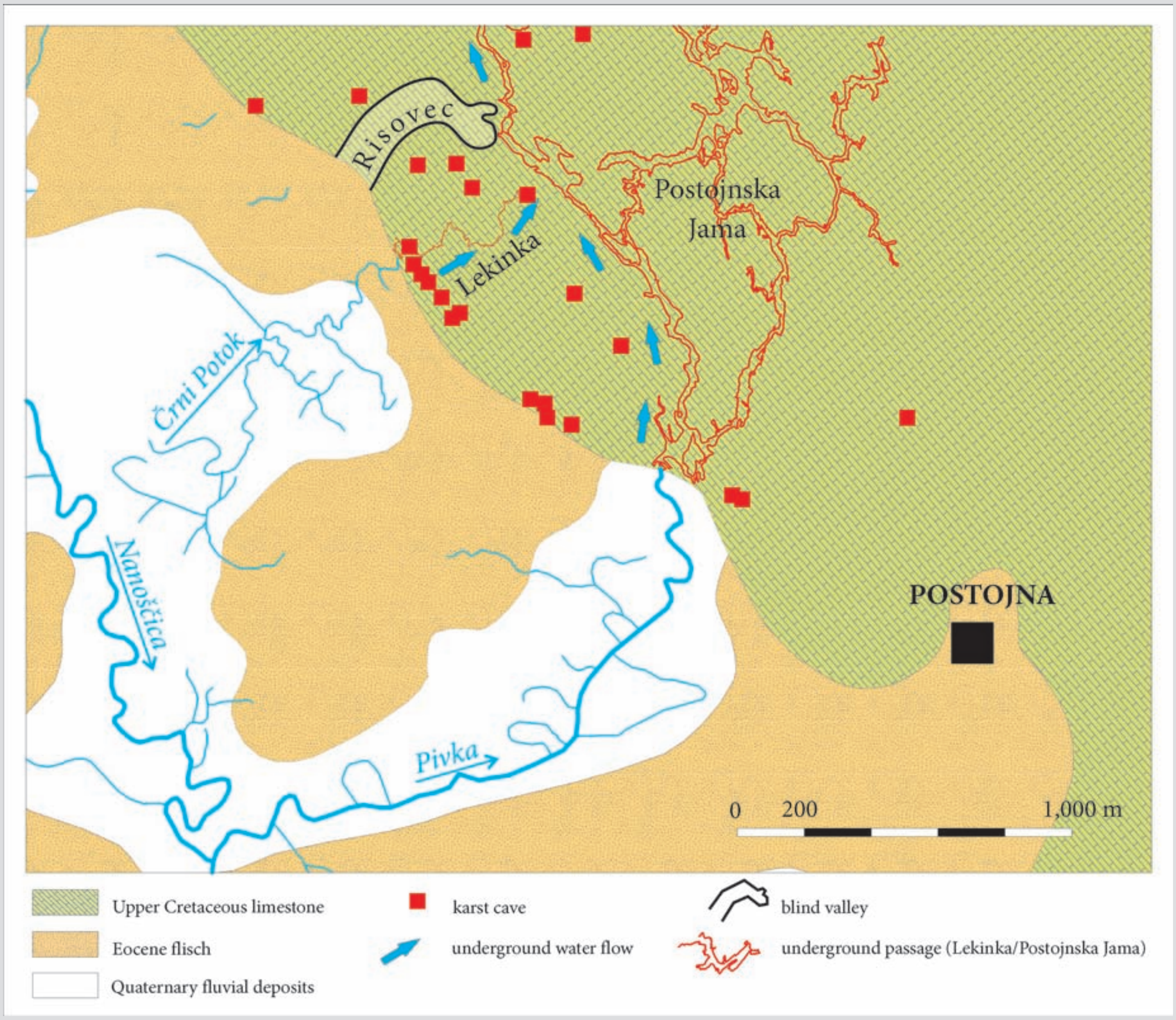


Figure 3.2.1. *General geological, hydrological and speleological map of the karst massif including Lekinka cave and its superficial catchment area (source of geological data: Buser et al. 1976).*

Contact karst at the NE edge of Postojna basin is subject to long-term term geomorphic evolution, where speleogenesis of epiphreatic passages began at least 530 ka ago (Zupan Hajna et al. 2007). Such a long geomorphic evolution resulted in large and extensive cave systems, while superficial contact karst is morphologically relatively poorly developed. For instance, only one blind valley is developed along NE contact (the fossil blind valley Risovec), while all other rivers (Pivka) and streams (Črni Potok, Osojca) have not developed any blind valley at their present ponor sites (Mihevc 1991). Active and abundant ponor caves are not dispersed all along the NE edge of Postojna basin, rather they are concentrated between the entrance to Postojna cave and the fossil blind valley Risovec (Fig. 3.2.1); this is at only 30 % of the whole of the NE contact between flysch rocks and limestone in the Postojna basin. Behind this 1.9 km long contact, all known passages of the Postojna and Lekinka caves are located. This characteristic shows that only this part of contact was under the long-term influence of sinking streams which flow underground toward the NE, that is toward Planinska Jama (Planina cave). On a smaller scale, two locations can be highlighted from this 1.9 km long contact: (a) the area near Postojnska Jama and (b) the area of the blind valley Risovec. On the surface, these two sinking points are divided by the 40 m high erosion terrace of Veliki Otok (545 m a.s.l.). In the vicinity of large ponor sites, much smaller caves are located at altitudes between 511 m a.s.l. (Lekinka cave) and 549 m a.s.l. The morphology of these passages is much different from that of the the large passages of Postojna cave system (i.e. width-height ratio of passages, presence of wall notches, combined vadose-phreatic morphology). From their morphology one can conclude that they were formed in conditions similar to those of the present-day in Lekinka cave. This finding is contradictory to some baseless statements (Brodar 1949; 99) that some of these narrow caves (e.g. Betalov Spodmol) were formed as branches of large rivers (i.e. Pivka or Nanoščica).

Gospodarič and Habič (1966) recognized Lekinka as a young ponor cave where dissolution still takes place. This statement is based on (a) chemical analyses of water, which showed an increase of total solute load from the entrance toward inner parts of the cave, (b) on general geomorphic evolution of terraces before ponors and (c) on the "freshness" of features on the cave wall. On the other hand, Gospodarič and Habič (1966; 17) were surprised at the low increase in solute load along the water course – therefore they also state that present-day dissolution is relatively weak or "some unknown chemical processes take place in Lekinka, which causes the increase or decrease of solute load along the underground water course". They concluded that the initiation of Lekinka's first passages started during the interglacial period Riss-Würm and that the formation of three wall notches found in the entrance parts of Lekinka correspond to three young terraces in Lekinka's catchment area.

Hydrological characteristics

The catchment area of Črni Potok (1.05 km^2) extends mainly over the Pleistocene accumulation terrace of Nanoščica (and Pivka; Fig. 3.2.1) between 510.5 m (the altitude of the ponor) and 546 m. The highest, though a much smaller portion, of the catchment area (~27 %) lies on the slope of an erosion terrace composed of deeply weathered flysch rocks. The very low mean inclination of the catchment area (~1°) hinders runoff and especially in marshy areas the outflow of brownish water rich in humic acids is common. As a result of low inclination, soils in the catchment area are mainly brown eutric epigleys and hypogleys (Šporar et al.). Soil contains some cations (mainly Ca^{2+}) due to weathered siliciclastic flysch rocks with a higher portion of calcite cement but at some places basic cations were already washed out and more acidic soil can be expected. As a result runoff is poor in dissolved calcite and rich with humic acids. SEC measurements show that values are mostly between 150 and 200 μS/cm. At high discharge, SEC can even be below 100 μS/cm, while at low discharge it can rise above 400 μS/cm.

The discharge of Črni Potok at the sink was calculated using a water gauge 75 m from the entrance (measurement location L-1 in Fig. 3.2.4) and the stage-discharge curve set by several discharge measurements using the salt dilution method. Mean discharge is estimated at 40 l/s. At very low water levels, less than 10 l/s is drained from the catchment area and at such a level all the water disappears into the swallow holes at the flysch-limestone contact 50 m from the cave's entrance. During such an occurrence, water flow in the entrance part of the cave is absent but further into the cave some water is contributed by tributaries. Discharge of more than 1 m^3/s occurs about once per year. At such and even much higher water levels, Lekinka's passages are big enough to conduct all the water without a significant rise in the water level. In Lekinka cave, the water level significantly rises due to backflooding from the side of the high Pivka River in Otoška Jama. In the latter, oscillations of more than 10 m higher than the usual water levels (~505 m) are common during a year and can flood the water gauging station at measurement location L-1 (~509.5 m). At even higher water levels, when the Pivka with the Nanoščica are flooding in front of Postojnska Jama at an elevation of more than 518-519 m, the waters of Nanoščica overflow its banks above Lekinka's catchment area and cause extensive floods in front of Lekinka. At the same time, the outflow of Črni Potok is blocked by the underground Pivka River. Such a situation happened on 12 December 2008 (Fig. 3.2.2).

During its 1,032 m long underground course through Lekinka, Črni Potok descends from

Figure 3.2.2. *Flood in front of Lekinka (the ponor is located at the bottom left of the photo about 6 m under the water level), when the Nanoščica River rose over its banks on 12 December 2008 (photo: Mitja Prelovšek).*

510.5 m to 505.5 m (Gospodarič & Habič 1966). Accordingly, the gradient amounts to 0.48 %, which is less than the underground Pivka River from the ponor to the first sump in Postojnska Jama (0.54 %) and the underground Pivka River in Planinska Jama (0.58 %; Hribar & Michler 1959). Although the water flows perpendicular to Senonian strata, the general deviation from the shortest connection with Otoška Jama is quite low (27° toward the south, this is upstream to the underground Pivka River in Otoška Jama; Fig. 3.2.1). This means that the underground Črni Potok is taking nearly the shortest direction to the confluence with the underground Pivka River and that the water flow through Lekinka was always directed to Otoška Jama. On a smaller scale, deviations from a direct connection to the underground Pivka River up to 160° are possible.

In Otoška Jama, Črni Potok flows into the underground Pivka River. The confluence was first recognized by Michler & Hribar (1959) when they measured water temperatures along the underground Pivka River. The caves were never connected due to small and branching passages, which present a problem for cave divers but not a significant hydrological barrier for the underground flow of Črni Potok.

In Lekinka cave, the main water course of Črni Potok is fed by several underground tributaries (Fig. 3.2.3). At medium water levels, seven significant tributaries can be visible because of their location above the water level. The exact location of one underwater tributary downstream from Stranski Podor (side breakdown) was never defined but was detected from SEC, temperature and pH measurements. Accordingly, eight tributaries were identified along the 790 m underground water course of Črni Potok. On the basis of high SEC (266-487 µS/cm) at low-middle discharge and relatively constant temperatures of tributary water (7.8-11.4 °C) we suppose that this is mostly autogenic water as a result of primary infiltration in the vicinity of the cave. At medium water levels (HL-1 ≈ 5 cm), the highest portion is contributed by the fifth tributary (28 % of the water that sinks at the ponor or <18 % of the entire water flow at Končni Sifon during low-middle discharge). The whole of the contribution of tributaries at Končni Sifon is estimated to be at least 40 %. At higher water levels, the situation was never observed due to flooding. At low water levels, the contribution of tributaries can be up to 100 % since Črni Potok sinks 50 m before Lekinka cave and was not detected in the cave at these lower levels.

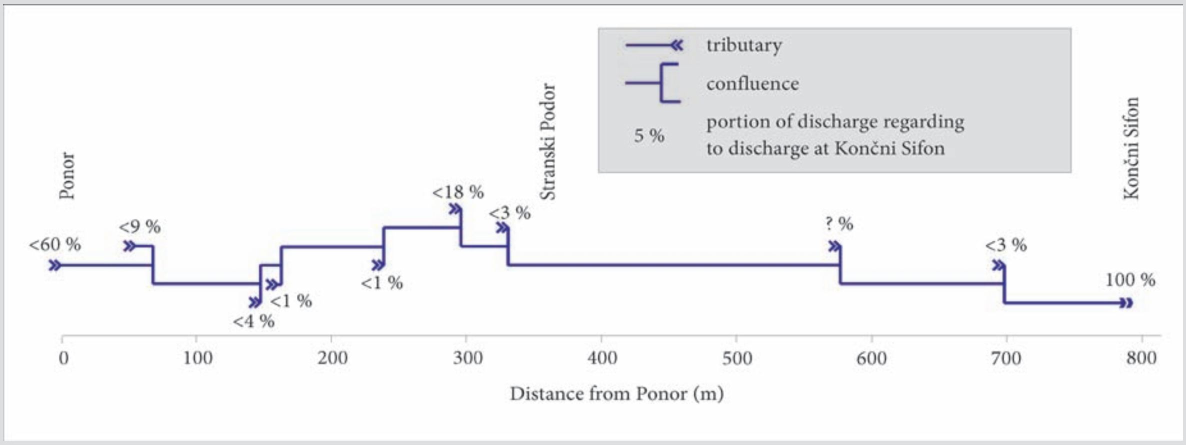


Figure 3.2.3. *Hydrological network of the Lekinka cave regarding visual observations, SEC, temperature and pH measurements at medium water level (HL-1 ≈ 5 cm) on 13 February 2008.*

Meteorological characteristics

At the ponor of Črni Potok are two entrances, which are connected through a short sump; about 3 m above the lower entrance, the higher dry one is located, which is flooded only when the Nanoščica and Pivka Rivers are exceptionally high.

Since the whole trunk passage of Lekinka is very well ventilated, especially in summer and winter months, a second entrance or connection with the ventilated Otoška Jama is obvious. Regarding higher cave air CO_2 concentration during summer, most probable is a connection with Otoška Jama as was already proposed by Gospodarič & Habič (1966).

Air flow can be felt throughout the cave. The intensity and direction depends on the difference between outside air temperature and air temperature in the cave (~8 °C). Nonetheless, water flow can cool down or warm up the cave by several degrees and therefore slightly influence the direction and intensity of ventilation. When the outside temperature exceeds the cave temperature, air flows from the passage close to Končni Sifon toward Ponor. When the temperature difference is reversed, air flows in the opposite direction. If the temperature is lower than 0 °C, freezing of the entrance part is common and mechanical weathering can be observed.

3.2.1 Measurement location L-1 – temporal variability of dissolution rates 75 m from the ponor

Since Lekinka cave is a typical stream cave with a catchment area in an accumulation terrace and exhibits low solute load at the entrance, we should expect relatively high dissolution rates – at least in the entrance part of the cave. High dissolution rates in a similar environment were confirmed in other karst areas (Droppa after Gams 1985; 368) and were anticipated in Lekinka by Gospodarič & Habič (1966). However, mean dissolution rates calculated from water hardness were surprising – the dissolution rates seemed to be lower than expected (Gospodarič & Habič 1966). Contrary to their findings, we measured by far the highest dissolution rates in the Dinaric Karst (Chapter 2.2.2). The most probable reason for the low dissolution rates measured by Gospodarič and Habič (1966) was the low discharge during which the cave was accessed and the water analysed. To confirm this idea and to acquire deeper insight into seasonal variations in dissolution rates, precise short-term measurements with limestone tablets was begun in the autumn of 2006. Short-term measurements had been proposed by Trudgill (1977; 256 after Gunn 1986; 382), who has written that "further work is needed in order to evaluate whether reliable measurements over shorter time scales are possible". He advised the use of a micrometer or limestone tablets.

Measurements of temporal variation in dissolution rates began on 25 September 2006 and finished on 5 April 2009. Measurement location L-1 was located 75 m downstream from Ponor and about 7 m downstream from the first left tributary (Fig. 3.2.5). The water flow was always turbulent with mean water velocities about 0.5 m/s. At very low water levels (H_{L-1} = -5 cm), water flow was absent. To obtain insight into the vertical variety of dissolution rates, 11 limestone tablets were exposed on a vertical water gauge. In this chapter we use only the average value of the lower two limestone tablets at H_{L-1} = -7.5 cm and H_{L-1} = -2.5 cm, since they were both under the water level during low-medium water levels. Limestone tablets were fixed on inox screws, nuts and felted washers and weighed in 15-day intervals on the same days as in Križna Jama (Chapter 3.1). Since Črni Potok transports a small quantity of bed and suspended load, corrasion was expected, especially on the lowest two limestone tablets during higher water levels.

Results from measurement location L-1 are presented in Fig. 3.2.6. As expected, the course of dissolution rates follows the course of the rain-snow discharge regime, which is typical for the central part of Slovenia. High dissolution rates were detected usually at higher discharge characteristic of autumn and spring. Low discharges are characteristic especially for summer months with less precipitation and high evapotranspiration. Dissolution rates during winter depend on snow retention that can be characteristic for at least two 15-day periods (winters 2007/2008 and 2008/2009) or absent during a warm winter (2006/2007; compare with sinter deposition rates in Chapter 3.1 in Fig. 3.1.11). Since a decrease of dissolution rates is of minor importance in winter, one maximum and one minimum in dissolution rates can be recognized from a best-fit polynomial trend line. The strongest dissolution rate amounts to -9 µm/15 days and is not related to the highest water level, while during very low water levels very low (sinter) deposition rates can be expected (0.2 µm/15 days). Even during low water levels ($H_{L-1} \approx 0$ cm), when discharge amounts to

Figure 3.2.4. *Measurement location L-1, used also as water gauge. The photo was taken at a very low water level (H_{L-1} = -5 cm) when only the lowest limestone tablet was under the water (photo: Mitja Prelovšek).*

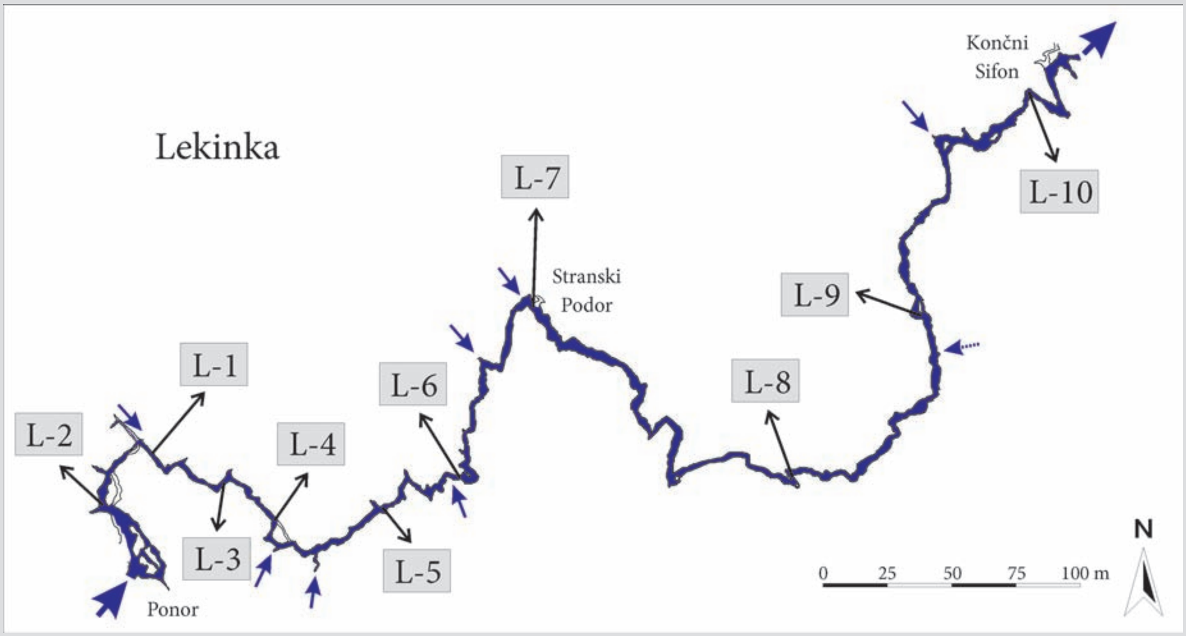


Figure 3.2.5. *Plan of Lekinka cave with measurement locations.*

~7 l/s, slight dissolution rates between 0.0 and -0.7 μm/15 days can be expected. At mean discharge (40 l/s; H_{L-1} = 5 cm), the average dissolution rates amount to -1.4 μm/15 days.

Results obtained at the two lowest limestone tablets at L-1 provide us important information about changeable annual dissolution rates (Fig. 3.2.6), which can be represented as a sequence of 12-month moving averages. According to a 12-month moving annual total, the minimum annual dissolution rate of -35.6 μm/a and maximum annual dissolution rate of -78.1 μm/a was obtained. The difference between these two values demonstrates a strong dependency of annual dissolution rates on precipitation during the year. Nevertheless, the average annual dissolution rate of -61.1 μm/a is at least a relatively good approximation of the magnitude of annual dissolution rates.

Since the dissolution rate during 15 days of exposure depends on two factors, namely (a) aggressiveness of water and (b) time of exposure to different degrees of aggressiveness of water during flood pulse, the highest dissolution rates are expected during intensive precipitation (the proxy for this can be maximum water level) and during long exposure to stream water (the proxy for this can be total amount of precipitation during 15-day periods). Fig. 3.2.6 demonstrates that high water levels are not at all responsible for the highest dissolution rates. As a result, the Pearson product moment correlation factor between dissolution rates and maximum height of water is low -0.37, especially due to the highest recorded water level during the measurement period (H_{L-1} = 730 cm), the result of an exceptional overflow of the Nanoščica. Without this event, the correlation is much better (-0.56; Fig. 3.2.7) but still lower due to several flush floods. The limiting factor for such events is the exposure of limestone tablets to stream water. Consequently, the highest dissolution rates were detected at medium water levels (from $H_{L-1} \approx 20$ cm to $H_{L-1} \approx 50$ cm). This is confirmed by a significantly higher Pearson product moment

Figure 3.2.6. *Average dissolution rates at the lowest two limestone tablets and their 12-month moving average between 25 September 2006 and 5 April 2009 at measurement location L-1.*

correlation factor between dissolution rates and total amount of precipitation (-0.74; Fig. 3.2.7), which, partly beside intensive precipitation, includes also medium but long-lasting water levels. In this case, summer months were excluded from calculation since evapotranspiration significantly reduces runoff. High positive correlation between dissolution rates and discharges (as a function of effective precipitation) was also confirmed by other researchers (Drew 1974 after Gunn 1986; 385, Gunn 1981b after Gunn 1986; 385).

Equations from Fig. 3.2.7 can also be used for the evaluation of a seasonal effect if predicted and actual rates are compared (Fig. 3.2.8). Besides seasonality as a result of the rain-snow discharge regime, other types of seasonality can be expected. Since the soil's CO_2 concentration and respiration in the water channel are strongly related to microbial activity, which is due to higher temperatures in summer, higher soil and water CO_2 concentrations (Atkinson 1977 after Gunn 1986; 373, Spötl et al. 2005; 2458) and higher aggressiveness of water can be expected during summer months. Some authors (e.g. Sweeting 1972; 219 and 226) attest to quite the contrary – aggressiveness of water should be higher in winter due to lower temperatures of water, which enhances higher solubility of CO_2. Some researchers (e.g. Bray 1977) pay special attention to the decay of organic matter, which can, with decomposition of organic matter to CO_2 and organic acids, form complexes with Ca^{2+} ions (the latter reduces the activity of Ca^{2+} ions and therefore influences equilibrium; Roques 1969; 144) and consequently enhance dissolution rates. According to Butturini & Sabater (2000), the highest dissolved organic carbon, which can be a proxy for the concentration of humic acids, are observed during flood events and in autumn and winter months. The longer the exposure to aggressive water, the higher the dissolution rates are expected to be within 15 days. Our results (Fig. 3.2.8) demonstrate that seasonality, which is not the result of the rain-snow discharge regime, is not a causal factor. Predicted low dissolution rates are stronger than actual ones but this is due to the overestimation of dissolution rates using calculated equations (Fig. 3.2.7) and appears all through the year. More intensive actual than predicted dissolution rates are characteristic for autumn and spring months, which can be attributed to underestimated dissolution rates when the latter are stronger. Lack of seasonality also neglects the influence of water temperature, which was predicted by Corbel[2] (1959 after White 1986; 261), Moore[3] (1964 after White

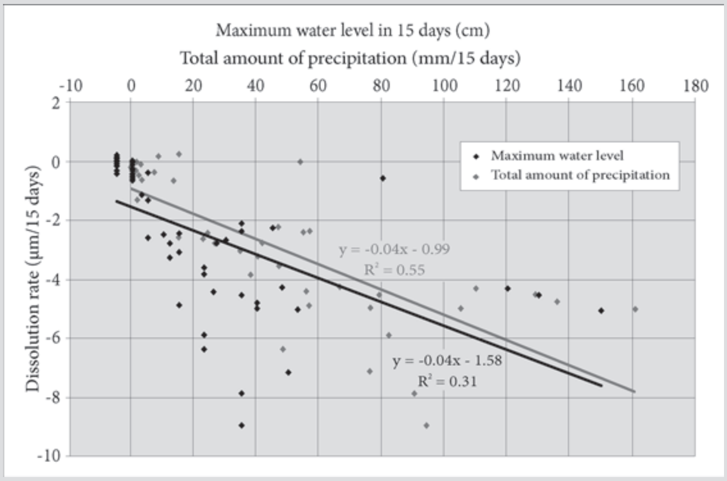


Figure 3.2.7. *Correlation between dissolution rate and (a) maximum height of water during 15 days and (b) total amount of precipitation during 15 days (source of data: Slovene Environmental Agency). An exceptionally high water level (H_{L-1} = 730 cm) is omitted from both calculations due to the specific character of the event (overflow of the Nanoščica) and data for summer months in case of correlation between dissolution rates and total amount of precipitation.*

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[2] *Higher aggressiveness is expected in winter due to higher solubility of CO_2 in cold water.*

[3] *Higher aggressiveness is expected in summer since the biological production of CO_2 is the highest in warm months.*

1986; 261) and observed by Gams (1966b; 13) on bare rock surfaces or in superficial streams (1966b; 35-37; in the latter case, differences in hardness along the watercourse are extremely slight and can therefore be attributed to errors). This does not mean that these factors do not influence dissolution rates but that their seasonality is not expressed or is of limited significance.

Caves develop under a variety of processes, among which dissolution and corrasion are usually highlighted. Delineation between them was often a challenge for geomorphologists and a source of many discussions. The generally accepted belief is that corrasion plays a minor role at "normal" water levels but can be a strong speleogenetic factor at high water levels. During floods both accelerate but corrasion can exceed dissolution (Newson 1971). Nevertheless, a strict distinction between them is not possible, since dissolution of limestone is usually incomplete and the remnants of dissolution (i.e. big crystals) are often torn away by the force of flowing water

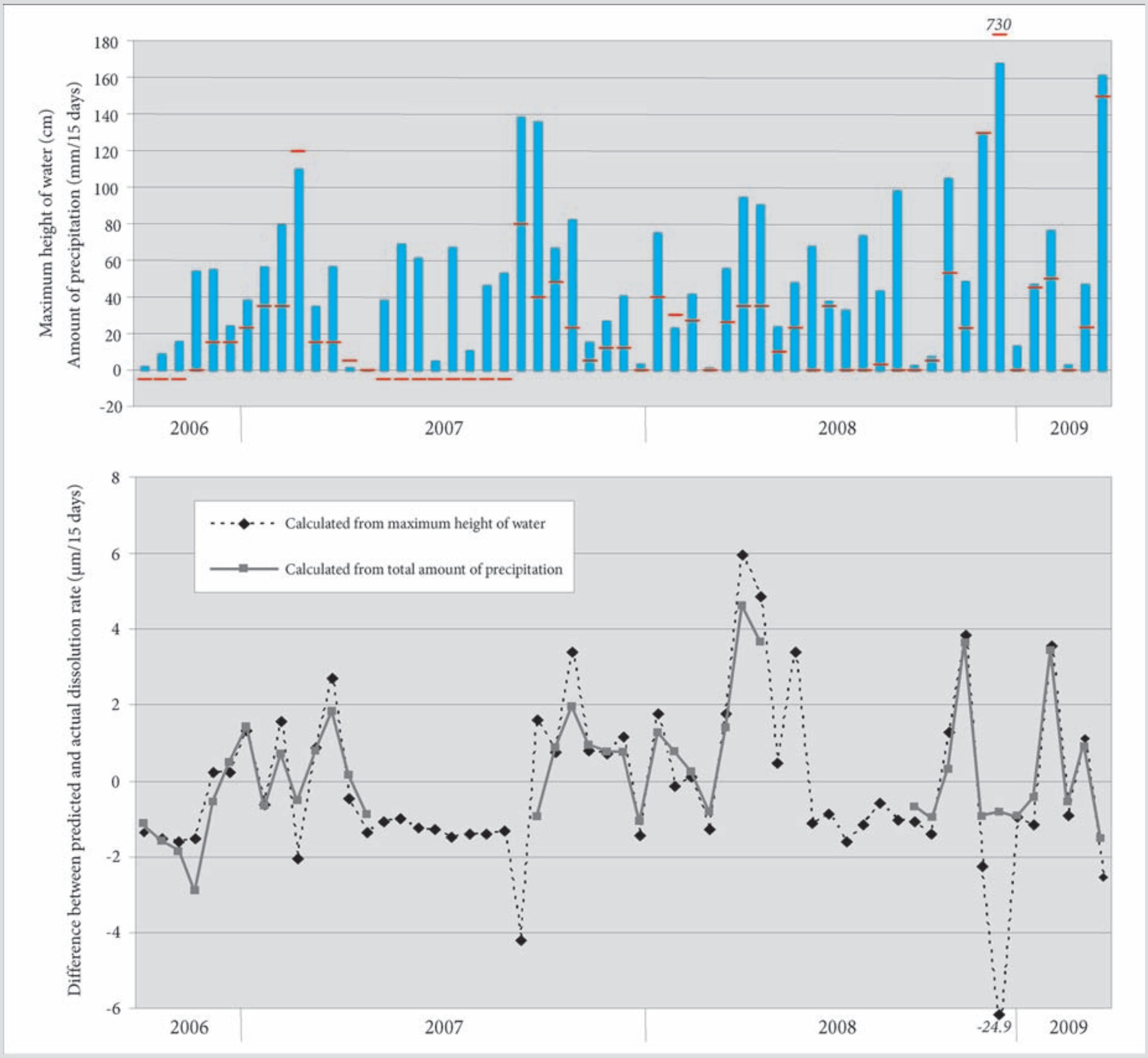


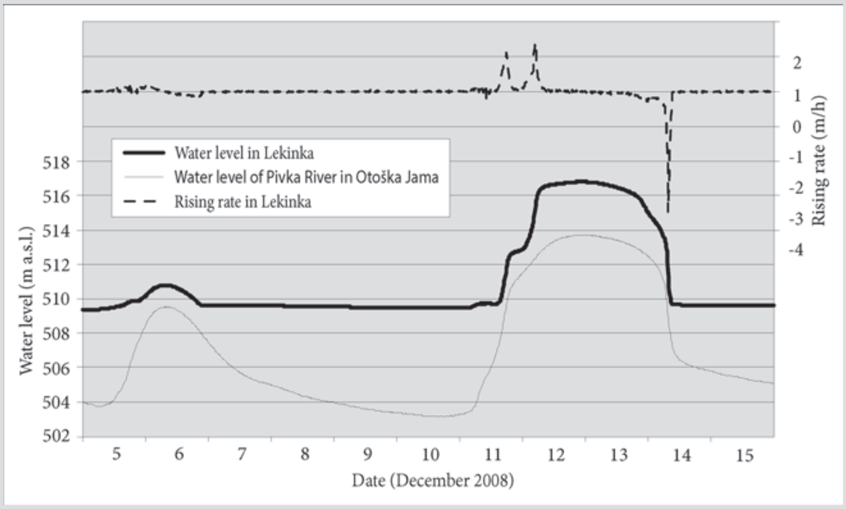
Figure 3.2.8. *Difference between predicted and actual dissolution rates with regard to the comparison between maximum height of water and total amount of precipitation. After 1 June 2008, data for amount of precipitation are not available.*

(Zupan Hajna 2003) with or without bed load or suspended load. In the case of Lekinka cave, high water transports a small amount of siliciclastic bed load but a lot of suspended load. The biggest and the most abrasive sediment moves close to the bottom of the channel but this is not reflected in stronger rates at the lowest limestone tablet – a tablet that is situated at H_{L-1} = -7.5 cm has almost the same dissolution rate (-63.2 μm/a) as one at H_{L-1} = -2.5 cm (-63.9 μm/a). This is contradictory to the expectations of Habič (1966; 18), who assumed high mechanical abrasion along the channel's bottom. Since we observed incomplete dissolution on the tablet's surface where partly dissolved crystals should be torn away more easily by bed load and suspended sediment, corrasion surely takes place but it is not increased at the lowest parts of the water channel. The only hint of corrasion can be a slight decline in rates at L-1, when the water level exceeds $H_{L-1} \approx 50$ cm (see Fig. 3.2.14 in Chapter 3.2.3), but this can also be a result of a thicker boundary layer that affects rates during backflooding and the consequential lowered flow velocity of Črni Potok in Lekinka cave.

If we assume average dissolution rates (-61.1 μm/a) for the last 12,000 years, about 73 cm of dissolution can be expected (dissolution rates in Senonian limestone from Lekinka are almost the same – see Fig. 2.8 in Chapter 2.2.3) and an actual 4 m high meander at L-1 could be developed in approximately 65,000 years. This is twice as fast as suggested by Habič and Gospodarič (1966), who state that the development of Lekinka began during the Würm-Riss Interglacial (114,000-130,000 years BP). In the case of lower amounts of precipitation during the Würmian Ice Age, the age of Lekinka cave defined by different methodologies can be similar.

High dissolution rates in Lekinka (will) have some regional effect on hydrology and geomorphology. In comparison with Postojnska Jama (Chapter 3.4), Lekinka has a lower entrance (510.5 m vs. 511.5 m). Continuous widening and lowering of Lekinka's entrance passages due to high dissolution rates and consecutive downcutting of Črni Potok will result in increasing incidence of overflow of the Nanoščica's water into the catchment area of Črni Potok. In December 2008, we were lucky to observe such - nowadays occasional - overflow (Fig. 3.2.9). From previous flood in Otoška Jama on 5 and 6 December 2008 it is evident that the underground waters of the Pivka River in Otoška Jama due to backflooding influences the water level of Črni Potok at the entrance to Lekinka when water levels exceed 508 m a.s.l. in Otoška Jama. On 11 December 2008 at the same water level, the rise of the water level started very quickly (1.2 m/h) but later remained almost stable. After 4 hours, another even faster rise in the water

Figure 3.2.9. *Water level of Črni Potok in Lekinka and of the Pivka River in Otoška Jama and rising rate in Lekinka cave. During the first flood between 5 and 6 December 2008, the Nanoščica River did not overflow its banks into Lekinka cave but during the second one (between 11 and 14 December 2008) it did.*



level occurred – this event is related to the overflow of the Nanoščica River into the Črni Potok catchment area over a 518-519 m high water divide. The highest water level was reached 30 hours after the first rise at $H_{L-1} \approx 730$ cm, when the Nanoščica reached its maximum. At that time, outflow through Lekinka was limited due to the high water level of the Pivka in Otoška Jama, but when the water level in Otoška Jama declined, the decrease of the water level in Lekinka was very rapid (more than 2.5 m/h), which confirms the good hydraulic permeability of Lekinka. Although the water level was higher than $H_{L-1} = 30$ cm for 69 hours, this exceptional hydrological event did not have any important speleological consequences. In Lekinka, we noticed some minor transport of bed load and medium high dissolution rates (-6.1 μm/15 days), a result of dissolution before or after the intrusion of the Nanoščica River. The Nanoščica River is responsible for only minor dissolution rates in the Postojna cave system (~-0.1 μm; third measurement period, Fig. 3.4.4 in Chapter 3.4). In the case of a permanent redirection of the Nanoščica River into Lekinka cave, which is possible in the future due to the gradual lowering of Lekinka's entrance and its high hydraulic permeability, dissolution rates in Lekinka will be much weaker; practically all remnants of the old catchment area will be lost and therefore important evidence of speleogenesis of Lekinka will no longer be observable. We suppose that at least some passages of Postojnska Jama were formed in a similar way with higher dissolution rates due to changes of catchment areas – at least at the time when the waters of the Nanoščica and Pivka sank into the Risovec blind valley (Fig. 3.2.1).

3.2.2 Measurement location L-1 – vertical variability of dissolution rates

At measurement location L-1, water fluctuation was observed from $H_{L-1} = -5$ cm to $H_{L-1} \approx 730$ cm. Dissolution rates should decrease with height – to what extent we tried to determine with a vertical set of limestone tablets located at measurement location L-1. We also tried to find out whether the actual cross-sectional morphology of passages corresponds to the vertical distribution of present-day dissolution rates.

Vertical variability of dissolution rates was measured with 11 limestone tablets on the water gauge 75 m from the sink (Fig. 3.2.5). In the lower section, the distance between limestone tablets was set to 5 cm, while in the upper section the distance was greater. The procedure and duration of measurement was the same as was described in Chapter 3.2.1.

The results of measurements at L-1 are presented in Fig. 3.2.10. Dissolution at $H_{L-1} = -7.5$ cm and $H_{L-1} = -2.5$ cm are nearly equal. Slightly stronger dissolution rates at $H_{L-1} = -2.5$ cm in comparison with $H_{L-1} = -7.5$ cm may be a result of very low sinter deposition rates when the water level remains below $H_{L-1} = -5$ cm (Fig 3.2.6). Above this level, water is always aggressive. Above $H_{L-1} = 0$ cm, a steep decline of dissolution rates was observed, which can be very effectively ($R^2 = 0.99$) described using a power function. An upward decrease of dissolution rates is a result of exposure time, although the aggressiveness of water most probably increases with the water level. At $H_{L-1} = 7.5$ cm, dissolution drops to half of that recorded at $H_{L-1} < 0$ cm. At $H_{L-1} = 25$ cm, exposure time is so short that only 10 % of dissolution is observed in comparison with $H_{L-1} < 0$ cm. At $H_{L-1} = 120$ cm, dissolution drops to less than 1 % (Tab. 3.2.1).

The upward decrease of dissolution presented in Fig. 3.2.10 and Tab. 3.2.1 is a sum of dissolution measured over 15 days. Fig. 3.2.11 provides better insight into vertical distribution of dissolution regarding maximum water level. For better illustration, 49 individual measurements are classified and averaged in four classes regarding maximum water levels during 15-day measurement periods. The third zone of maximum water level turned out to be the most frequent (and therefore the most representative) over 15 day periods. In general, the lowest the maximum water level results in the highest vertical decrease of dissolution. During such a hydrological regime the most evident wall notch could be formed. The most gradual transition of a wall notch into the vertical wall could be expected with a high oscillation of water levels due to flush floods. It is interesting that dissolution below H_{L-1} = 5 cm is the highest in the third class and not in the fourth, which is a result of lower dissolution rates at the lowest limestone tablets when the water levels exceed H_{L-1} = 50 cm. Decrease of dissolution rates is possible through slower water flow which decreases corrasion rates and the rate of tearing away partly dissolved crystals or/and reduces dissolution rates through a thickening of a diffusion boundary layer.

A strong decrease of dissolution with height (Fig. 3.2.10) has an important speleogenetic consequence – the upper part of a passage suffers almost no dissolutional transformation while the lower part widens and incises. The ratio between widening and incising depends on the morphology of a passage and fluvial transport of bed load material. The latter protects the bed of a passage against dissolution or at least severely reduces incision of a passage, while the widening of the passage continues in both lateral directions. Long term continuation of such a process would result in vast lateral extension in the lower part of a passage that even enhances further sedimentation of bed load material due

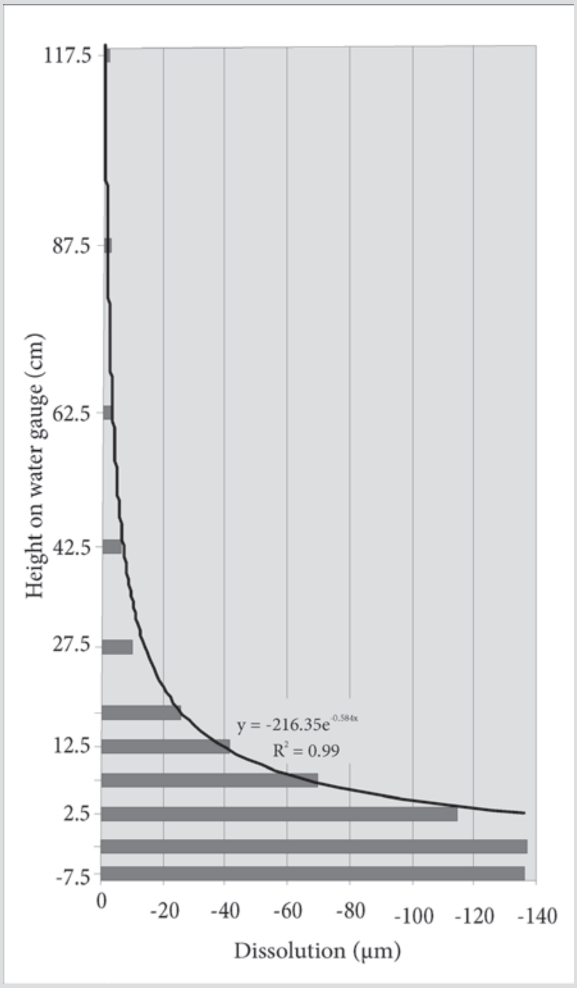


Figure 3.2.10. *Decrease of dissolution with height measured at L-1 from 14 November 2006 to 8 January 2009 (786 days).*

Table 3.2.1. *Portion of dissolution at different height at measurement location L-1 in comparison with the lowest two limestone tablets at L-1 between 14 November 2006 and 8 January 2009.*

Height of limestone tablet (cm)	-7.5	-2.5	2.5	7.5	12.5	17.5	27.5	42.5	62.5	87.5	117.5
Portion of dissolution with the lowest 2 limestone tablets at L-1 (%)	100.0		83.6	50.9	30.2	18.5	7.2	4.2	2.1	1.7	0.9

to decreased depth/width ratio (Skinner et al. 2004; 365). Since such morphology is absent in Lekinka cave, long-term accumulation of bed load material has not been characteristic for Lekinka as a result of (a) limited availability of such material, (b) high dissolution rates and (c) fast water flow that distributes bed load over an extensive surface that is then more susceptible to dissolution.

Vast lateral extension of the lower part of a passage could also be possible without accumulated bed load if the lower walls are perpendicular to the water level. In such a case, water widens the passage twice as quickly as it incises (since the widening takes place in two directions and incision only in one). In reality, walls and beds of channels are not truly perpendicular to each other as they are transitional. For uniform incision of a vadose meander, an equilibrated shape of the lower part of the meander has to be established (Fig. 3.2.12). The radius of curvature between vertical walls and the bed of a channel depends strongly on (a) vertical variability of dissolution rates and (b) fluctuation of water levels – the smallest radius (this means a steep transition from bottom to wall) is expected if vertical variability of dissolution rates is high and oscillation of discharge is low. Due to strong dissolution rates even at lower and medium water levels and quite weak rates at high water levels, quite a sharp transition between vertical walls and the bed of a channel is expected in Lekinka if the present-day processes are equilibrated with cross-sectional morphology. Although it is difficult to observe clear examples of vadose meanders in Lekinka, in the case of Fig. 3.2.12, the transition between the bed of the channel and the vertical walls is quite sharp, which proves that the majority of dissolution occurs during low and middle water levels, which is in agreement with expectations.

At measurement location L-1 (Fig. 3.2.4), the walls are perpendicular to the bed of the channel since the latter is covered by bed load material. Such conditions favour the formation of wall notches. Actual wall notch morphology more

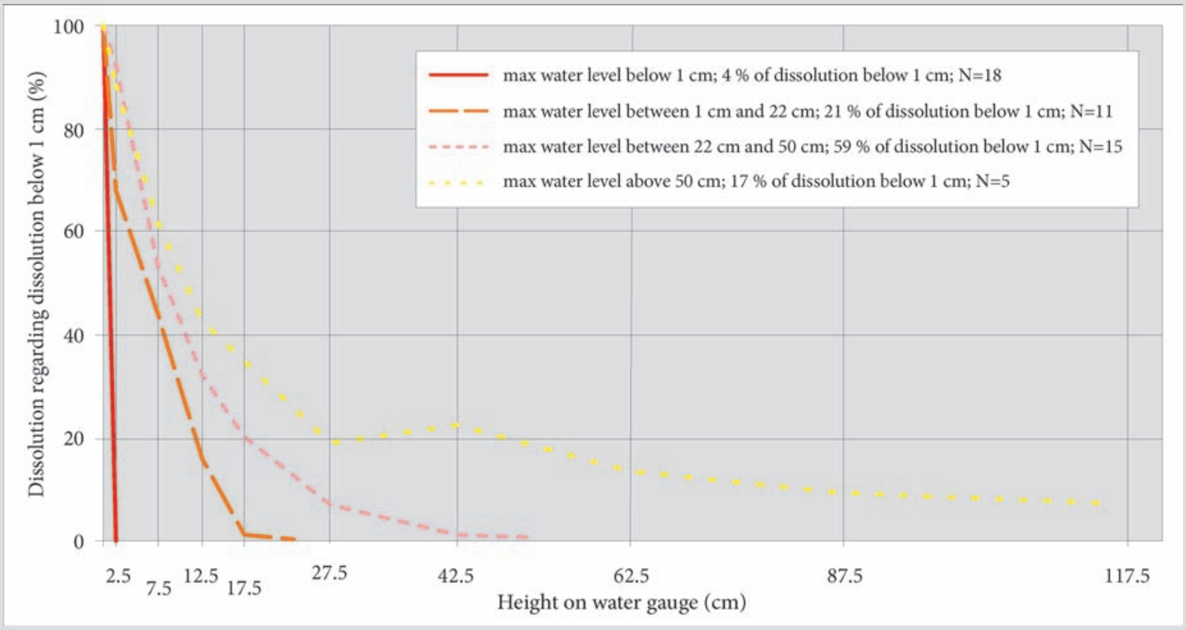


Figure 3.2.11. *Comparison between average dissolution at individual height and dissolution* H_{L-1} *< 1 cm with regard to four different zones of maximum water level. Data represented in this figure were obtained at measurement location L-1 from 14 November 2006 to 8 January 2009.*

or less corresponds to the vertical decrease of dissolution presented in Fig. 3.2.10. Generally, the wall notch extends about 14 cm into each lateral direction, which would correspond to about 2,300 years of dissolution at annual dissolution rates -61.1 μm/a.

Above H_{L-1} = 75 cm, a fossil wall notch can be recognized (Fig. 3.2.4). According to Gospodarič and Habič (1966), this wall notch could correspond to the lowest accumulation terrace of Črni Potok. Two higher wall notches, which are mildly developed at L-1 but can be observed several tens of metres downstream, should correspond to two even higher accumulation terraces in the Črni Potok catchment area (Gospodarič & Habič 1966; 27). According to Gospodarič and Habič, the development of wall notches corresponds to increased production and accumulation of bed load material inside and outside the cave, which could have been climatically driven during the last (Würmian) Ice Age. According to our measurements, dissolutional development of a wall notch caused by bed load accumulation is possible since the accumulation holds up incision but does not inhibit the lateral extension of passages. Decreased supply of bed load material is followed by a gradual complete removal of bed load material and the subsequent incision forming a new vadose meander, whose width corresponds to the most effective width of channel regarding discharge and dissolution during higher water levels. According to the present-day dissolution rate (-61.1 μm/a), the end of fossil wall notch development and the beginning of incision would date to 12,300 years B.P., which corresponds to the Younger Dryas stadial.

Figure 3.2.12. *Typical meander cross-section about 300 m from Lekinka's entrance, where the cross-sectional area reflects uniform incision of a meander without significant widening. Wall notches are the result of past events (photo: Mitja Prelovšek).*

3.2.3 Measurement locations L-2, L-1, L-3, L-4, L-5, and L-6 – longitudinal variability of dissolution in the entrance part of Lekinka (along a 250 m long watercourse)

A decrease in dissolution rates from the entrance to the inner part of a cave can be expected in all kinds of ponor caves where the water is very aggressive at the entrance. A similar case on the surface of contact karst was studied by Droppa in the valley of Demänova (Gams 1985; 368), where the dissolution rates in the middle of a limestone valley fall to 14 % of dissolution rates detected at the first contact with limestone. Downstream, where the river leaves the limestone valley, dissolution rates were only slightly lower (12 % of dissolution rates detected at the first contact with limestone). In general, the decline in dissolution rates is related to the increasing saturation of water along its flow over the karstifiable rocks. Bray (1972, 1977) asserts that downstream decrease of dissolution rates in ponor caves can be reduced due to gradual decay of organic matter that increases the concentration of H^+ in the water. The same phenomena can be expected in Lekinka cave. Through longitudinal dissolution measurements, we tried to quantify the level of decreasing dissolution rates at different discharges, to determine the most relevant factors that control dissolution, and to link present-day speleogenetic processes with actual cave morphology.

The longitudinal variability of karst processes was studied at six locations. The procedure and interval of measurement was the same as at L-1 (Chapter 4.2.1). The first measurement location (L-2) was located 40 m from the entrance, the second (the lowest limestone tablet at L-1) 75 m, L-3 115 m, L-4 145 m, L-5 205 m and L-6 250 m. Measurement locations L-2, L-1, L-3, and L-5 were characterized by fast flowing supercritical turbulent flow with velocities of about 0.5 m/s during middle discharge. Measurement location L-4 was located in a 1.6 m wide and 0.4 m deep water channel. Therefore, at L-4 water flow was subcritical and at least 10-times slower in comparison with the other locations. During the time of very low discharge, the limestone tablets were mostly under the water level. At very high discharge the limestone tablets were under slow flowing water since the Pivka River in Otoška Jama caused backflooding in Lekinka. Measurements at L-2, L-1, L-3, L-4 and L-5 started on 15 April 2007 and finished on 5 April 2009.

Spatial measurements of physicochemical properties of water (SEC; T and pH) were done using a WTW Multiline P4 in different hydrological conditions.

The highest dissolution rates most probably take place 30 m before the entrance to Lekinka, where Črni Potok interacts with the first limestone blocks in the water channel. Further dissolution rates are presented in Fig. 3.2.13. Dissolution rates become weaker between the first (L-2) and last (L-6) measurement locations, which is as expected. Although we would expect that weakening of dissolution rates is due to the dissolution of limestone, further study (Covington et al. in press) suggests that the outgassing of CO_2 from the water is responsible for weakening of dissolution rates. The greatest deviation is noticed at L-4 due to slowly flowing water, which reduces the R^2 of the best fit exponential correlation from 0.99 to 0.97. Nevertheless, the difference is relatively slight (10 % between expected and actual dissolution). According to Fig. 3.2.14, the highest deviation between L-4 and all others measurement locations appears at middle water levels (between $H_{L-1} \approx 22$ cm and $H_{L-1} \approx 50$ cm), when differences in flow velocity and the effective dissolution are the highest. At lower water levels, dissolution is absent downstream of L-1, while at higher water levels, flow velocities are similar at all measurement locations due to backflooding. Lower rates are the result of a thicker diffusion boundary layer (Liu & Dreybrodt 1997), lower corrasion rates or/and the reduced mechanical force of flowing water that tears away partly dissolved calcite crystals.

The decrease of dissolution from L-2 to L-6 can easily be described with a logarithmic equation, which fits the real data quite well ($R^2 = 0.97$; Fig. 3.2.13). This means that the weakening of dissolution is the greatest near the contact (by 37 % per 100 m of water course between L-2 and L-3), while further from the contact, the drop of dissolution rates is much lower (by 27 % per 100 m of water course between L-3 and L-6). In spite of this, the drop of dissolution rates during the first 250 m of underground flow is very high (54 %). Regarding the equation in Fig. 3.2.13, at the end of Lekinka (after 790 m of water flow) dissolution of about -18 μm is expected during the measurement period, which is only 12 % of the dissolution rate measured close to the entrance (L-2).

The decrease of dissolution rates presented in Fig. 3.2.13 is not constant but fluctuates significantly during different discharges (Fig. 3.2.14). At very low water levels ($H_{L-1} < 0$ cm), water is already saturated before Črni Potok enters Lekinka. During such low water levels, dissolution between L-2 and L-6 is not increased even due to the decay of organic matter or higher CO_2 concentrations (up to 1,440 ppm) during the summer months. At measurement locations L-2 and L-1, the first dissolution rates were detected when the water level exceeded $H_{L-1} = 0$ cm ($Q \approx 7$ l/s). During such water levels, differences in dissolution rates between L-2 and L-1 on one side and all other measurement locations on the other are the greatest, since dissolution is absent downstream of L-1 (Fig. 3.2.14; groups of averaged values correspond to zones already defined in Chapter 3.2.2). Downstream of L-2 and L-1, dissolution appears at slightly higher discharge, when the water level exceeds $H_{L-1} \approx 10$ cm. If the maximum water level exceeds $H_{L-1} \approx 10$ cm but remains below $H_{L-1} = 22$ cm, dissolution at L-6 amounts to 32 % of the dissolution measured at L-2. A further rise of the maximum water level leads to higher absolute but lower relative differences between measurement locations, but

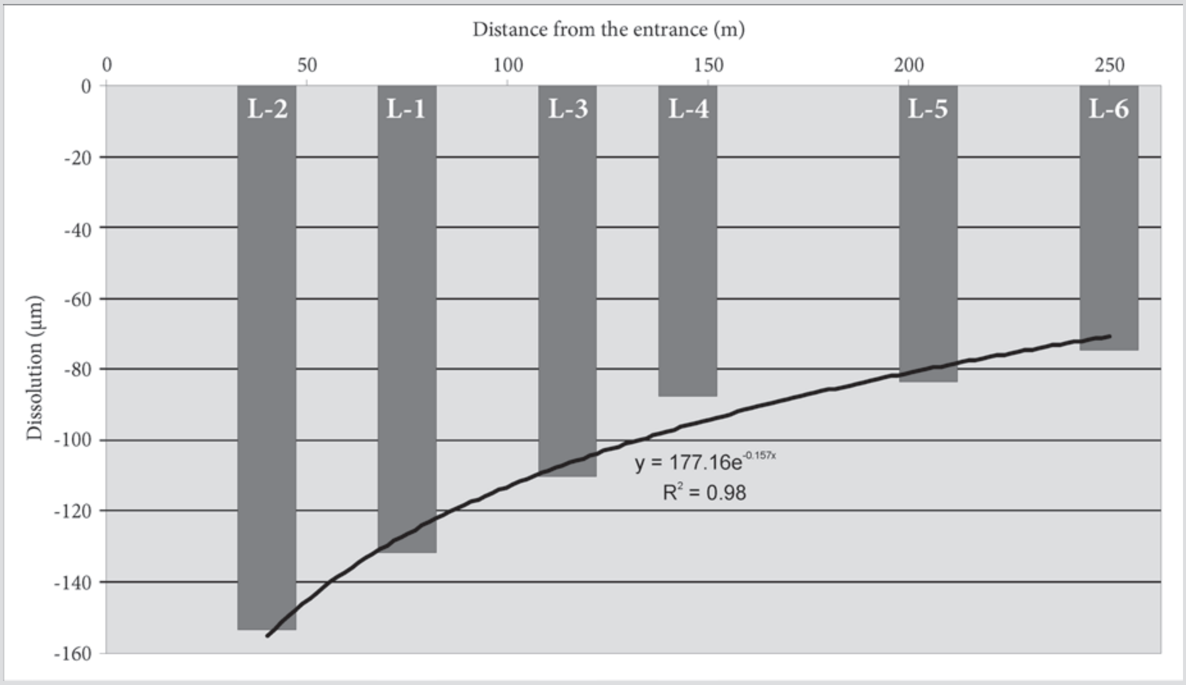


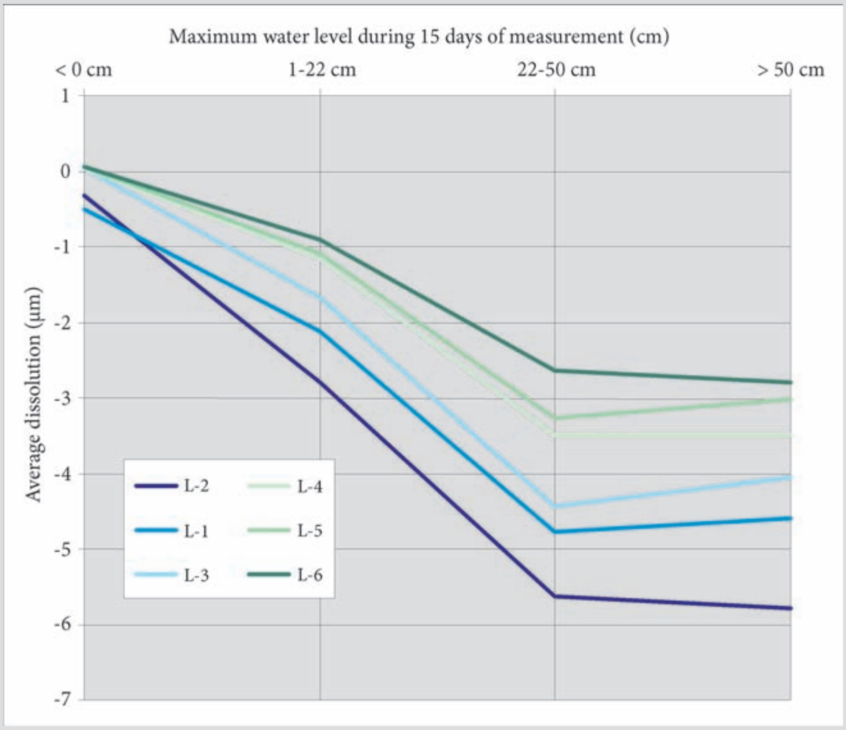
Figure 3.2.13. *The results of 15-day dissolution measurement intervals at L-2, L-1, L-3, L-4, L-5, and L-6 from 5 April 2007 to 5 April 2009.*

only to H_{L-1} = 50 cm, when absolute differences remain the same even at higher water levels due to backflooding. Lower dissolution rates due to decreased velocity of flow were also confirmed with measurements at L-4 (Fig. 3.2.13).

Gospodarič and Habič (1966) measured the total hardness of Črni Potok between Ponor and Končni Sifon. They attributed the growth in total hardness to dissolution, but dissolution is not the only process that increases the total hardness of water along a cave stream. From the entrance to 250 m into Lekinka, four tributaries fed by autogenic percolation water join the main water course. They have high SECs and very stable temperatures during the year. Since the outgassing of CO_2 can be observed along their accessible water passages, tributary waters should flow through the karst massif with higher CO_2 partial pressure in comparison with a well ventilated main passage. The first right tributary deposits sinter due to the rapid outgassing of CO_2 and consequential rise of SIC. Although the rise of SEC as a proxy for total hardness was always observed between tributaries (although the water level was low), which indicates dissolution, tributaries are much more responsible for total hardness increase (Fig. 3.2.15). Their contribution to total hardness increases with increased discharge of the main water course due to the high quantity of water and high flow velocity of the cave stream that reduces the reaction of water with limestone. During such high discharge, the rise of SEC over the first 250 m of the cave amounts to up to 3 µS/cm (12 %), while the rise of SEC contributed by tributaries amounts to about 23 µS/cm (88 %). During low discharge, changes in total hardness along the cave stream are much greater due to more effective reaction of water with limestone walls. During low discharge, dissolution is responsible for a 26 µS/cm (26 %) rise of SEC, while the tributaries contribute up to 74 µS/cm (74 %).

Downstream the decrease of dissolution rates influences morphology differently in meanders and in passages characterized by deeper water in pools. The width of pools should decrease

Figure 3.2.14. *Average dissolution within each of four classes of maximum water level at measurement locations between Ponor (L-2) and the first pool 250 m from Ponor (L-6). Data are calculated from measurements that began on 15 April 2007 and ended on 5 April 2009.*



downstream along 250 m from the entrance passages. At the places where vadose meanders are developed, the width of the meander depends only on discharge and generally speaking not on differences in dissolution rates. Consequently, downstream decreases of rates results only in the decrease of the longitudinal gradient due to more intensive dissolution rates close to the entrance. Due to stronger dissolution rates, the meanders should be higher close to the entrance. Since the dissolution rates are lower in pools and higher in meanders, a gradual transition from pools to meanders should be characteristic if the water level does not inhibit the incision of the meanders. The latter transition should result in an increase of pools from the Ponor to the Končni Sifon. All this is in agreement with present-day morphology (Gospodarič & Habič 1966) since the height of passages generally decreases from the Ponor to the Končni Sifon and the portion of passages developed as meanders decreases from the entrance. Nevertheless, the width of pools increases downstream, which is contradictory to the downstream decrease of dissolution rates but in agreement with the longer exposure time of pools downstream, enhanced by backflooding from the underground Pivka River.

Gospodarič and Habič (1966; 14-15) were the first to notice three wall notches that gradually disappear about 300 m from the entrance. According to them, wall notches disappear due to sumps, which were located about 300 m from the entrance and hindered high-middle discharge, and should be formed at the times of high discharge. However, this explanation is controversial if we know that backflooding more commonly creates the phreatic enlargement of passages and not wall notches. According to our observations in Lekinka cave, wall notches develop if (a) water is aggressive at low and middle discharge, (b) water oscillations are low and (c) water transports bed load material which protects the bed of a channel against dissolution. Since we have no evidence that the conditions were much different in the past, the formation of fossil wall notches can be attributed to the same factors.

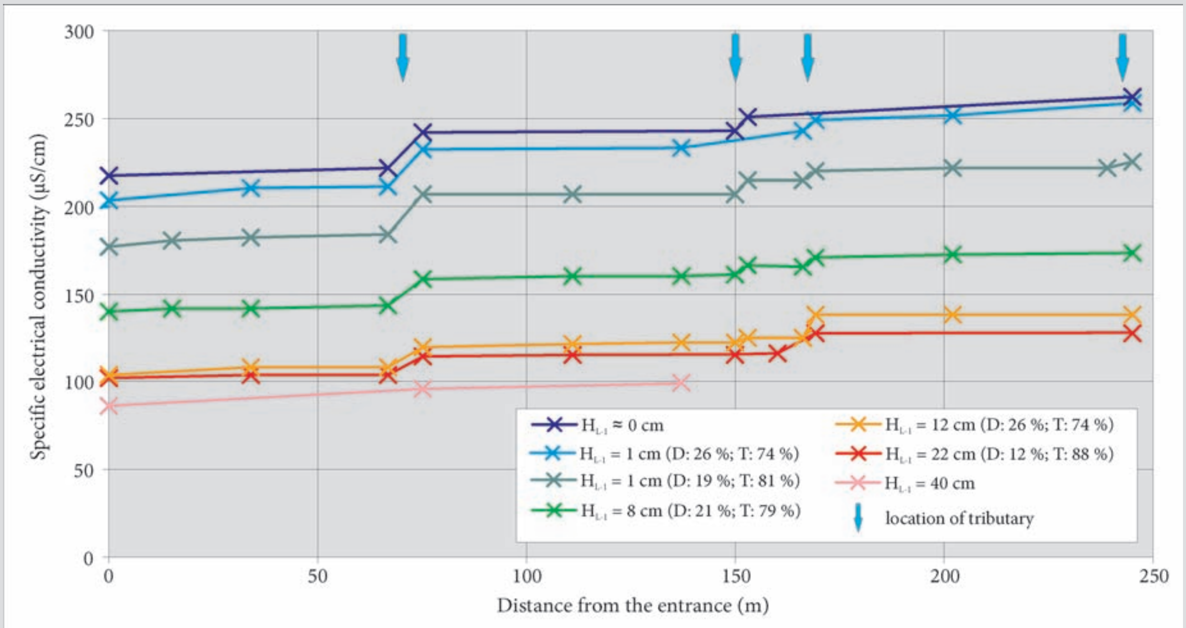


Figure 3.2.15. *Growth of SEC due to dissolution (D) and due to four tributaries (T) characterized by high total hardness.*

3.2.4 Measurement locations L-2, L-1, L-3, L-5, L-6, L-7, L-8, L-9, and L-10 – longitudinal variability of dissolution rates all along the underground water course in Lekinka (from the entrance to the sump)

In Chapter 3.2.3, measurements were made only along the first 250 m of Lekinka cave. Further into the cave, several deep and long pools make access more complicated and measurements more difficult to take. Therefore, much longer intervals were chosen for dissolution measurements along the complete cave stream to the Končni Sifon (790 m).

Dissolution measurements at L-7, L-8, L-9, and L-10 began on 13 February 2008 and finished on 17 April 2009. Between these dates, limestone tablets were replaced once on 5 September 2008. The procedure of weighing and fixing was the same as at L-1 (Chapter 3.2.1); only the exposure time and number of exposed limestone tablets at each measurement location (3 vs. 1) were different. Measurement location L-7 was located 340 m from the entrance, L-8 510 m, L-9 630 m and L-10 750 m. Limestone tablets were placed in similar hydrodynamic conditions, at least during low-middle discharge (supercritical turbulent water flow). For comparison we took into account results from measurement locations L-2, L-1, L-3, L-5, and L-6, which are the sums of data from 15-day measurement intervals.

The results of the measurements are presented in Fig. 3.2.16. Between L-2 and L-10, dissolution rates weaken by 55 %. This is much lower than expected (88 %) with extrapolation of dissolution rates from the first 250 m of the cave (Fig. 3.2.13). Results demonstrate that dissolution rates remain more or less constant downstream from L-6 since the outgassing of CO_2 from the water decreases due to a very low longitudinal gradient downstream from L-6 and deeper and longer pools. Between L-2 and L-10, the decrease of dissolution rates is higher during the first measurement period (by 64 %) in comparison with the second measurement period (by 49 %; Tab. 3.2.2). This is a result of much higher discharge during the second measurement period, which can also be observed from higher dissolution rates in the entrance part of Lekinka (Tab. 3.2.2).

Although dissolution decreases more or less constantly between L-2 and L-10, some results show other poorly examined factors that can increase or decrease dissolution rates along an allogenic cave stream. The greatest differences were produced during the second measurement period, when discharge were the highest (Tab. 3.2.2). During high discharge, the most distant limestone tablets are the most

Table 3.2.2. *Dissolution rates in Lekinka measured out from the Ponor to the Končni Sifon from 13 February 2008 to 17 April 2009.*

	L-2	L-1	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10
First measurement period (µm/a; % of dissolution at L-2)	-72.9	-76.9	-65.5	-45.4	-50.7	-39.9	-40.7	-30.1	-29.5	-26.4
	100	106	90	62	69	53	56	41	40	36
Second measurement period (µm/a; % of dissolution at L-2)	-85.3	-77.7	-58.4	-51.5	-43.0	-40.2	-54.2	-56.8	-40.8	-43.2
	100	91	69	60	50	47	64	67	48	51

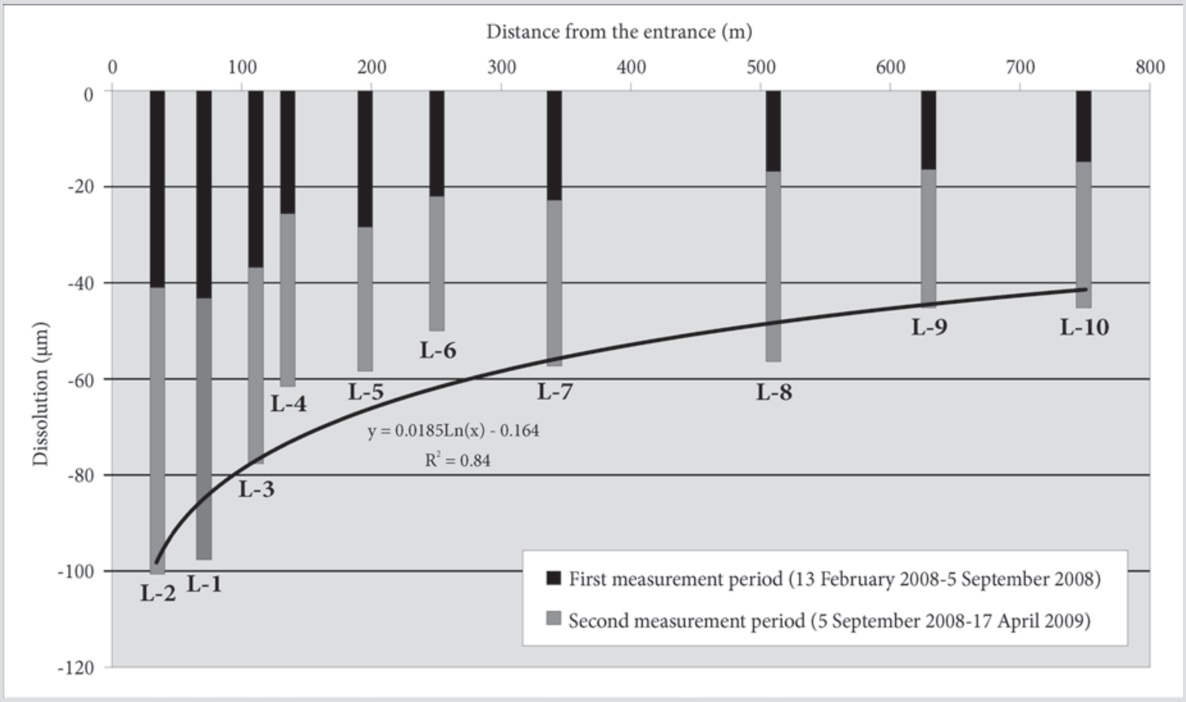


Figure 3.2.16. *Decrease of dissolution between Ponor and Končni Sifon. Dissolution at L-2, L-1, L-3, L-4, L-5, and L-6 is the sum of 15 day dissolution measurement intervals.*

influenced by aggressive water. Additionally, hydrodynamic and hydrochemical differences between measurement locations are the lowest during high water levels. This is demonstrated by the dissolution rates at L-4 during the second measurement period when we were not able to observe the influence of usually slowly flowing water on lower dissolution rates due to a thicker diffusion boundary layer that is responsible for slower diffusion of H^+ ions to the limestone surface (Dreybrodt 1988; 113). On the contrary, it seems that that poorly understood factor is responsible for the increase of dissolution rates at L-7 and L-8 rather than the decrease of rates at L-6, L-9, and L-10.

In Lekinka, the aggressiveness of water supports the enlargement of the underground passages all along the water course at high rates (-77.4 µm/a at L-2 and -35.7 µm/a at L-10). The direction of passage enlargement depends on the morphology of present-day passages – in phreatic ones, dissolution takes place in lateral and downward directions, while in vadose meanders, by far the highest downward incision is characteristic. Therefore, phreatic passages should be wider but lower in comparison with meander-type passages, which is consistent with the actual morphology of Lekinka. Due to a sometimes higher reaction surface, the cross-section of phreatic passages far from the entrance is often larger than the cross-section of meander-type passages close to the entrance, although dissolution rates are much higher at the entrance. The direction of enlargement of downstream passages in Lekinka also depends on the height of the Pivka River in Otoška Jama – if the latter is high, dissolution can also take place on the ceiling.

Downstream decrease of dissolution rates and backflooding from the Pivka River result in the important morphological transition from the Ponor to the Končni Sifon. Meanders are typical for passages close to the entrance. The longest (~350 m with very short phreatic passages) and the tallest meander developed in the entrance zone, while the downstream part of Lekinka is mostly formed in several metres wide phreatic passages. At many places, vertical incision downward from the initially phreatic passage can be observed (Fig. 3.2.17), which is a result of the adaptation of the longitudinal profile to the level of the Pivka River. Such transitions are common in caves which were initially formed in phreatic conditions and followed by aggressive water flow in vadose conditions (Häuselmann 2002; 98, Häuselmann 2007) but can be absent if the passage is fully flooded only occasionally in epiphreatic conditions (Palmer 2002). A consequence of backflooding is also a reduction of flow velocity through Lekinka cave, which is reflected in quite rare and over 5 cm long scallops found close to the Končni Sifon while the scallops in the entrance meanders are several centimetres shorter.

Figure 3.2.17. *Incision of vadose meander on the bottom of an initially phreatic passage (photo: Mitja Prelovšek).*

3.2.5 Conclusion

Lekinka cave drains a marshy catchment area about 1 km^2 wide with low inclination and low carbonate content in soils. Therefore the water of Črni Potok that flows into Lekinka is highly undersaturated with respect to Ca^{2+}, which results in high dissolution rates at the entrance and further toward the Končni Sifon. On average, dissolution rates at the entrance amount to -61.1 µm/a. 750 m from the ponor, dissolution rates still amount to -38.2 µm/a. If such rates are characteristic for longer periods, rapid enlargement of Lekinka cave can be dated to the lower Würmian glaciation.

The rate of dissolution mainly depends on discharge, which is a function of the amount of precipitation, evapotranspiration and snow retention. Therefore, the highest dissolution rates were observed during autumn, spring and winter months, while the lowest are characteristic for summer months. This corresponds to the rain-snow discharge regime with the highest peaks in autumn and spring and in winter-spring, when the snow is melting. During very low discharge ($Q<7$ l/s), water is at equilibrium and dissolution rates are absent. During low discharge ($Q\approx7$ l/s), dissolution can be detected with limestone tablets successfully about 100 m from the ponor. Further into the cave, dissolution rates can be detected during higher discharge and can amount to up to -9 µm/15 days. The highest dissolution rates are not characteristic for the highest discharge but rather for long-lasting middle-high discharge. Seasonal variation as a result of fluctuation of air and water temperature, CO_2 production or content of organic acids, was not recognized. Corrasion seems to be relatively low although high turbidity of water can be observed at high-middle discharge. Lower rates are expected in pools, where slow water flow thickens the diffusion boundary layer and decreases the diffusion rate of H^+.

Dissolution is concentrated in the lower parts in the cross-sectional profile. The upward decrease of dissolution is rapid (50 cm above low water level, only 3 % of dissolution measured in the bed of the channel was detected), which indicates relatively constant discharge with occasional flush floods and the most expressed dissolution during low-middle water levels. Therefore an upper part of the passage remains dissolutionally almost unchanged, while the lower part incises downward or laterally. The prevailing direction of enlargement depends on the present-day passage cross-section and supply of bed load material. The latter reduces downward incision and supports lateral extension of the passage and hence the formation of wall notches. The formation of wall notches could not be possible in the case of very high and frequent water fluctuation or an absence of aggressiveness during low-middle discharge. A wall notch that is developing in present-day conditions started to form about 2,300 years B.P. and the higher one can be dated to the Younger Dryas stadial. By far downward incision is the most characteristic for meander-type passages, which are mainly vertical in their upper part but rounded close to the bed of the channel. At middle water levels, when the dissolution is the most expressed, walls form with water levels at an angle slightly higher than 90°. Only such a shape supports vertical incision of passages. In pools, dissolution rates are slightly lower in comparison with meanders but dissolution does takes place in a downward and lateral direction.

Downstream, dissolution rates decrease. In the first 250 m of underground water flow, the decrease of dissolution rates can be described with an exponential function most probably due to the outgassing of CO_2 from the water (Covington et al. in press). Downstream from 250 m to the confluence with the Pivka River, dissolution rates are nearly constant. Although at least eight tributaries with high total hardness and high partial pressure of CO_2 were detected along the cave stream, they are not strong enough to turn dissolution into sinter deposition.

Downward incision in the downstream part of Lekinka is influenced by the Pivka River in Otoška Jama. The Pivka River causes backflooding in Lekinka and therefore hinders the process of prevailing downward incision, especially near Končni Sifon. Therefore, phreatic cross-sectional morphology is more common in the downstream part of Lekinka. Deeper incision is possible and can be observed especially in the entrance part, which influences the longitudinal profile. Ongoing incision will result in retrograde lowering of the water divide with the Nanoščica River, which can use Lekinka cave as a permanent shortcut to Otoška Jama due to its lower entrance in comparison with Postojnska Jama. If capture does occur, dissolution rates will be significantly reduced in Lekinka. (Over)saturated water at low and middle discharge and slightly aggressive water at high water levels will enhance passage enlargement at phreatic conditions and obstruct wall notch formation.

3.3 ŠKOCJANSKE JAME

Škocjanske Jame (Škocjan caves; Reg. No. 735) together with the morphological phenomena of the underground Reka River presents the greatest natural curiosity of the whole Classical Karst between the Gulf of Trieste and Vipava Valley. Together with the blind valley of Vreme and Divaški Kras (Divača karst) along the narrow ponor border of the Reka River they comprise part of a typical morphogenetical unit of contact karst, unique in Europe regarding its phenomena and dimensions (Gams 1983). Due to its extreme dimensions and unique karst landscape with an early and rich history of explorations, Škocjanske Jame were listed among UNESCO natural and cultural heritage of the world in 1986. Škocjanske Jame are known also because of the existence of one of the largest underground chambers in the world (Martelova Dvorana - Martel's chamber), which is 308 m long, up to 123 m wide and up to 146 m high. The volume of this chamber, through which the Reka River flows, is estimated to be 2,100,000 m3 (Mihevc 2001; 79).

The first real exploration of the entrance area along the underground water course began in the 1st half of the 19th century, when 500 m of cave was examined (Habič et al. 1989, 4). Further research was much more difficult, since the water flows in a narrow passage with steep walls and over several waterfalls. Nevertheless, new exploration which was started in 1884 by Deutscher und Österreichischer Alpenverein (German and Austrian Alpine Club) from Trieste ended in 1890 at the terminal sump. The latter was successfully dived in 1991 and in recent years, but a connection at least 900 m long with Kačna Jama downstream is still under exploration.

In Škocjanske Jame, scientific research started as early as in the second half of the 19th century (for details see Habič et al. 1989; 7), but serious and extensive speleological research within the cave itself began in the 1980s. The geological structure, long-term speleogenesis and first datings were done by Gospodarič (1983, 1984). He developed a 4-phase model of development of Škocjanske Jame from the primary horizontal passages to the final Würmian vadose incision of Hankejev Kanal (Hanke's channel). Development of the latter is likely related to a colder climate given the huge production of gravel, while the warmer periods likely correspond to the more gentle development of Škocjanske Jame with its accumulation of sinter (Gospodarič 1983, Gospodarič 1984). Transport of sediment through Škocjanske Jame was studied by Kranjc (1986). In the 1980s, Kogovšek (1984) took under consideration vertical percolation of water in Škocjanske Jame, which dissolves carbonates in the epikarstic zone and deposits them in some passages in Škocjanske Jame. Later, the lithological structure with emphasis on initial development of the channel along bedding planes was investigated by Knez (1996). The speleogenetic study of the whole system and the first measurements of its processes were made by Mihevc (2001), while Slabe (1992, 1995; 109) examined the micro-morphology of the water channel. Lastly, scientific research brought some new information on water oscillations and the physicochemical characteristics of underground water flow, which was carried out by monitoring flood pulses at many underground sites between Škocjanske Jame and Timava spring (Cuchi & Zinni 2002 after Gabrovšek & Peric 2006; 37, Gabrovšek & Peric 2006).

Geological and geomorphological characteristics

The Škocjanske Jame are located about 7.5 km NW from the contact between Eocene flysch rocks and older Cretaceous limestone. A whole stratigraphic sequence of Carboniferous rocks is located in a low tectonically deformed monocline, which is inclined at 20-35° toward the SSW (Gospodarič 1983; 165). Therefore, the youngest sediments (Eocene flysch rocks) are found in the SSW and the oldest (thick-bedded to non-bedded Turonian limestone) are found in the NNE (Gospodarič 1983, Knez 1996). Between them, very pure (the portion of $CaCO_3$ usually exceeds 99.5 %; Knez 1996) micrite bedded Senonian and thin-bedded Paleocene limestone are developed. All known passages of Škocjanske Jame are located within thick-bedded or non-bedded Senonian and Turonian strata, except Tiha Jama (silent cave; southwestern, today dry, passage of Škocjanske Jame), which developed in thin-bedded limestone. Thick-bedded carbonate rocks are nowhere highly tectonically damaged, which supports the development of long and high passages without significant collapses.

From a speleogenetic point of view, the most important geological structures for the formation of Škocjanske Jame are five tectonised bedding planes, where the initiation of the first phreatic passages took place (Knez 1996). Later, the development of Škocjanske Jame was characterized by the incision of a vadose meander in epiphreatic conditions. The most impressive incision is the 570 m long Hankejev Kanal (Hanke's channel), where the initiation of the first phreatic passage started in the upper bedding plane, denoted 300 (Knez 1996; 23-24). In continuation, the passage incised by about 90 m to the stratigraphically lower bedding planes (called 400 and 500, in Martelova Dvorana also 600, 700; Mihevc 2001; 60) and formed a deep meander with almost vertical walls. At the bottom, Hankejev Kanal is on average 10 m wide. The lack of significant lateral extension in the cross-sectional profile indicates regular incision without interruptions (Mihevc 2001; 83). Finally, the present-day keyhole passage was formed.

Underground active passages of Škocjanske Jame are rich in corrasional and dissolutional micro-features, which spatially alternate among each other. Corrasional features (potholes, polished surfaces, scratches) are related to the exceptionally high amount of transport of allochthonous material from the Reka River catchment area (Kranjc 1986). Corrasion rates were measured by Mihevc (2001; 65) with a MEM at 17 measurement locations. Over 6 years of measurements, the highest values were found at places where the pebbles are hitting the wall (from -160 to -40 μm/a) while much lower values were measured at places of polishing (about -20 μm/a). Dissolutional features (scallops) show that we can also expect some dissolution rates. Dissolutional and corrasional features are only developed in the lower 1-5 m high portion of the water channel. Higher, the wall is weathered by mechanical breakdown or condensation corrosion. Another very intensive process in the underground water channel is sinter deposition due to percolation water, which takes place even at the bottom of Hankejev Kanal (Slabe 1992; 198, Mihevc 2001; 74). The location of sinter formations suggests that sinter deposition is higher than dissolution – at some places even higher than corrasion.

The enlargement of passages in Škocjanske Jame is crucial for development of the superficial upstream catchment area and the downstream karst aquifer. The caves are the only points where an upstream water and sediment (about 242.4 Mm^3 of limestone and much more flysch rocks; Gams 1962; 267) can be drained through the aquifer. Škocjanske Jame act as a restriction for the lowering of longitudinal profile since the highest gradient is observed here. Where the Reka River flows over flysch rocks, the average gradient is 2.8 ‰. Between the lithological contact of flysch with limestone and ponor (the hydrological beginning of Škocjanske jame), along a 7.1 km water flow through the narrow gorge, the gradient is increased to 5 ‰

(Mihevc 1991). In Škocjanske Jame, the gradient increases to 45 ‰ (Habič et al. 1989; 12) while the continuation of underground flow continues with an average gradient of 6.3 ‰. Therefore, the critical point for water flow and also erosional base for the catchment area of the Reka River is in Škocjanske Jame, since all the water must be conducted through one passage. Downstream in the aquifer restrictions are more easily avoided since the water flow braids to several semi-parallel flow paths. The dissolutional character of the Reka River plays an important role in underground gradient, since it defines the speed and where the restrictions can be removed.

Hydrological characteristics

The free-surface underground course of the Reka River is 2.7 km long and usually 3-15 m wide at medium water levels (Kranjc 1986; 112). At average discharge, from 8.26 to 8.95 m^3/s (Uhan 2007, Mihevc 2001; 52) passes by the hydrological station 7.5 km upstream from the ponor to the Škocjanske Jame. About 1 m^3/s is lost in the water channel immediately downstream from the contact between flysch rocks and Paleocene limestone and some more water further downstream (Radinja 1967 after Mihevc 1991). This sub-parallel water course does not appear in Škocjanske Jame (Habič et al. 1989; 11). In Škocjanske Jame, no important tributaries or sinks were noticed at low and middle water levels (Mihevc 2001; 62).

In the case of strong precipitation, the rapid response of Reka discharge can be observed. The highest discharge was measured in 1972, when it reached 305 m^3/s (Uhan 2007), while the highest discharge with a recurrence period of 100 years is estimated to be 453 m^3/s (ZVSS 1978 after Mihevc 1991).

Allogenic recharge has strong control over the hydrological conditions and cave development. The most evident consequence is flooding, since the outer river channel supports high discharge amounts while the narrows in the cave function as restrictions at high water levels. Therefore, several tens of metre high floods in Martelova Dvorana usually occur every year. At the highest discharge (for example in 1826), water can rise 132 m above the medium water level in the final lake in Martelova Dvorana (Boegan 1938 after Habe 1966; 47) and flood the bottom of all passages except Tiha Jama.

Therefore, the characteristics of the catchment area are extremely important for geomorphic activity in Škocjanske Jame. According to several sources (Rojšek 1983; 52, Kranjc & Mihevc 1988 after Mihevc 2001; 52, Habič et al. 1989; 10, Uhan 2007), the catchment area of the Reka River extends from over 332 to 378 km^2. Karstified carbonate rocks (mainly Cretaceous limestone) cover about 28 % of the catchment area, especially in the SE part, from where the Reka River receives some important springs at the contact with flysch rocks. The latter extend over 60-74 % of the catchment area, mainly at the Brkini Mountains (Kranjc 1986; 112, Habič et al. 1989; 10, Kranjc & Mihevc 1988 after Mihevc 1991). For the superficial drainage system, which is developed on this fluvio-denudational relief, fast runoff with short and high peaks in discharge is characteristic. This has important consequences regarding the discharge duration curve, which (with a very concave form) shows great differences in discharge with a relatively small percentage of medium discharge. The torrential character of the Reka River can also be seen from a comparison of the lowest (0.16 m^3/s; Uhan 2007) and the highest observed discharge (305 m3/s; Uhan 2007), since it amounts to 1: 1,906. Streams from the Brkini Mountains decrease total hardness of the Reka River downstream of the karst springs from Mt. Snežnik. Nonetheless, this decrease is not so important since the total hardness falls from 10.7 °NT to a still high 10.3 °NT between springs below Mt. Snežnik and flysch-limestone contact (Gams 1962; 278). Only a small amount of the catchment area (12 %; Kranjc 1986; 112) is covered with nonconsolidated alluvial sediments along the Reka River and its tributaries.

Another very important influence of the Reka River is the transport of suspended and bed load material. Since the Reka River valley has only one possible outlet through Škocjanske Jame, all the material that once filled the Reka River valley was washed away through the cave. In the current situation, on average 30,000 m^3 of material is transported every year through the Škocjanske Jame (Kranjc 1986). The majority of flysch material is transported as bed load (83 %; Kranjc 1986; 114) and the rest (17 %) as suspended load. Below the flysch-limestone lithological contact, the percentage of flysch pebbles strongly decreases (by 8.5 % per km of water course; Kranjc 1983 after Mihevc 1991). It is very significant that the percentage of flysch pebbles is not reduced just due to rounding, which would indicate corrasion, but rather due to crushing, which was confirmed by the almost longitudinally stagnant index of roundness (Kranjc 1986; 114). Although the crushing of pebbles is recognized as an important process that leads to the reduction of flysch pebbles downstream from lithological contact, the longitudinally stagnant index of roundness could not be possible without the rounding of freshly crushed pebbles. The transport of flysch material can be an intensive process for high corrasion rates if the crushing and rounding occurs at the contact with a limestone water channel. Since the superficial and underground water channel is mostly formed in solid limestone (Kranjc 1986; 112, Mihevc 2001), and only in some parts is the river bed covered with pebbles and breakdown material (for example, in Martelova Dvorana), the transport of flysch material definitely is an important process responsible for high corrasion rates, as already confirmed by Mihevc (2001; 65). Another important process is mechanical erosion and the transport of limestone blocks, since the percentage of limestone increases from 0 % at the lithological contact to 20 % at Škocjanske Jame (Kranjc 1986; 114).

Dissolution is a much lesser known process in the Reka River in comparison with corrasion. Regarding the high oscillation of discharge and catchment area in siliciclastic flysch rocks, expected dissolution rates may be high, especially at high discharge. Occasional spatial measurements of total hardness of the water in the Reka River gorge at middle water levels (Gams 1962, 1966b) does not prove this. Even at high discharge rates, dissolution seems to be low since Gams (1966b) detected relatively high total hardness (9.7 °N) and Mihevc (2001; 64) very low dissolution rates, as measured by MEM. The high total hardness of the Reka River is a result of karst springs that feed the main water course of the Reka River under Mt. Snežnik and a result of the dissolution of calcite cement between particles in flysch. Cement comprises from 20 to 24 % of the flysch rock. Nevertheless, the cement in the catchment area can also be siliceous (Šikić & Pleničar 1975; 22); therefore high differences can be expected in total hardness among tributaries from the Brkini Mountains.

Meteorological characteristics

Due to its two natural big entrances, all passages of Škocjanske Jame (except Tiha Jama) are very well ventilated. Especially during summer and winter, when temperature differences inside and outside are the highest, strong air currents can be felt all along the water channel. In winter, cold air enters the cave through the lower entrance and if the outer temperatures remain below 0 °C for several days, which is common due to temperature inversion in the collapse dolines, freezing along the underground Reka River is common all along the Martelovo Jezero (Martel's lake). Warmer air exits the cave under the roof. During summer, air flows in the opposite direction. Since the outer air cools down near the cave's roof, relative humidity approaches 100 % and condensation appears. For this reason, dripping from the roof and walls is abundant in Hankejev Kanal (Mihevc 2001; 63).

In Tiha Jama, annual temperature differences are very low due to weak ventilation. Air temperature fluctuates between 11 and 12.5 °C (Kogovšek 1983 after Habič et al. 1989; 13).

3.3.1 Measurement place S-1 and S-2 – temporal variability of processes at Swidovo Razgledišče

The first measurements of dissolution in Škocjanske jame were made by Mihevc (2001; 64). Although MEM measurements were made after several years of exposure, results showed dissolution rates in the range of the measurement error (-10 µm/a). To observe dissolution even in shorter intervals, measurements using limestone tablets seem to be the only possible way. The only problem is the vast quantity of bed load material that is transported through Škocjanske Jame during each flood and its destructive influence on the limestone tablets. This was recognized already by Gams (1996; 103), who failed in making measurements with limestone tablets in Škocjanske Jame.

Our first observation was done during a test study in a relatively remote (non-corrasional) place in Hankejev Kanal (Chapter 2.2.2). Results confirmed low intensity of dissolution (-1.6 µm/a) but during that period discharge was quite low and without any significant flash flooding, when higher dissolution is expected. Therefore we continued with measurements at the same location, here named S-1 and S-2.

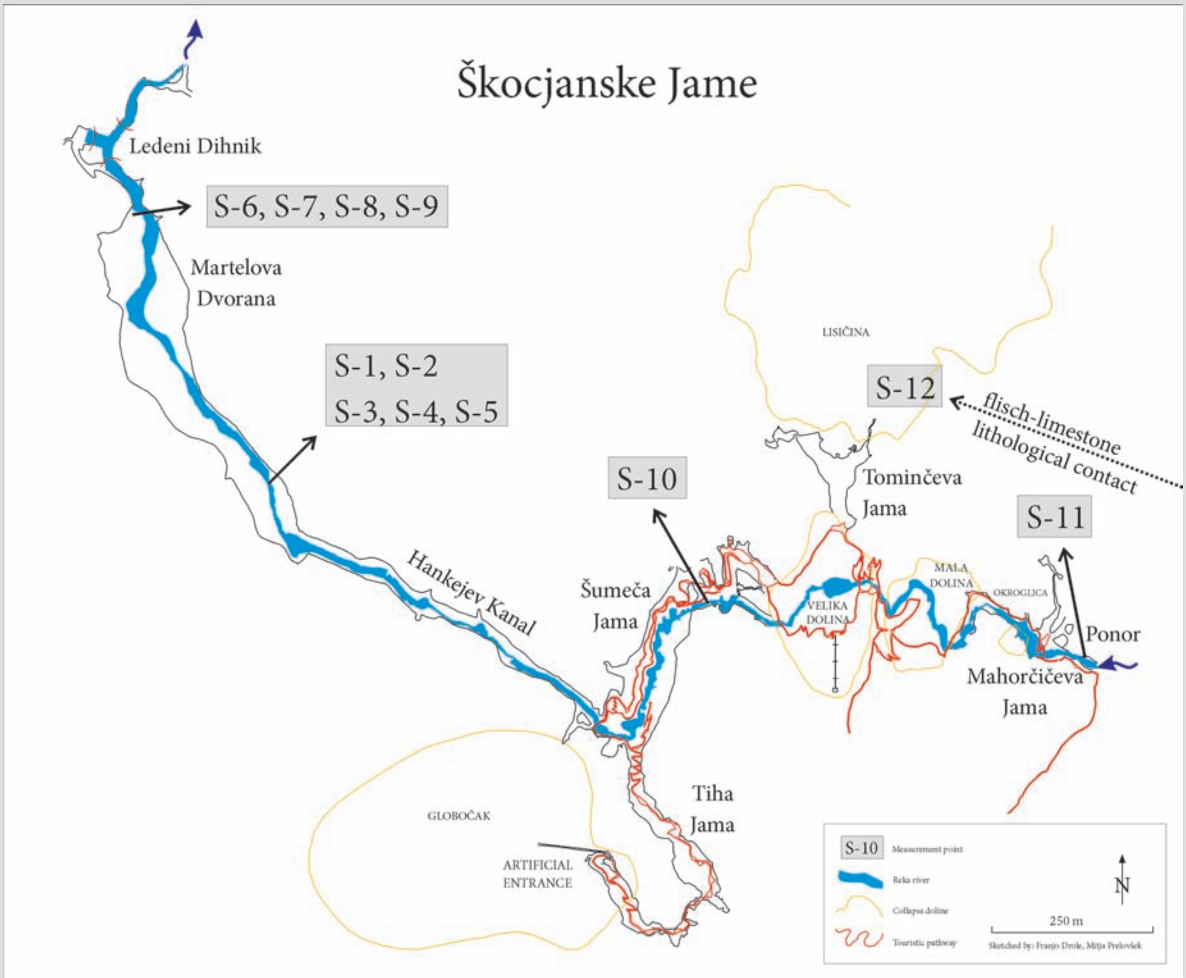


Figure 3.3.1. *Position of measurement places from S-1 to S-12 in Škocjanske Jame and on Reka River upward from the caves (source of plan: Archive at IZRK ZRC SAZU).*

Measurement places S-1 and S-2 were located in the centre of an underground water channel at Swidovo Razgledišče (Swida's viewpoint) at the downstream end of Hankejev Kanal (Fig. 3.3.1). Only 1.5 m away, a moderate sum of corrasion and dissolution rates (-20 μm/a) was measured with a MEM by Mihevc (2001; 65). Since the limestone tablets were placed in the middle of the water channel where the velocity of water flow exceeds even 5 m/s and water transports a lot of bed load and suspended material, a microlocation of measurements was chosen with great caution to minimize the influence of mechanical erosion. Measurement points S-1 and S-2 were always under the water when the discharge of the Reka River exceeded 3 m³/s (on average 58 % of exposure). At each measurement place, one limestone tablet was fixed with iron screws, nuts and felted washers. Misleading dissolution due to iron oxide seemed to be (almost) absent. Measurements were taken from 1 February 2006 to 10 October 2011 in 5 measurement periods.

The results from measurement points S-1 and S-2 are presented in Fig. 3.3.2. In the first measurement period, several discharges reached 50 m³/s. Although discharge was quite high, the sum of dissolution and corrasion rates is relatively small (on average -1.2 μm/a). The majority of weight loss is probably a result of crumbling and grinding, which was evidently seen at the limestone tablet located at S-1 (Fig. 3.3.3). Therefore dissolution rates have to be even smaller, if they exist at all. During the second and third measurement periods, discharge was quite low. Thus there was only weak mobilization of bed load material and the limestone tablets showed no corrasional damages. Rates show weak dissolution (-0.2 μm/a) or slight sinter deposition (0.8 μm/a). The highest sum of dissolution and corrasion rates was detected during the fourth measurement period, which was characterized by two strong flash flood events with discharge of more than 100 m³/s. Limestone tablets were strongly damaged due to crumbling and grinding – dissolution rates therefore cannot be determined. The same happened during the fifth measurement period but since low water conditions also are characteristic for this long of a period, average rates are lower in comparison with the fourth measurement period. In absolute

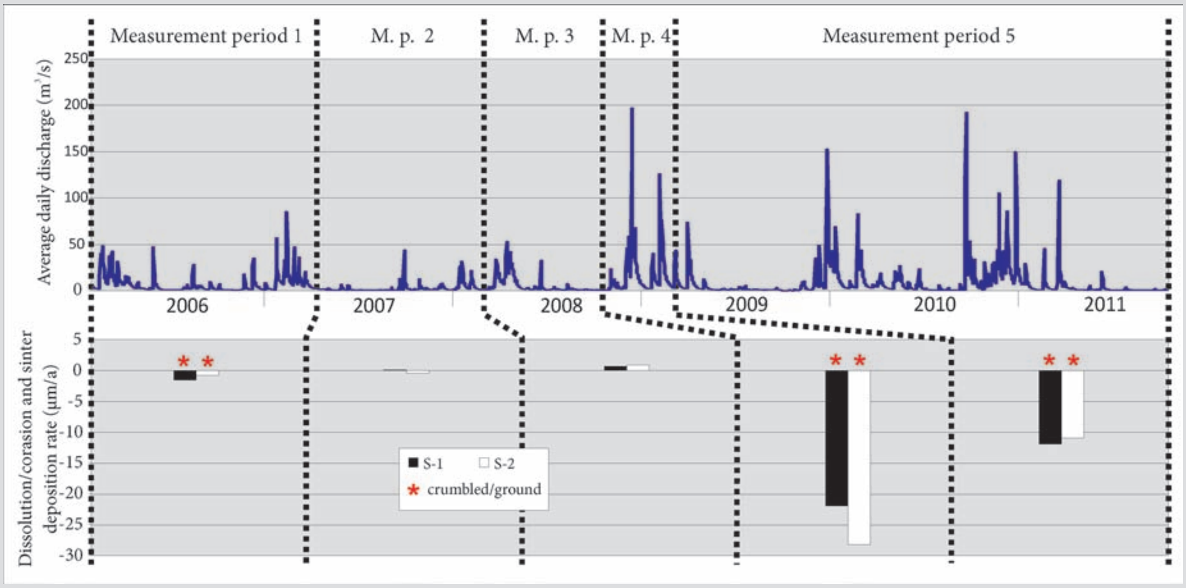


Figure 3.3.2. *Dissolution/corrasion and deposition rates at S-1 and S-2 during 5 measurement periods between 1 February 2006 and 10 October 2011 together with average daily discharge (source of hydrological data: Reka discharge data for 2006-2011).*

terms, corrasion during the fifth measurement period was 3.1-times higher than during the fourth measurement period due to several floods with discharges of over 50 m^3/s. Nevertheless, weight loss due to crumbling and grounding can be taken only in relative terms for corrasion rates since limestone tablets are exposed to much higher corrasion than the bed of a channel nearby.

Due to crumbling and grinding, we were not able to observe dissolution rates at high water level at S-1 and S-2. But at least we can say that they are very small or even absent if discharge remains under ~50 m^3/s. Results from the third measurement period suggest that (sinter) deposition is possible during low discharge.

From a morphological point of view, three different types of surfaces can be recognized in the water channel: surfaces with black coating, polished surfaces as a result of corrasion and surfaces with scallops as a result of dissolution. Black coating is several millimetres thick. It is distributed widely in the lower portion of a water channel, which is under water at low and medium discharges. It is absent only at locations where corrasion takes place (polished surfaces, potholes). Where it is located at the contact of collapse blocks, the black coating usually sticks collapse material together. This proves that sticking of blocks is younger than collapsing or moving of collapsed blocks. The reaction of black coating with 10 % solution of HCl is intensive, which indicates calcite (flowstone). Besides calcite, 13 % of impurities (weathered flysch rock, organic material) were detected with dissolution of flowstone coating in an HCl solution. If we take into account results from the second and third measurement periods, when the limestone tablets were not damaged by corrasion, the average net sinter deposition rate of 0.3 µm/a could be responsible for at least 3 mm thick flowstone coating - if we suppose the same rate of process during the Holocene. Potential thickness of flowstone coating corresponds in magnitude to actual thickness.

The second type of surface, corrasional, is developed at places where vast bed load transport and whirling takes place. Corrasion rates are very different and strongly depend on microlocation, as was already measured by Mihevc (2001; 65);

Figure 3.3.3. *Crumbled and ground edge of limestone tablet at S-1.*

this is from -20 μm/a at polished surface to -160 μm/a at places where bed load is hitting the wall. From our measurements we can conclude that at several places they are higher than sinter deposition rates where they appear. Nevertheless, corrasion can be extremely small in some places, and there sinter deposition prevails.

Surfaces with scallops are relatively rare. On the walls, scallops are usually absent. The most characteristic are on the tops of large collapse blocks in the water channel, which are flooded when discharge exceeds ~10 m³/s. The morphology of scallops is interesting, since they are long and narrow. The transitional angle between scallops is very low, amounting to 75-90° (Slabe 1992; 31). They form at places with very little corrasion and within a zone between sinter deposition and back flooding (Fig. 3.3.7). This statement was tested by measurement of the vertical variability of processes (Chapter 3.3.2).

3.3.2 Measurement places S-3, S-4, S-5 and S-6, S-7, S-8, and S-9 – vertical variability of processes at Swidovo Razgledišče and at Martelovo Jezero

Measurement locations S-1 and S-2 show sinter deposition at low (and medium) water levels. At high water levels, limestone tablets were altered by corrasion. The latter effect overwhelms possible dissolution, which is probably the highest at very high water levels and as such also within the focus of our interest. To avoid corrasion, we began to measure with two vertical sets of limestone tablets: at Swidovo Razgledišče (Swida's viewpoint; Fig. 3.3.4; S-3, S-4, and S-5) and at Martelovo Jezero (Martel's lake; S-6, S-7, S-8, and S-9).

At Swidovo Razgledišče , water flow can be characterized as supercritical turbulent at low, middle and high water levels. At Martelovo Jezero, water flow is slightly less turbulent. During very high discharges, velocity of flow is reduced significantly at both places since the backflooding causes a vast enlargement of the cross-sectional profile of water flow. At each of 7 measurement points, 3 limestone tablets were exposed to obtain better results. They were fixed with stainless steel screws, nuts and felted washers. Measurement point S-3 was fixed only 40 cm from S-2. Measurement point S-4 was located 2.5 m above S-3, while the measurement point S-5 was located 4.9 m above S-3. At Martelovo Jezero, we were measuring at 4 measurement points within a higher vertical span. Measurement point S-6 was located 0.4 m above geodetic point 58 (located at the shore of Martelovo Jezero) and seemed to be beyond the reach of corrasion. Measurement point S-7 was placed 1.6 m higher than S-6, S-8 4.5 m higher than S-7 and S-9 5.5 m above S-8 (12.0 m above geodetic point 58). Limestone tablets were replaced and weighed at the same time as S-1 and S-2 (Chapter 3.3.1). Due to the later establishment of measurement places, overall 3 measurement periods are available at Swidovo Razgledišče and 4 measurement points at Martelovo Jezero.

Results of measurements from the vertical set at Swidovo Razgledišče are represented in Fig. 3.3.5. Measurement point S-3, similarly to S-1 and S-2, suffered from crumbling and grinding. At S-3, corrasion took place during all three measurement periods. Corrasion reduced the weight of the limestone tablet at S-3 between 27 February 2008 and 14 October 2008, which shows that measurement point S-3 is even more under the influence of corrasion than measurement point S-1 or S-2 (compare with measurement period 3 in Fig. 3.3.2). Corrasion at S-3 overwhelmed possible dissolution.

On the contrary, corrasion was not recognized at measurement points S-4 and S-5. Rates at S-4 and S-5 are almost equal, which is most probably a result of the rapid rising of water that flooded both measurement points almost simultaneously, or too weak a difference in rates between two measurement places. During the first measurement period, slight sinter deposition (0.7 μm/a) was detected at S-4 and S-5. During the

Figure 3.3.4. *Cross-section through Hankejev Kanal at Swidovo Razgledišče. Lines on the several tens of metres high right wall are not bedding planes but traces of past flood events. A stalagmite in the water channel is 2 m tall (photo: Borut Lozej, conservationist at Park Škocjanske jame).*

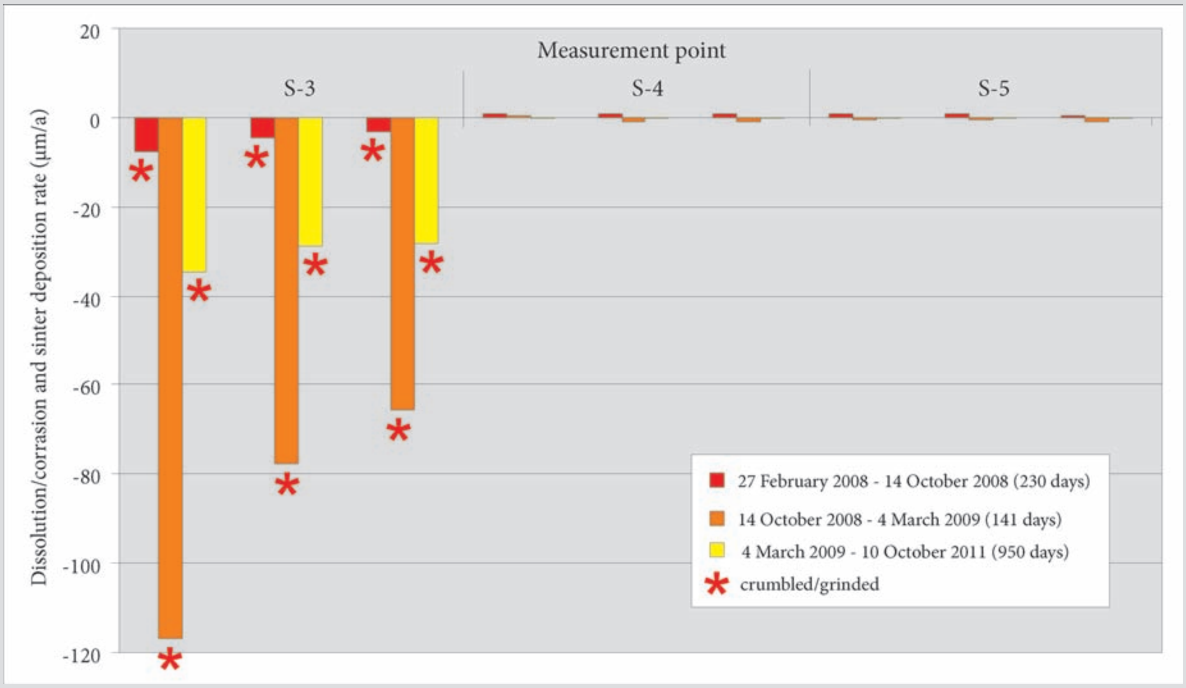


Figure 3.3.5. *Dissolution/corrasion and sinter deposition rates measured at Swidovo Razgledišče between 27 February 2008 and 10 October 2011.*

second measurement period, slight dissolution (-0.6 μm/a) was detected. The last and the longest measurement period shows slight dissolution (-0.1 μm/a). Overall, the average at S-4 and S-5 shows neither dissolution nor sinter deposition. Weak dissolution rates within measurement error are surprising since several very big flash flood events are characteristic for the last two measurement periods. Results prove that the aggressiveness of the Reka River is very low or almost absent even at very high discharge. It is interesting that suspended material, which is abundant in water at high discharges, did not cause visual damage but also did not reduce the weight of limestone tablets. We can assume that only bed load material is responsible for high corrasion rates detected by Mihevc (2001).

The measurement location of Martelovo Jezero was chosen due to lack of corrasional morphology at all measurement points. Therefore more can be said about sinter deposition at low discharge and slight or absent dissolution at high water levels. The result of measurements at S-6, S-7, S-8 and S-9 (Fig. 3.3.6) confirmed lack of corrasion at the lowest measurement point. Weight loss in one limestone tablet during the first measurement period is a result of artificial damage during fixation. Although values are rather small, evident transition from net sinter deposition at S-6 toward dissolution at higher measurement points can be observed. The highest average dissolution rate (-0.25 μm/a) was detected at S-8, which is located 6.1 m above measurement point S-6. Upward, dissolution rates are weaker due to shorter exposure times. Downward (1.6 m above S-6 at S-7), net dissolution rates are weaker most probably due to sinter deposition during moments of middle water levels. Sinter deposition is even greater at the

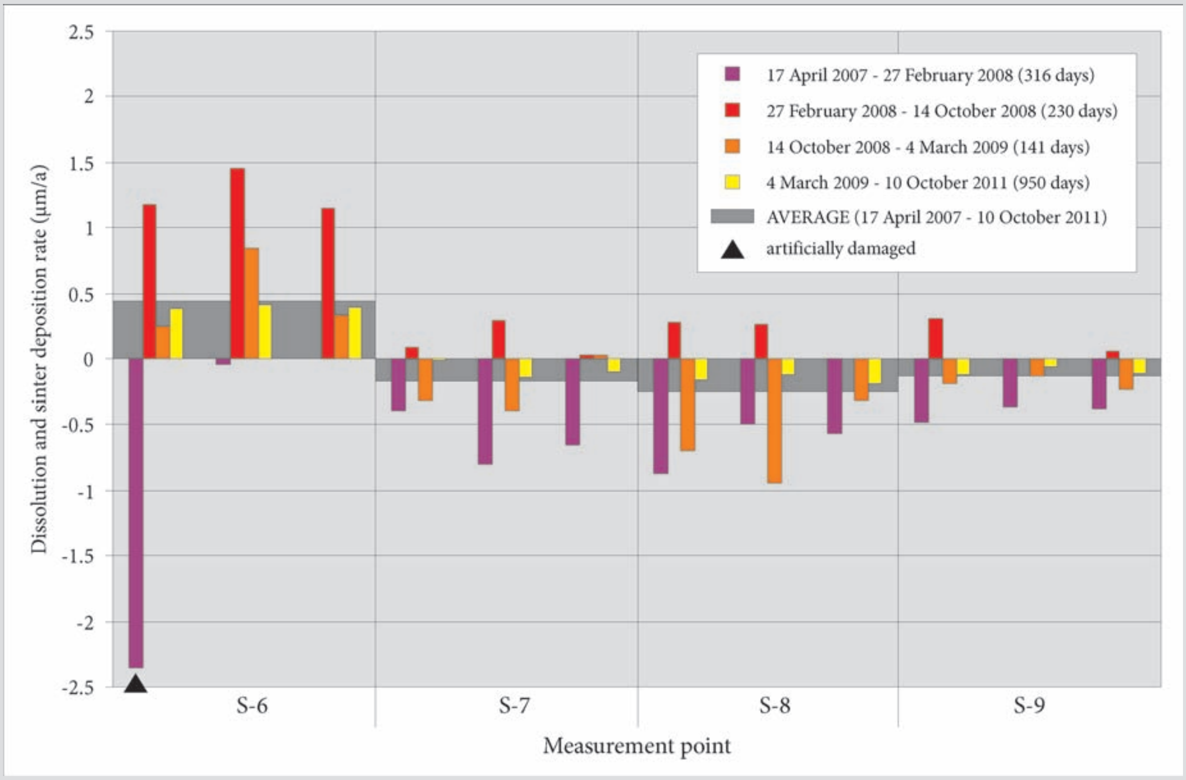


Figure 3.3.6. *Dissolution and sinter deposition rates measured at Martelovo Jezero between 17 April 2007 and 10 October 2011. An artificially damaged limestone tablet was excluded from the calculated average.*

lowest limestone tablets (measurement point S-6) where it prevails over dissolution. During high water levels, dissolution also takes place at the lowest measurement place, but during middle and low discharges, net sinter deposition prevails with 0.44 μm/a. This is similar to the average at S-1 and S-2 (0.3 μm/a; Chapter 3.3.1). Deposition was very obvious during the second measurement period, which was characterized by low discharges.

The results of measurements at Swidovo Razgledišče and Martelovo Jezero demonstrate that we can expect deposition at low water levels and dissolution at high water levels. Change from net deposition to net dissolution seems to occur when the water level in an underground channel rises 1.5 m above low water level (this is at Q ≈ 20 m^3/s after Gabrovšek & Peric 2006; 40). This corresponds to the lower limit of scallops (Slabe 1992; 32, Slabe 1995; 23), which are developed at the big collapse blocks in the water channel out of corrasional locations. At higher water level, backflooding prevents the development of scallops due to the decrease of water flow velocity. Dissolution rates in upper portions of the underground channel (above 6.5 m) are probably guided by the most aggressive water but they decrease due to shorter exposure times. The morphology of temporarily flooded passages rarely shows dissolutional features. More often disintegrated rock surfaces can be seen, slightly blurred by dissolution.

Comparison between measured (and estimated-mechanical weathering) processes, key factors and theoretical features in the inner parts of Škocjanske Jame shows that present-day conditions correspond to the actual present-day micromorphology of the water passages. Nevertheless, some features (i.e. scallops) can also be inherited from the past and are just sustained in present-day conditions. Processes, key factors and features can therefore be summarized in the general scheme represented in Fig. 3.3.7.

Can we say something about pre-Holocene processes? We already stressed that thickness of flowstone coating at the most remote places in the bottom of the water channel corresponds to the product of sinter deposition rates and the duration of the Holocene. This indicates that sinter deposition was absent or at least much lower than today. As per Gams (1996; 103),

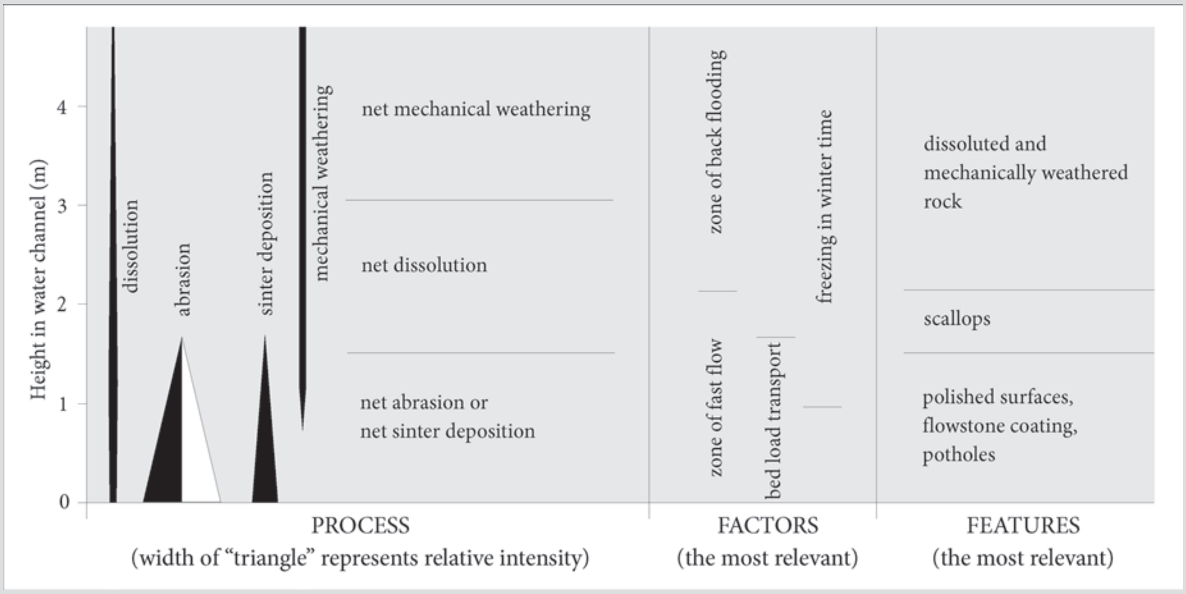


Figure 3.3.7. *The most relevant present-day processes, factors and features characteristic for Škocjanske Jame.*

higher aggressiveness of water during Ice Ages can be expected due to frozen ground, which promotes superficial runoff without interaction with carbonates within the soil. Additionally, lower saturation of waters can also be a result of weaker biological activity in soils, lower soil CO_2 concentration, weaker dissolution rates in soil, lower water CO_2 concentration at karst springs and higher potential to dissolve rock underground especially during high discharges.

3.3.3 Measurement places S-6, S-3, S-10, S-11, and S-12 – longitudinal variability of processes between flysch-limestone contact and Martelovo Jezero

Weak dissolution rates in Škocjanske Jame can be a result of (a) gradual saturation of the Reka River along the more than 7.5 km long water course between the lithological contact flysch-limestone or (b) already saturated water at the lithological contact flysch-limestone. Proof for one of these two possibilities can be helpful for understanding the genesis of the limestone gorge upstream from Škocjanske Jame and the related development of Škocjanske Jame. Therefore we decided to measure chemical processes in a longitudinal section from the contact flysch-limestone to the Martelovo Jezero in Škocjanske Jame.

Limestone tablets were placed at five different measurement points. The farthest upstream (S-12) was located at the lithological contact of limestone with flysch, S-11 was located at the ponor (where the Reka River starts to flow underground), S-10 was located in the entrance chamber of Škocjanske Jame (Rudolfova Dvorana; Rudolf's chamber), while the most downstream limestone tablets were located at the previously described Swidovo Razgledišče (S-3) and Martelovo Jezero (S-6; Chapter 3.3.2). At each point, measurements were done using three limestone tablets. They were fixed with stainless steel screws, nuts and felted washers at non or weakly corraded measurement places. All measurement points demonstrate very similar hydraulic conditions – turbulent supercritical water flow with velocities usually several m/s. Results are available for three measurement periods between 2 February 2008 and 10 October 2011.

Although limestone tablets were fixed at places where the corrasion is supposed to be weak, corrasion is obvious especially at measurement places S-10 and S-3 (Fig. 3.3.8). Corrasion was occasionally observed also at S-12 and S-11, especially during the second measurement period, when discharges exceeded 100 m^3/s, and to a lesser extent during the third measurement period.

In the first measurement period, which is characterized by relatively low water levels, deposition was detected at all measurement points. Deposition rates from the lithological contact (S-12) remain more or less constant at ~1.2 µm/a all the way to Martelovo Jezero (S-6). Only at the ponor (S-11), are they higher (2.4 µm/a) for some unknown reason. During high discharge that was characteristic for the second and third measurement periods, the Reka River seems to be at equilibrium or can display low sinter deposition, especially at Martelovo Jezero. Since several limestone tablets were altered by crumbling and grounding it is difficult to say whether dissolution rates increase or decrease from the contact of flysch with limestone. If we compare the average at S-12 (lithological contact) and at S-6 (Martelovo Jezero), sinter deposition rates slightly increase downstream, which proves either (a) slightly reduced dissolution rates downstream during high water levels, (b) higher sinter deposition rates downstream during low water levels or (c) both. Nevertheless, although the Reka River is slightly aggressive at high discharge, average values at both measurement places show that sinter deposition prevails over dissolution. Net sinter deposition rates range between 0.3 and 0.5 µm/a.

The main reason for the low aggressiveness of the Reka River in Škocjanske Jame certainly is not the superficial flow of the Reka River over limestone 7.5 km from the ponor; otherwise we could observe at least net dissolution at the lithological contact. The reason for the low aggressiveness of the Reka River resides in its catchment area. The most reliable explanation can be found in karst springs that feed the Reka River and are oversaturated with respect to calcite in open atmosphere conditions. Some of them deposit tufa in high quantities (e.g. Podstenjšek; Kogovšek 2006) and are highly oversaturated even during middle discharge. Many tributaries from the Brkini Mountains decrease the total hardness of the Reka River (Gams 1962; 278), but they are too weak to substantially increase the aggressiveness of the water even at the beginning of flood events.

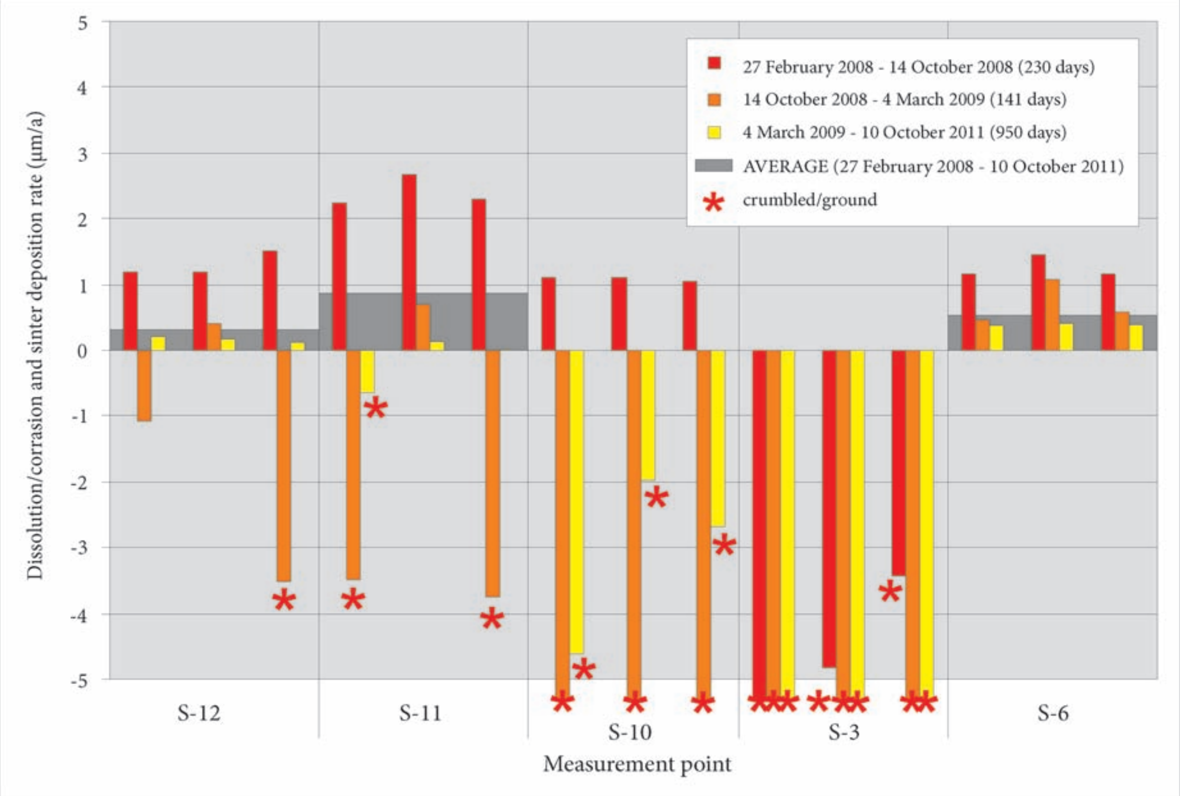


Figure 3.3.8. *Dissolution/corrasion and sinter deposition rates measured between flysch-limestone contact (S-12) and Martelovo Jezero (S-6) between 27 February 2008 and 10 October 2011. Crumbled and ground limestone tablets are not included in the calculated average.*

3.3.4 Conclusion

If we just take into account chemical processes, sinter deposition can be defined as the strongest geomorphic process in the epiphreatic part of Škocjanske Jame. The most characteristic is for low discharge. During medium discharge, sinter deposition rates are much lower. According to measurements at Martelovo Jezero and the measurement point at the lithological contact limestone-flysch, net sinter deposition amounts to 0.3-0.5 μm/a in the lower portions of the water channel. Morphologically, sinter deposition can be seen as black flowstone coating, which covers and sticks collapse blocks together in the water channel of Škocjanske Jame. The highest dissolution rate (up to -0.25 μm/a 6 m above the low water level) appears at high water level, when discharge exceeds about 20 m^3/s. Dissolution rates most probably rise with higher discharges, but for a very short time. The most problematic factor for high dissolution is the time of exposure, which is low due to the torrential character of the Reka River.

About 1.5 m above low water level when discharge is higher than 20 m^3/s, slight net dissolution rates become higher than net sinter deposition rates. This is also the lowest vertical point, above which the dissolutional forms can be observed. The most obvious are scallops, which disappear upward because of backflooding and the decrease of flow velocity due to the increase of the cross-sectional area of water flow. Walls in a flooding zone are characterized by slightly dissolutionally blurred primary mechanically weathered rock. Here, slight dissolution due to flooding is accompanied by condensation dissolution. Distinguishing between them is usually impossible.

Due to the vast quantity of flysch material transported through Škocjanske Jame, corrasional features are well developed on the bottom of the underground channel. The location of such features points out that they were formed by the whirling of bed load material, while the geomorphic action of suspended load is absent. Rates of corrasion from bed load transport were measured by Mihevc (2001). Measurements and morphological observations reveal that they can be much stronger than sinter deposition and dissolution, but also much weaker at calm places.

Although the rate of chemical processes is low, present-day processes correspond to present-day factors and actual microfeatures along the water course in Škocjanske Jame. Nevertheless, the thickness of flowstone cover (several millimetres) shows that the intensity of chemical processes was different before the Holocene. At that time, sinter deposition rates were weaker or dissolution rates stronger, since we lack thicker flowstone coating. In spite of this, the deep vertical incision of the meander (Hankejev Kanal) suggests that lateral extension of the meander due to dissolution (during low or high water levels) was also weak. This is suggested also by the lack of wall notches, which could form in a water channel that is partially blocked by collapse material or where deepening of a meander is slowed by collapse blocks accumulated at the bottom of the passage due to mechanical breakdown. Dissolutional features of fast water flow at vertical walls are also absent. The most probable cause for the incision of the meander is the corrasional activity of water, where bed load material is much more important in comparison with the action of suspended load. The strongest geomorphic activity takes place at the bottom of the water passage and leads more toward corrasional incision than toward dissolutional lateral extension of the passage. This accounts for the highly differential characters of Škocjanske Jame and Lekinka cave (Chapter 3.2).

3.4 POSTOJNA BASIN-PLANINA POLJE CAVE SYSTEM

The drainage between the Postojna basin and the Planina polje is completely subterranean and, due to its explored length and large cross-sectional profile of passages, one of the most important in the Dinaric karst. This hydrologically active cave system is composed of two major caves: Postojna cave system (Reg. No. 747) and Planinska Jama (Planina cave; Reg. No. 748). Postojna cave system and Planinska Jama together have 27.2 km of known underground passages – some of them are characterized by the underground Pivka River flow while the other passages are currently dry (Fig. 3.4.1). The vast majority of passages are horizontal and thought to have been formed in epiphreatic conditions by the Pivka River. Planinska Jama is accessible through one entrance that acts as a spring and ends in the upstream direction in a more than 25 m deep sump (Vrhovec 2000). Passages of Postojna cave system connect several entrances, from which the cave was explored in the past and therefore differently named (Postojnska Jama, Otoška Jama, Magdalena Jama, Črna Jama, Pivka Jama; Fig. 3.4.1). Some of the listed parts of Postojnska Jama were connected after the First World War by diving or with artificial tunnels.

Today, Postojna cave system is famous due to its having the greatest biodiversity of underground species (84 species of troglobionts) in the world (Culver & Sket 2000; 15). It is also the type locality of a number of "first cave" animals, including the first described troglobionts – the beetle Leptodirus hochenwarti and the European cave salamander, Proteus anguinus. (Culver & Sket 2000; 13). From a touristic point of view, Postojna cave system is first among all tourist attractions in Slovenia and is the most recognized show cave in Europe. The attraction of the cave as a location for tourism began with the discovery of dry and impressively decorated parts of the cave behind Pivka ponor in 1818, the construction of a single-track underground railway in 1872 and a double-track underground railway in 1964 (Gams 2003; 297).

The first scientific research into Postojna cave system began with archaeological investigations of the entrance area of Postojnska Jama soon after the discovery of some of its inner parts. Work was done by very famous scientists and technicians of that time (A. Schaffenrath, H. Freyer, F. v. Hohenwart, A. Schmidl, F. Kraus, E. A. Martel; for details see Gospodarič 1976; 11-12). The latter two were also the first who touched on the question about the speleogenesis of underground passages. Although some work was also done by Italians between the First and Second World Wars, a new era of research started with archaeological investigations (Brodar 1951, Brodar 1966), hydrological investigation of the underground Pivka River (Michler & Hribar 1959), the study of wider hydrological conditions between Postojna, Planina and Cerknica (Gams 1966a) and geological investigations (Pleničar 1961, Šebela 1998) after the Second World War. The knowledge of geology and speleology was substantially deepened by Gospodarič (1976), who comprehensively studied the whole cave system between Postojna basin and Planina polje from the viewpoint of allochthonous sediments, speleogenesis and related ages of sediments (1980). The age of much older sediments was studied recently and published by Zupan Hajna et al. (2008). The geomorphologic evolution of the underground passages connected with development of superficial relief was studied by Gams (1965). Although Postojna cave system is among the most speleologically studied caves in the world, the study of speleogenesis is a very hard task due to the long multiphase evolution of cave systems.

Geological and geomorphological characteristics

Postojna cave system and Planinska Jama are located between Postojna basin (~530 m a.s.l.) and Planina polje (~450 m a.s.l.). Postojna basin is a closed depression underlain by Eocene siliclastic flysch rocks in the northern part and Cretaceous limestone in the southern part. The relief of Postojna basin is characterized by low gradients due to mechanically non-resistant flysch rocks, relatively tectonically stable long-lasting geomorphic evolution and low nearby hydraulic gradients. Planina polje is one of the most typical karst poljes of all (a closed depression with a flat bottom, complete karst inflow and outflow, regularly flooded) located on Mesozoic carbonate rocks along the dextral strike-slip Idrija fault zone. Between Postojna basin and Planina polje, the karst surface on Cretaceous rocks is characterized by several conical and elongated hills, which are incorporated within the system of elongated ("dry") valleys and dolines (Gams, 1965) – probably a geomorphic modification of tectonic structures. The cave system with underground water flow is situated under this karst surface with elevations from ~580 m a.s.l. to ~750 m a.s.l. Due to sometimes thin and heavily fractured roofs, several collapse dolines devel-

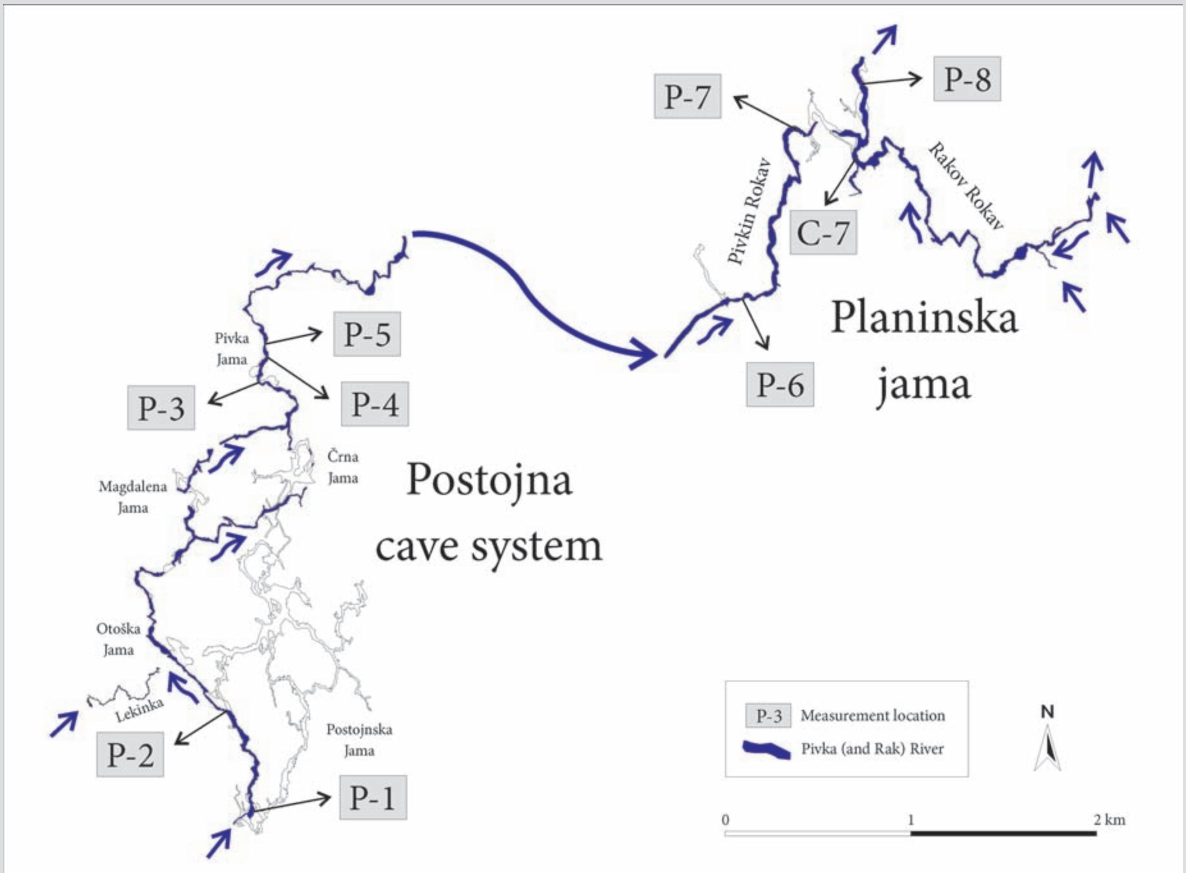


Figure 3.4.1. Plan of cave system between Postojna basin and Planina polje with measurement locations investigated in this study.

oped, especially in the area of Postojnska Jama. In Pivka Jama and Črna Jama, collapsing formed a new entrance to the cave system.

The general geological structure of the karst massif where Postojna cave system and Planinska Jama are located is very simple. It is composed of Upper and Lower Cretaceous limestone, which are folded due to compression in a SW-NE direction (Fig. 9.4.2). The farthest SW fold is the Postojna anticline, in which the majority of passages of Postojna cave system are developed. To the northeast, the Studeno syncline is developed, where the downstream passages of Postojna cave system and the unexplored connection with Planinska Jama are formed (Gospodarič 1976; 21). Water flow between Pivka basin and Planina polje crosses the folded structure in a perpendicular direction and therefore crosses the same lithostratigraphic units several times. The whole karst massif is dissected with several tectonic structures in NE-SW and NW-SE directions (Čar & Gospodarič 1984, Šebela 1998) but none of them alter significantly the general pattern of the folded structure. At the contact with Eocene flysch rocks (E1,2), the dip of the strata can be almost vertical but elsewhere is usually less than 45 °.

The youngest rocks, in which the entrance parts of the Postojnska Jama and Pivka Jama passages are developed, are Senonian layers (K_2^3), which are developed as thick-bedded limestone. The upper layers of Turonian limestone (K_2^2) are similar to Senonian – thick-bedded or even non-bedded. Lower Turonian limestone is usually characterized by thinner layers and can be rich with up to a decimetre thick layer of chert. The consequence of chert in Lower Turonian limestone is higher occurrence of pipe flow.

Cenomanian limestone (K_2^1) is non-bedded and can be reached just at the downstream end of Pivka Jama and in a dry passage called Paradiž (paradise) in Planinska Jama. The non-bedded structure of this limestone is most probably responsible for the development of deep sumps between Postojna cave system and Planinska Jama, although some short passages with free-surface flow exist in them (Vrhovec 2000). Almost all passages of Planinska Jama are formed in Lower Cretaceous limestone (K_1, Gospodarič 1976). Lower Cretaceous limestone can be thick-bedded or thin-bedded. They contain layers of dolomite and brecciated limestone. At the transition with Cenomanian strata, layers of chert can be found. Passages that are developed in limestone with chert are smaller.

The cave system between Postojna basin and Planina polje is comprised of at least two almost horizontal levels that can be uniform in some cases (Veliki Dom in Postojnska Jama, the majority of passages in Planinska Jama). The upper level is dry and only the lower one is hydrologically active. The drainage pattern between Postojna basin and Planina polje also changed laterally, which results in several passages being at

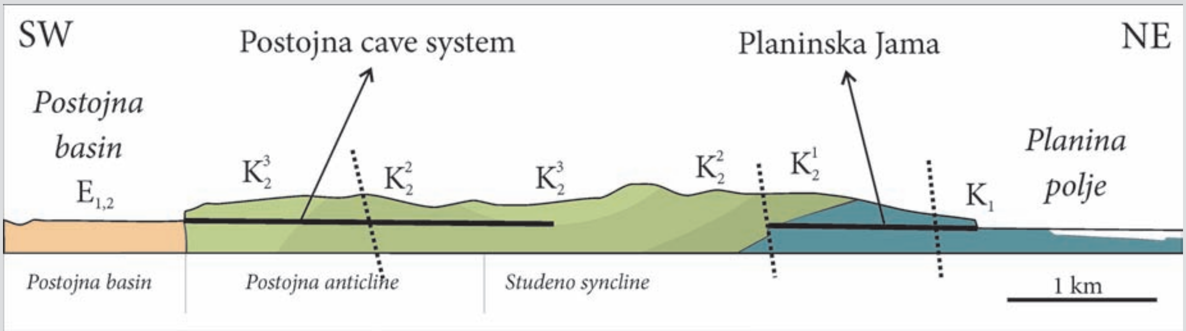


Figure 3.4.2. *General geological SW-NE cross-section between Postojna basin and Planina polje with position of Postojna cave system and Planinska Jama (modified after Gospodarič 1976; 25).*

the same elevation. At the same time, cave passages have been developed under the influence of vertical percolation and the underground water flow of Pivka River. Gospodarič (1976; 15) states that different parts of the cave system were influenced by very different speleogenetic processes and factors often at the same time and that many erosion-accumulation phases even within individual passages occurred as well. At present, even such abundant knowledge regarding Postojna cave system and Planinska Jama, which was accumulated by Gospodarič (1968, 1976), and later deepend by others (i.e. Zupan Hajna et al. (2008), is insufficient for a temporal and spatial speleogenetic interpretation of the whole cave system.

The present-day dissolution rates of the Pivka River were measured only by Gams (1966b; 35). Although he strongly supported the idea of dissolutional formation of passages along the underground Pivka River, his measurements only partially confirmed his expectations; his hydrochemical measurements between the entrance to Postojnska Jama and Spodnji Tartar (the lower Tartarus) confirmed a downstream increase of hardness in just 11 cases while in about 14 cases he found either no evidence of an increase or even a decrease of hardness. In addition, downstream increase of hardness was almost always within or very close to the range of error. Low rates were confirmed also with further measurements with three limestone tablets made in the entrance area of Postojnska Jama (Gams 1996). Due to such low rates, Gams was not able to provide absolute dissolution rates. Downstream, the aggressiveness of the underground Pivka River all the way to Planina polje is unknown.

Hydrological characteristics

The hydrological backbone of the Postojna cave system and Planinska Jama is the Pivka River, which joins the underground Rak River in Planinska Jama. Together they are called the Unica River, which flows through Planina polje. This hydrological connection between Postojna cave system and Planinska Jama was confirmed by several tracing tests.

The Pivka River originates from a karst spring located 16 km south of the entrance to Postojna cave system. During middle and high water levels, several karst springs, mainly from the east (the Javorniki Mountains), feed the superficial Pivka River course. Tributaries from the western side are also numerous but relatively small. Their catchment area extends mainly over siliciclastic flysch rocks. During middle water levels, discharge of Pivka River at the lithological contact limestone-flysch (11 km downstream from the source) amounts to 2.86 m^3/s (Kolbezen & Pristov 1998). During low water levels, all the water from the upper Postojna basin, which is made up of Cretaceous limestone, flows underground toward Malni springs and Planinska Jama (Habič 1989; 240). During high water levels, discharge reaches up to 26.4 m^3/s (Kolbezen & Pristov 1998) due to the rise of a piezometric surface under the Javorniki Mountains and therefore abundant karst springs below them.

Between lithological contact limestone-flysch and the ponor of the Pivka River, the most important tributary of the Pivka River is the Nanoščica River, which contributes 1.41 m^3/s during middle water levels and up to 15.9 m^3/s during high water levels (Kolbezen & Pristov 1998). The catchment area of the Nanoščica River extends over the lower Postojna basin, which is formed by siliciclastic flysch rocks. Therefore the Nanoščica River is fed mainly by superficial runoff. However, it is also fed by several small karst springs under Nanos Mountains and from the karst spring Korentan, which drains the partly isolated karst of Orehek (Gospodarič et al. 1970, Petrič & Šebela 2004).

Only 2.3 km downstream from the confluence of the Pivka and Nanoščica Rivers, the ponor of the Pivka River is situated at 511.5 m a.s.l – several metres below the dry entrance to Postojnska Jama. The lowest discharge is characteristic for summer months when it amounts to several tens of l/s. High water level is characteristic for the late autumn and spring months. In the case of long-lasting intensive precipitation, discharge up to 65 m^3/s can appear (Habe 1966; 50). In such cases, a large portion of free-surface flow in Postojna cave system turns to pipe flow, yet without significant damming. The most intensive damming occurs at rare narrow places (e.g. in Magdalena Jama) and in some collapse chambers (e.g. Martelova Dvorana; Martel's chamber). Therefore, the general gradient between the ponor of the Pivka River in Postojna cave system and the spring of the Unica River from Planinska Jama (455 m a.s.l.) amounts to 10.6 ‰ (D = 5.3 km; ΔH = 56 m).

Water flow in the Postojna cave system and Planinska Jama is influenced by a water gradient that is perpendicular to strata dip and the main tectonic structures (crushed zones, Šušteršič et al. 2001), and all this obstructed unidirectional water flows toward Planina polje. Water flow is of a zigzag character since water chooses the most effective way through widened bedding planes and faults/cracks. Where the underground Pivka River flows along strike, free surface flow in subhorizontal passages is developed. Water passages are usually more than 10 m wide and more than 5 m high. A challenge for underground water flow is a flow perpendicular to strata dip (Pleničar 1961), which is often accompanied by several sumps often acting as restrictions. The bed of a water channel is usually covered with collapse material and allochthonous flysch material, consisting mainly of clay and silt, sand and pebbles being less common (Kranjc 1989; 65).

Along the underground flow of the Pivka River, several tributaries are recognized, both visually (Michler & Hribar 1959, Gams 1966a) and through tracing tests (Habič 1989, Kogovšek 1999). The first one is the underground Črni Potok, which joins the underground Pivka River in Otoška Jama from the left side through the Lekinka cave (see Fig. 3.4.1). The next three right tributaries were recognized by Michler (1959) in Magdalena Jama but not by Gams (1966a), who observed another weak tributary (Q ≈ 1 l/s at low water level) of vadose water in Perkov Rov (Perko's passage). It is possible that they are active only during higher water levels and dry up during low water levels. The next two tributaries were observed only by divers since they are located downstream from the downstream sump of Pivka Jama. The first one could be the underground water flow of superficial streams sinking north of the Postojna cave system and Planinska Jama (Vrhovec 2000; 167). The second tributary is very strong (estimated at 20 % of the Pivka River, Vrhovec 2000; 168) and should have its catchment area at the Javorniki Mountains or in the upper Pivka basin, since some tracing tests confirmed the connection of these areas via an unexplored passage between Pivka Jama and the Pivka branch in Planinska Jama (Habič 1989, Kogovšek 1999; 184-185). Further downstream, where an unexplored connection between Postojna cave system and Planinska Jama is located, we can also expect tributaries from the northern area, where some sinking streams from flysch rocks near Studeno are located. The latter can flow toward Vipava spring as well, but such conditions are less probable. In Planinska Jama, the Pivka River receives the strongest tributary – the Rak River. The hydrogeological characteristics of the latter are even more diverse than the hydrogeology of the Pivka River.

The Postojna cave system and Planinska Jama drains the area of Postojna basin, which is quite densely populated, without tertiary treatment of waste water and sometimes with runoff water of strong agricultural influence. Biologically decomposed organic matter in water treatment plants or in the water channels highly increase the natural background of dissoluted salts in water which can influence dissolution (or sinter) deposition rates.

Meteorological characteristics

Due to the many entrances to Postojna cave system, the latter is very well ventilated (Gams 1970). Only smaller passages close to the sumps are less ventilated, while the majority of water passages are characterized by intensive air flows (e.g. between the entrance to Postojnska Jama all the way to the Magdalena Jama, the entrance part of Pivka Jama). Therefore, CO_2 concentration is relatively low even during summer months (Gams 1974; Šebela et al. 2012).

On the contrary, Planinska Jama is well ventilated only in the entrance zone due to its large entrance, which enables two contrary wind directions in vertical cross-section. Inner passages (above the confluence of the Pivka and Rak Rivers) are less ventilated, especially the Pivka branch. The latter statement was confirmed through CO_2 concentrations, which were relatively high even at the end of winter (~1,500 ppm).

3.4.1 Measurement location P-1 – temporal and vertical variability of processes in the entrance area of Postojna cave system

The first research that considered dissolution rates in Postojna cave system was by Gams (1966b; 35). Several times he observed differences in water hardness between Veliki dom (big chamber) and Spodnji Tartar (lower Tartar). Most often these occur at low water levels between January and March, when the majority of water comes from the Nanoščica River and the portion of the Pivka River is small. Later, Gams (1996) measured cumulative dissolution rates using three limestone tablets placed in the Pivka River in Veliki Dom (the entrance chamber of Postojnska Jama). His results show that dissolution rates are extremely low, if they exist at all. He was not able to provide exact values.

Our first observation was done with two limestone tablets during a test study close to Gams' (1966b, 1996) measurement location in Veliki Dom (Chapter 2.2.2). Unfortunately, the lower limestone tablet was broken due to the transport load of the Pivka River. About 1 m higher a limestone tablet indicated slight dissolution (-0.1 μm/a). In 2007 we continued with measurements at a more appropriate location (measurement location P-1), which is less influenced by the bed load sediments of the Pivka River.

Measurement location P-1 was located about 150 m downstream of the ponor of the Pivka River in Veliki Dom on the right side of the underground Pivka River. The whole set of 16 limestone tablets was arranged on a metal bar in an oblique position (Fig. 3.4.3), where the vertical distance between the centres of the limestone tablets amounted to 6 cm. This vertical arrangement was used to obtain insight into the vertical variability of processes and to evaluate the influence of different discharges within 78 cm of the high measurement zone. At the lower position ($H_{Veliki\ dom} = 0$ cm), three limestone tablets were installed instead of one to obtain better precision for longitudinal comparison of karst processes rates (Chapter 3.4.2). These limestone tablets were always under the water, while the upper tablets were temporarily above the water level. The limestone tablets were fixed with stainless steel screws, nuts and felted washers to avoid any influence of iron oxides. Due to the width of the chamber, water flow can be defined as low turbulent and subcritical at low and middle discharges. At high discharge, water flow is characterized by large eddies. During very high discharge, backflooding of 7-8 m results in lower velocity of water flow (~0.5 m/s).

At the end of the measurement, results for four measurement periods were available. In the last measurement periods, the lowest limestone tablets were damaged by floating debris and washed away during extremely high water levels.

Results for four measurement periods and for the average are presented in Fig. 3.4.4. Although we cannot reliably calculate the average for the two lowest measurement locations, the average is certainly positive with values up to ~1 μm/a. This means that up to $H_{Veliki\ dom} = 30$ cm dissolution is absent on average (it can exist occasionally but is exceeded by deposition). Above, dissolution is the highest at $H_{Veliki\ dom} = 60$ cm where amounts were -0.6 μm/a. An upward weakening of dissolution rates is expected but cannot be confirmed within a 78 cm high measurement zone due to slight and therefore unreliable differences. Transition from

Figure 3.4.3. *Limestone tablets at measurement location P-1 in Veliki Dom in Postojnska Jama during low water level.*

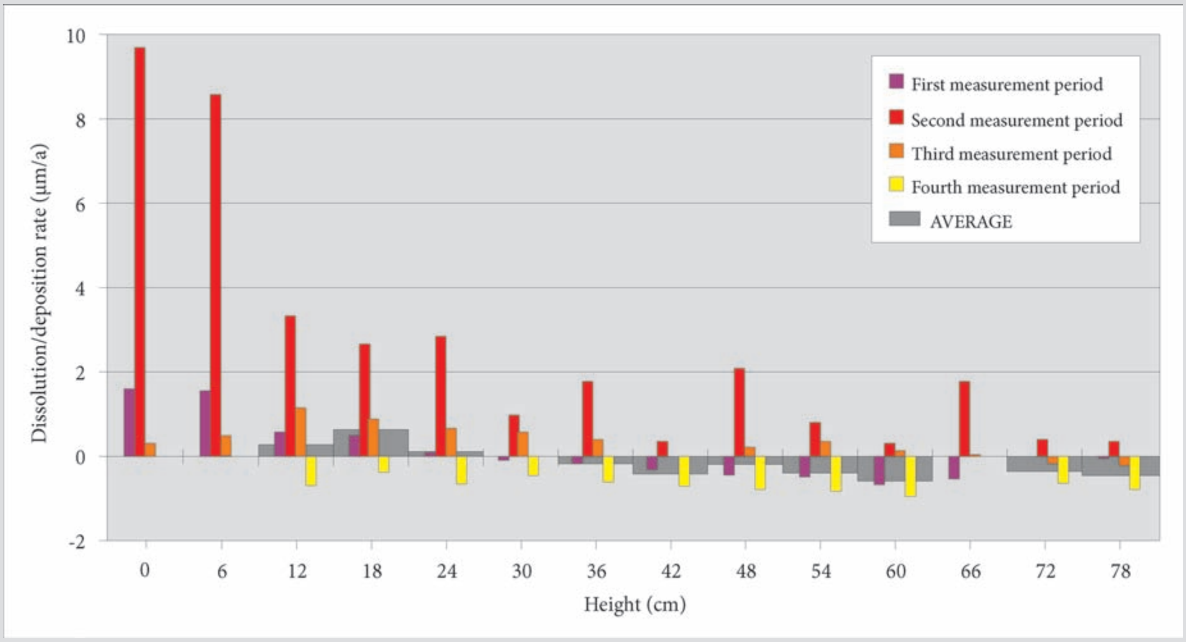


Figure 3.4.4. *Dissolution and deposition rates in four measurement periods and average periods between 26 September 2007 and 24 August 2011 at measurement location P-1.*

deposition into dissolution is gradual and can be described very well up to 78 cm high with a logarithmic curve since R^2 amounts to 0.77.

A detailed view into individual measurement periods displays a much more diverse situation in comparison with average values. During the first measurement period, water most probably flooded all limestone tablets (Fig. 3.4.5). The transition from moderate deposition into dissolution is gradual. At $H_{\text{Veliki dom}} = 70$ cm dissolution diminishes since the highest water level reached the upper limestone tablets for a very short time. During such autumn and winter peak discharge at least the initial contribution of the Nanoščica River is important due to fast superficial runoff from the nearby area covered by flysch rocks, while later it is followed by the prevailing runoff from the karst area (Habe 1966; 50). Dissolution was detected during autumn and winter months, which corresponds to the findings of Gams (1966b; 35). During low water levels, deposition prevails. Corrasion should not be seen as an important process since the biggest weight loss is not related to the lowest limestone tablets.

During the second measurement period, the portion of the Nanoščica River was small during higher discharges. Additionally, the water level was quite low in the second part of the measurement period (summer 2008) when the waters of the Nanoščica River strongly prevailed. As a result, deposition prevailed over dissolution at all vertical zones. The highest deposition rate was characteristic for the lowest limestone tablets where amounts were almost 10 µm/a. At least a small portion of weight gain (this indicates deposition) can be contributed to the organics deposited especially on the lowest limestone tablets (pollution) which could not be adequately removed from the tablets' surfaces.

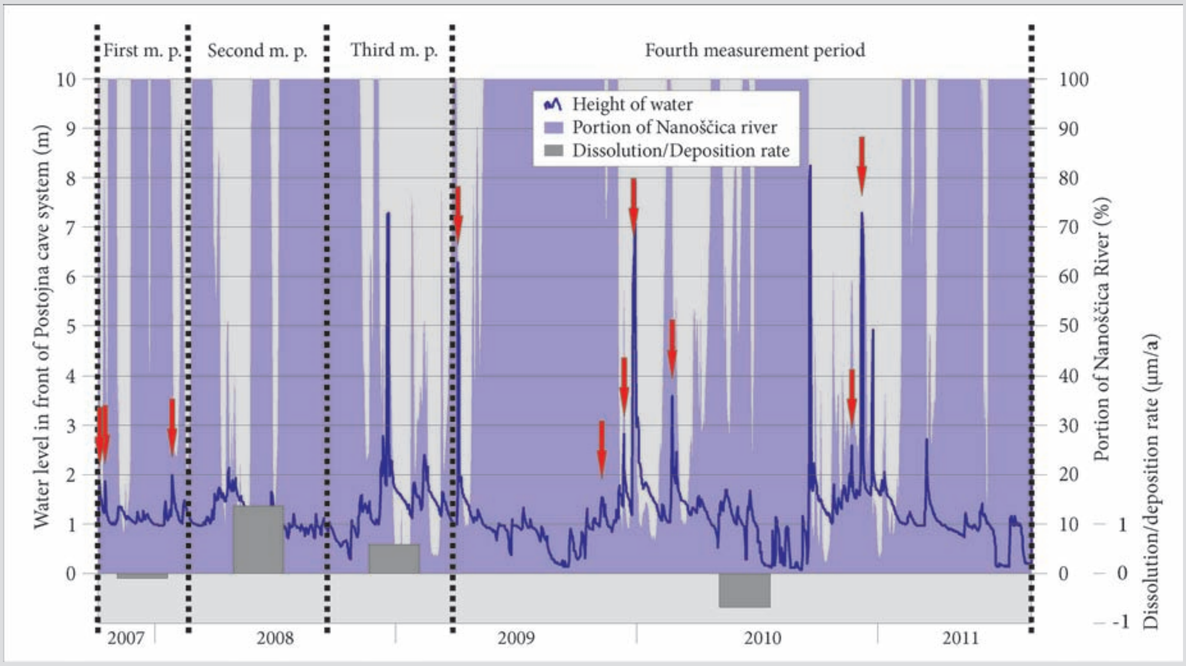


Figure 3.4.5. *Water level, portion of the Nanoščica River and average dissolution/deposition rates at measurement location P-1 during four measurement periods between 26 September 2007 and 24 August 2011. Red arrows show the ten highest culminations of the high portion of the Nanoščica River and high water level in front of Postojnska Jama. The rise of the water level presented in this figure fits quite well with the rise of water at measurement location P-1.*

One of the highest discharges was characteristic for the third measurement period, when water flooded all the limestone tablets for several meters (Fig. 3.4.6). At such a high water level, which is usually also long lasting, the discharge of the Pivka River strongly prevails over that of the Nanoščica River. This is the reason for the low dissolution rates that were detected only at the top of the vertical zone at value -0.2 µm/a. This is even lower than during much lower water levels from the first measurement period. The hydrological situation during the third measurement period confirms that the most important factor for high dissolution rates is not just discharge but also the portion of the more aggressive Nanoščica River in the sinking stream. The lowest two measurement points at measurement location P-1 could indicate weak corrasion from the side of bed load material. Nevertheless, corrasion was only strong enough to remove part of the relatively soft organic material, while the limestone tablets remained visually uncorraded.

The fourth measurement period was characterized by very low and very high discharges during which the Nanoščica River contributed an important portion of water (Fig. 3.4.5). Unfortunately, long measurement periods average extreme events. One of them was a flood in September 2010, which was exceptional since it was the second highest in the last 100 years (Šebela 2010); it was generally an effect of the prevailing portion of the Pivka River. Average values (Fig. 3.4.5) and individual values at specific measurement points at measurement location P-1 (Fig. 3.4.4) were the lowest observed ever. At all vertical zones dissolution prevails over

Figure 3.4.6. *Flood in Veliki Dom (entrance chamber of Postojnska Jama) on 12 December 2008. Measurement location P-1 is located at the arrow about 8 m below the water level (photo: Mitja Prelovšek).*

deposition with an average value of -0.7 μm/a. Nevertheless, if we take into account that circumstances were in favour of high dissolution rates (7 of the 10 highest culminations of the high portion of the Nanoščica River and high water level in the front of Postojnska Jama in the whole measurement time span), the latter are still small.

3.4.2 Measurement locations P-1, P-2, P-3, P-4, P-5, P-6, P-7, and P-8 – temporal and longitudinal variability of processes along underground water flow from Postojna basin to Planina polje

Underground water flow of the Pivka and Unica Rivers (downstream from the confluence with the Rak River) is more than 10 km long. Since for non-divers the inaccessible distance between terminal sumps in Pivka Jama and Planinska Jama amounts to only ~1.5 km, already explored passages with numerous accesses to the underground flow provide us with an excellent opportunity to measure the rate of processes all along the underground water flow. The latter is crucial for studying the hydrological connection between the Pivka basin and Planina polje and therefore indirectly dictates the geomorphological evolution of both depressions.

The rate of dissolution or deposition was measured at eight measurement locations along the underground water course (Fig. 3.4.1). The upper one (P-1) was located 150 m from the entrance to Postojnska Jama and the lowest one 175 m upstream from the entrance to Planinska Jama. All measurement locations were placed at a similar depth and were under the water even during low water levels. The most evident difference between them is the velocity of water flow, which was the lowest at measurement locations P-1 and P-5 and the highest at P-3, P-2 and P-6. At all locations, measurements were done using three limestone tablets at the same time for better precision. Limestone tablets were fixed on stainless steel screws, nuts and felted washers.

At P-1, P-2, P-3, P-4, P-5 and P-8, measurement started on 26 September 2007 or before while at P-6 and P-7, measurement started on 19 February 2008. Due to some troubles (crumbling/grinding, washing away, uncompleted gathering of tablets), results are not always available for all four measurement periods.

The average rates of processes can be calculated only for measurement locations where all the results are available. These are, namely, P-2 (Spodnji Tartar) and P-5 (Pivka Jama). In both cases deposition prevails over dissolution but is significantly reduced away from the ponor (from 1.1 to 0.1 μm/a). Deposition in Spodnji Tartar can be related to biogenic film (organic material), which appears as a black coating on the limestone tablets. Growth of biogenic film is enhanced by pollutants that contain nutrients – concentration of the latter substantially decreases from the entrance to Postojnska Jama to Pivka Jama (Sket & Velkavrh 1980). Therefore, at least a portion of decreased deposition rates between Spodnji Tartar (P-2) and Pivka Jama (P-5) can be attributed to decreased growth of organic film.

Fig. 3.4.7 reveals some differences between measurement periods. Generally speaking, during all measurement periods a gradual decrease of deposition rates is characteristic between Veliki Dom (P-1) and Pivka Jama (P-3, P-4 and P-5). Further downstream, deposition becomes stagnant or gradually increases again. The highest deposition (and later decrease) was detected in the entrance part of Postojnska Jama, especially during the second measurement period. The latter period lasted over the summer when discharges were lower and water temperatures higher. The accumulation of biogenic film on the limestone tablets at P-1 and P-2 was visually obvious in the cave and was later incorporated into weight gain since it was not possible to remove it completely before weighing the tablets. Much lower values of deposition were characteristic for the autumn and winter months during the first and third measurement periods. During the fourth measurement period, the deposition rate at P-2 amounts to 0.6 µm/a, higher than expected at P-1 (see Fig. 3.4.4) and also higher in comparison with measurement locations P-3 and P-5, where slight dissolution was detected (-0.2 µm/a).

In Planinska Jama more than 7 km from the ponor of the Pivka River, the deposition of biogenic film was not visually observed on limestone tablets but deposition remained. The deposition rate increases constantly and unequivocally from P-6 (0.8 µm/a), to P-7 (0.9 µm/a) to P-8 (1.1 µm/a). Highly sensitive pH measurements from P-6 and P-8 showed a constant pH value (8.07-8.09). If we take into account that we detected outgassing of CO_2 in front of Planinska Jama and that outgassing of CO_2 can also be expected along the underground Pivka River in Planinska Jama due to the contribution of autogenic recharge along underground water flow and from the Javorniki Mountains, a constant pH value can be sustained only by sinter deposition. This conclusion should be verified in the future, but up to now it gives us the most reliable explanation for increasing deposition rates along the Pivka River in Planinska Jama.

Along the underground Pivka and Unica Rivers, passages have been formed along faults and tectonically deformed bedding planes (Šebela 1998; 78). A strong prevalence of breakdown morphology is therefore expected, but according to our results it can be dissolutionally modified on the ceiling and depositionally modified at the bottom of the water channel. The most evident dissolutional features along the underground water course of the Pivka River are scallops, which form during fast water flow, where dissolutionally widened cracks and poorly developed boxwork exist, formed initially when the water flow was relatively slow. The formation of all dissolu-

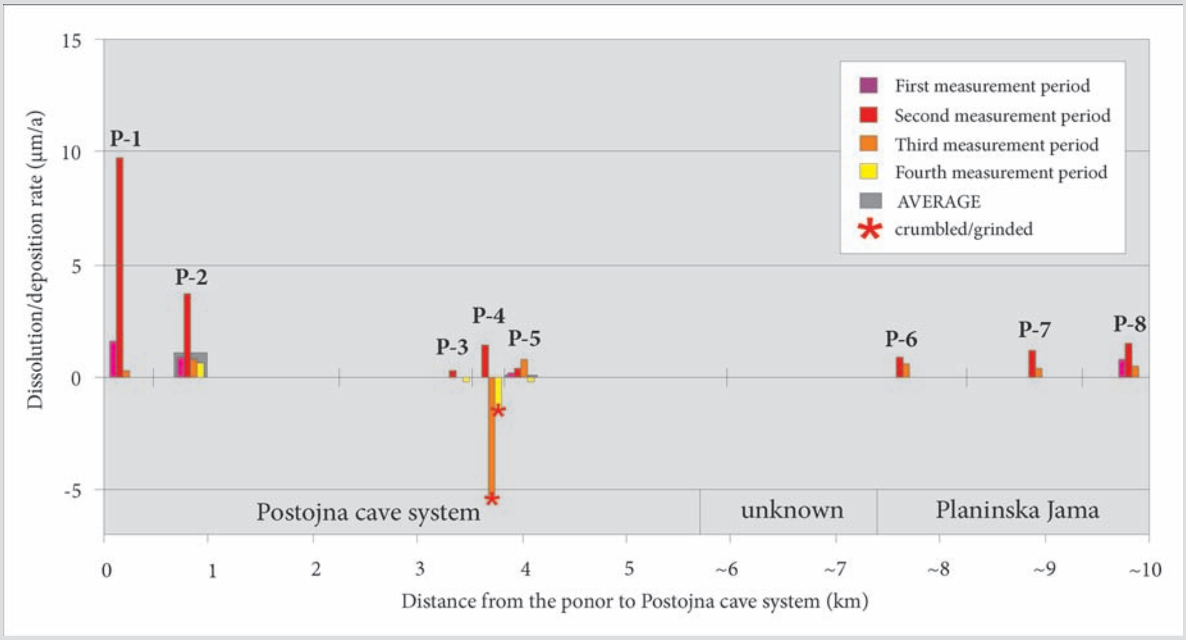


Figure 3.4.7. *Dissolution/deposition rates during four measurement periods between Postojna basin and Planina polje (in Postojna cave system and Planinska Jama) between 26 September 2007 and 24 August 2011. Due to some missing data, average dissolution/deposition rates are only calculated for P-2 and P-5.*

Figure 3.4.8. *Dissolutional morphology and limestone tablets at P-5 (Pivka Jama). TD Diver for measuring water level and temperature was used by Janez Turk.*

tional features can be explained by present-day processes, but for the formation of the whole feature, several tens of thousands of years are needed. In Planinska Jama, the absence or at least very weak dissolution is proven also by the many thin and fragile carbonate cave snail shells that are deposited on the banks and cannot be dissolved by the Pivka or Unica Rivers. Features that are observed in the lower portion of the water channel (Fig. 3.4.9) cannot be formed by present-day processes (present-day chemical processes are able to preserve them but not to renew them) and are therefore inherited from the past when the chemical characteristics of the water were different. This is also evident from the smoothened transitions between scallops (Fig. 3.4.9).

3.4.3 Measurement locations P-7, P-8 and C-7 – measurement of mixing corrosion at underground confluence of Pivka River and Rak River

The confluence of the Pivka River and the Rak River is one of the biggest underground confluences in the world. At a specific hydrological situation (middle-low discharges), both streams that join at Sotočje (confluence) have very different catchment areas; the Pivka River drains mostly allogenic waters from the northern Pivka basin while the Rak River drains the autogenically recharged water of the Javorniki Mountains. During winter and summer months water temperature and related chemical parameters are also different, which can lead to mixing corrosion. At high discharge, the hydrological situation is much more complex – both rivers are fed by diffuse autogenic, concentrated autogenic and allogenic recharge.

To observe possible dissolution due to mixing, three measurement locations were used. Measurement location P-7 was located in the underground Pivka River, C-7 in the Rak

River and P-8 300 m downstream from the confluence in the underground Unica River where waters were well mixed. At each measurement location three limestone tablets were used at the same time to obtain more precise data. All limestone tablets were placed in very similar hydrological conditions; they were flooded at low and high water levels and dry only at very low water levels. The water flow can be characterized as turbulent and subcritical; only at C-7, given a higher velocity can the flow be characterized as supercritical. Limestone tablets were fixed with stainless steel screws, nuts and felted washers.

Measurement at P-8 began on 26 September 2007, on P-7 and C-7 on 19 February 2008. Therefore, only data from 19 February 2008 till 26 March 2009 (end of measurements) were used for evaluation.

Results are presented in Tab. 3.4.1. On average, all measurement locations indicate deposition, which, due to the absence of black organic coating, is thought to be sinter deposition. The lowest rates were observed in the Rak River (C-7), where the average rate corresponds to rates at Malni springs and in Tkalca Jama located upstream (Prelovšek 2009). Deposition is slightly higher at P-7 (Pivka River) and the highest downstream from confluence in the Unica River. It is worthy of note that the same succession was observed during the second and third measurement periods. During the third measurement period, slight dissolution in the range of average error was observed in the Rak River. During the second measurement period, which was characterized by low discharges especially in the second part of the measurement period (Fig. 3.4.5), the rates in the Pivka River were similar to those in the Rak River although the catchment areas were characterized by various types of recharge.

Instead of possible dissolution or the lowest sinter deposition due to mixing, the highest sinter deposition rates were observed downstream from the confluence at P-8. A possible explanation is that outgassing of CO_2 from the water, which is the highest downstream of the confluence due to the nearness of the well ventilated entrance to Planinska Jama, prevails over mixing. If mixing dissolution (or lower sinter deposition) occurs, it is limited to several tens of meters downstream from the confluence where measurements are difficult to perform due to a spatially extensive zone of mixing.

Table 3.4.1. *Dissolution or deposition rates (µm/a) at the underground confluence of the Pivka River and the Rak River between 19 February 2008 and 26 March 2009.*

	P-7 (Pivka River)	C-7 (Rak River)	P-8 (Unica River)
First measurement period	/	/	0.8
Second measurement period	1.2	1.1	1.5
Third measurement period	0.4	-0.1	0.5
AVERAGE	**0.9**	**0.6**	**1.1**

3.4.4 Conclusion

The cave system between Postojna basin and Planina polje (Postojna cave system and Planinska Jama) connects two extensive closed depressions. The relationship between depressions and cave systems is bidirectional – the cave system provides a drainage system for the basins but conditions in basins influence cave system genesis.

The lowest and therefore hydrologically active passages of this cave system are currently influenced by the Pivka River. The latter (downstream from the confluence with the Nanoščica River) shifts from undersaturated during high water levels (in cases when the Nanoščica River strongly prevails) to oversaturated when the water level is low. In the case of high water levels and a small portion of the Nanoščica River, the dissolution rate is absent or too low to be reliably detected with limestone tablets (under -0.1 µm/a). Since both processes overlap, especially in the lower parts of water passages, we should speak about net deposition rates instead of deposition rates since net rates are composed of deposition during low water levels and occasional dissolution during high water levels. The shortest and the most extreme the measurement period is, the most extreme the rates are to be expected.

The main chemical net process in the lower portion of water passages is net (sinter) deposition that on average amounts 1.1 to 0.1 µm/a. It is higher in the entrance part of Postojna cave system and Planinska Jama. The middle part of the underground system (Pivka Jama) indicates lower net deposition rates (0.5 µm/a) due to lower deposition rates during low-middle water levels. In shorter measurement periods (if only summer low water levels are taken into account – e.g., during the second measurement period) net deposition rates can be up to 10 µm/a high.

Dissolution is characteristic for the upper portion of water passages and can (on average) amount in the entrance part of Postojnska Jama up to -0.6 µm/a. The strongest dissolution rates were detected during the fourth measurement period (-1 µm/a) when the Nanoščica River prevailed at least at the rising limb of high water levels. On average, vertical net transition from net deposition to net dissolution occurs when water rises by about 30 cm above the low water level in Veliki Dom.

Although several tributaries with different water characteristics join the underground Pivka River (the strongest one being the Rak River in Planinska Jama), rates of chemical processes are not influenced much. Results from Planinska Jama show that theoretic mixing dissolution is overshadowed by outgassing of CO_2 from the water. Consequentially, even higher sinter deposition is characteristic for measurement locations downstream of the confluence.

Although the prevailing morphology of hydrologically active passages indicates a strong influence of collapsing, some parts of the passages show (epi)phreatic dissolutional morphology. Present-day processes support the formation of such morphology only in the upper parts of the water passages over longer periods of time (several tens of thousands of years). Due to prevailing deposition, the formation of dissolutional morphology in the lower parts of water passages is not possible and present-day features at such locations have to have been inherited from the past. One possible period for their formation is during a colder climate, when a higher percentage of superficial runoff and lower CO_2 concentration in diffuse autogenic recharged water would certainly support higher aggressiveness of the water that sinks into Postojnska Jama.

4

GENERAL CONCLUSIONS, DISCUSSION AND POTENTIAL FOR FURTHER RESEARCH

4.1 Methodology

Measurements of karst processes require the use of special techniques, among which the use of micrometer (MEM), hydrochemical methods, and limestone tablets are the most widely known. The MEM provides the most direct way to observe surface lowering or rising and is therefore the most relevant methodology for defining absolute rates of processes at specific locations. However, the influence of error increases with decreasing rates or with frequent MEM measurements. Since the rate of chemical processes on the karst is usually low, the effective use of a micrometer is limited to places with exceptionally strong dissolution rates or where several years are available for single measurements.

In specific situations, the highest accuracy can be achieved through hydrochemical analysis; for example, if a cave stream extends over several hundreds of meters without tributaries and the reaction surface is known. These conditions are hard to come by, though. The hydrochemical method averages rates over several hundreds of meters, which can be problematic at places where microlocal changes occur due to different flow velocities (in our cases in Križna Jama and in Lekinka cave).

The use of limestone tablets is a site-specific methodology and from this perspective falls between the MEM and hydrochemical methods. The biggest advantage of measuring with limestone tablets is their high precision (up to ±0.05 μm) and accuracy (on average ±0.2 μm; maximum error ±0.4 μm) if we dry them in a desiccator and oven or if we use a correction equation to reduce the influence of relative humidity. Another advantage is having the ability to compare dissolution or sinter deposition rates regardless of lithological differences between measurement locations (e.g. caves). The latter can be a problem if we are interested in absolute rates at a specific measurement location in the cave, especially if net sinter deposition is observed or the lithology at the measurement location is much different in comparison with standard limestone tablets (in our case in Križna Jama). If we are observing net dissolution rates, the naturalization of the limestone tablet's surface can be achieved with exposure to a measurement location for an assumed period when about 25 μm of the limestone tablet's surface is dissolved. Limestone tablets should be fixed with non-oxidizing and non-abrasive material like stainless steel (inox) or plastic (PVC). Shorter intervals of measurements reduce the influence of cave microorganisms, which can play a significant role at weak dissolution rates but require stable living conditions, which are significantly changed with short measurement intervals when the limestone tablets are dried. A similar poorly understood influence is caused by washing out the deposited fine-grained sediment. At places with high corrasion rates, the use of limestone tablets yields irrelevant results; a MEM is better – although, in such cases we are not measuring just dissolution rates but a spatially highly changeable sum of dissolution and corrasion rates. The use of limestone tablets is the simplest one in the field since it requires only limestone tablets, screws, nuts and felt washers for fixation and some standard equipment for single rope technique (i.e. a drill). Preparation of limestone tablets can be done in a laboratory.

To conclude, the use of appropriate methodology for measurements depends mainly on rates of processes, presence of corrasion, goals of measurements (absolute vs. relative rates) and accessibility of passages (limestone tablets are easier to transport). At least in the Slovene (Prelovšek 2009) and Australian stream caves (Spate et al. 1985) where precise measurements were already taken, rates of chemical processes are usually so low that use of limestone tablets is practically the only suitable methodology for defining dissolution or sinter deposition rates within several years. Some additional experiences with limestone tablets are needed to confirm the suitability of this methodology for correct absolute (at least net dissolution) rates. Although we took some measurements, additional work can be done with contemporary measurements over shorter and longer intervals to evaluate the role of cave microorganisms and clay/silt sedimentation in dissolution and sinter deposition. Additional comparable measurements with limestone tablets and a MEM would also be beneficial.

4.2 Rates of dissolution/sinter deposition

It is hard to simplify and average underground dissolution or sinter deposition rates in stream caves since they depend on many factors besides discharge. This is the reason for very different directions and rates of processes evident at the same time (Fig. 4.1). For nearly all case studies (the only exception might be Lekinka cave), chemical processes are bidirectional in the bed of a water channel. This means that at the same measurement locations, dissolution and sinter deposition was detected during a year, a circumstance confirmed in other caves (Palmer 2007). If cumulative rates are measured over longer periods, net rates depend on the intensity and duration of dissolution and sinter deposition rates. It is somehow surprising that net dissolution prevails over net deposition only in Lekinka. This is a result of the origin of the water that derives from diffuse infiltration through soil and the vadose zone and becomes oversaturated due to the outgassing of CO_2 from the water at well ventilated passages and at the surface. From the Slovene perspective it is interesting that the aggressiveness of the main karst streams was denied by Oertly's hydrochemical measurements, a questionable matter for Melik (1955) and generally accepted by Gams. It is possible that net dissolution takes place in weakly or non-aerated passages but such passages can be accessed only by divers. Several decimetres or metres above the bed of a channel, only (net) dissolution can be expected.

In general, annual dissolution or sinter deposition rates in stream caves are low, which corresponds to the notion of the long-term evolution of individual passages. Along the most known cave streams (e.g. Škocjanske Jame, Postojna-Planina cave system and Cerknica-Planina polje cave system (Prelovšek 2009 and non-published data)), rates weaker than µm/a are common. Such rates are characteristic for caves influenced by diffuse autogenic recharge, mixed autogenic-allogenic recharge and even allogenic recharge, where a sinking stream at least partly

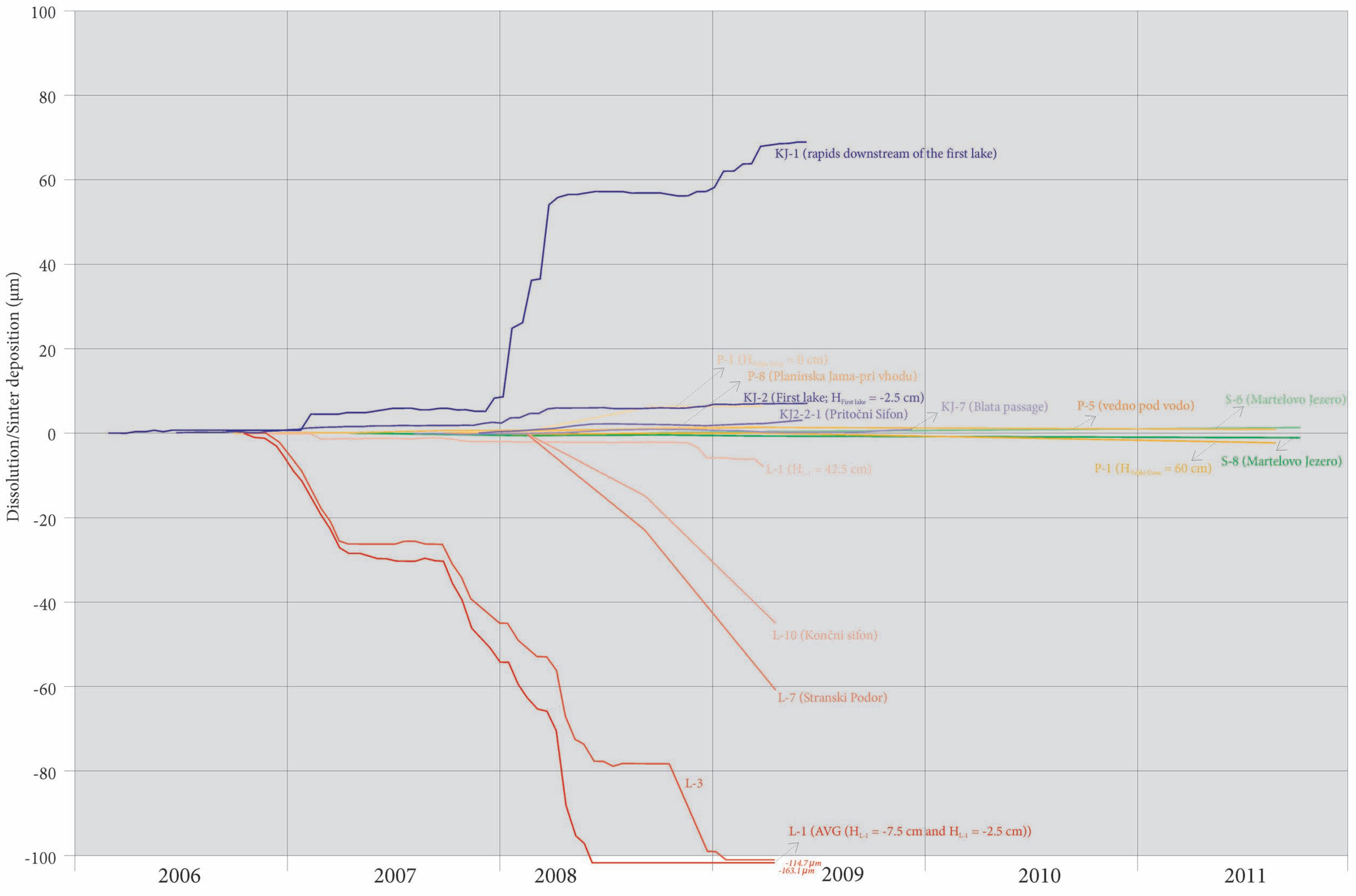


Figure 4.1. *Temporal course of dissolution and sinter deposition at the most characteristic measurement locations obtained in case studies.*

drains the catchment area underlain by carbonate rocks. In the case of Škocjanske Jame calcite precipitates from the water already at the contact between siliciclastic flysch rocks and limestone and the same process with similar rates continues in the underground Reka River. Nevertheless, dissolution rates a magnitude higher are expected during hundreds of thousands (even of a million or more) of years since (a) present-day sinter deposition rates do not result in dissolutional enlargement of beds of passages (Križna Jama-Križna Jama 2 cave system, Škocjanske Jame, Postojna-Planina cave system) or (b) dissolution rates during suitable conditions are too low to produce an actual cross-sectional profile of passages in several millions of years. Shift from (a) prevailing sinter deposition to dissolution or (b) from weak dissolution to stronger dissolution rates, can be achieved with climate changes or changes of hydrological systems. The thickness of flowstone coating in Škocjanske Jame and in Križna Jama suggests that annual net sinter deposition rates are characteristic for the Holocene epoch but not for the Pre-Holocene – during the Pre-Holocene net dissolution rates prevailed or at least equilibrium between annual dissolution and annual sinter deposition was reached.

The strongest dissolution or sinter deposition rates are characteristic only for places where the strongest deviation from $SI_C = 0$ exist; this is due to high H^+ concentration and low Ca^{2+} concentration (e.g. Lekinka cave) or due to the depletion of H^+ cations (rise of pH) as a result of the outgassing of CO_2 from the water (e.g. Križna Jama). The strongest annual dissolution rates were detected in Lekinka (on average -61.1 µm/a at measurement location L-1) and the highest sinter deposition rates in Križna Jama (on average 87.4 µm/a at Brzice (rapids) downstream from the first lake). Rates during the 15-day measurement period can be, due to very high weekly and even daily variation, much higher, for example -9.0 µm/15 days (-219 µm/a for comparison) for dissolution rates and more than 17.0 µm/15 days (413.7 µm/a for comparison) for sinter deposition rates. Even stronger rates are to be expected if the rates are measured in shorter intervals - i.e., per week, per day or per hour.

Temporal variability was already discussed in the previous paragraph. We could expect that sinter deposition is characteristic for lower discharge and dissolution for higher discharge. But since discharge is not the only factor, we can only say that sinter deposition cannot take place during high discharge and, aside from in Križna Jama-Križna Jama 2 and Lekinka cave, dissolution cannot take place during low water levels. Other important factors that influence direction and intensity of rates are origin of water and seasonal changes of soil CO_2 concentration or seasonal changes in ventilation. Usually, the highest dissolution and sinter deposition rates do not depend on the highest or the lowest discharge. Only in the case of Škocjanske Jame, were the highest dissolution rates observed during the highest water levels and it seems that the highest sinter deposition rates occur at the lowest water levels. The strongest dissolution rates at other locations (Postojna-Planina cave system, Lekinka cave, Križna Jama-Križna Jama 2 cave system) primary depend on the influence of other factors (origin of high water, seasonal changes of soil CO_2 concentration, seasonal changes in ventilation…). Similarly, the highest recorded sinter deposition rates were not related to the lowest discharge but on winter ventilation of the cave (Križna Jama). Nevertheless, for the highest sinter deposition rates discharge should not be very high. It would be interesting to observe seasonal variation of dissolution and sinter deposition in other stream caves since a similar course of processes can be expected in other caves recharged by intensive diffuse infiltration of percolation water and can therefore be a universal phenomenon of temperate zones.

Usually, spatial variability of dissolution or sinter deposition rates along cave streams are low (Škocjanske Jame, Postojna-Planina cave system), but if we are close to changes of CO_2 and Ca^{2+} in the water and if the exchange of matter between carbonates-water-air is considerable, very high spatial variability can be observed. Tributaries of allogenically and autogenically recharged water in the Postojna-Planina cave system do not significantly influence dissolution or sinter deposition rates, while in Križna Jama the highest sinter deposition rates are significantly reduced downstream of the confluence with autogenically recharged tributaries that have higher partial pressure of CO_2. The influence of mixing corrosion can be detected at some measurement locations (e.g. at Kalvarija (calvary) in Križna Jama) but it seems that its importance is exaggerated in the literature since we observed other factors of greater importance (e.g. outgassing of CO_2 from the water at the confluence of the Pivka and Rak Rivers in the Postojna-Planina cave system). Up to a 10-times high difference in sinter deposition rates (Križna Jama-Križna Jama 2 cave system) or about 10 % difference in dissolution rates (Lekinka cave) can also be a result of hydraulic differences between measurement locations, in our cases between rapids and pools/lakes.

Although dissolution and corrasion are quite different processes, they can be 'cooperative' and support each other (dissolution can remove cement and corrasion tears off the weakly attached crystals). Therefore, strict differentiation between the two is not possible. Nevertheless, in some cases corrasion strongly prevails over dissolution and can be responsible for the majority of denudation. In our case studies, a higher influence of corrasion can be expected in Škocjanske Jame and in Lekinka cave since they are both fed by allogenic streams. Corrasion due to bed load transport can be seen in Škocjanske Jame as polished surfaces in the bed of a channel and corrasion rates there are much higher than rates of dissolution. At such places, limestone tablets were severely damaged by bed load material. Nevertheless, even some centimetres away, where high concentration of suspended load can be expected, net sinter deposition rates (0.4 µm/a) can be stronger than rates of corrasion, which can be proven by the presence of preserved (and most probably thickening) flowstone coating. Measurements undertaken several metres higher in the water channel show that corrasion rates from suspended load together with dissolution is weaker than -0.2 µm/a. In Lekinka cave, the influence of corrasion is less expressed in morphology. Results of measurements at least show that corrasion as a result of suspended load is negligible compared with dissolution.

In many cases, rates of dissolution or sinter/tufa deposition are not equal in cave streams and in surface streams. In the latter, dissolution rates can be much higher due to high biocorrosion (up to -150 µm/a). Therefore, rates at illuminated springs or ponors cannot be applied to caves located upstream or downstream.

4.3 Relation between present-day processes, factors and features

We suppose and did indirectly confirm that factors can change significantly over several hundreds of thousands (even a million or more) of years. This influences the direction and rate of chemical processes and results in a changeable morphology of caves. Although we performed short-term measurements with a chosen methodology, sometimes serious discrepancies were detected between actual and potential morphology even though the measurements were taken during times of significant discharge with a return period of ~50 years. Such discrepancies were greatest where the direction of present-day processes is of controversial morphology (i.e. dissolutional morphology with prevailing sinter deposition) and rates are weak. In such cases, inherited features are obvious in the bed of a channel (Postojna-Planina cave system) or slightly higher up (Križna Jama and to some extent Križna Jama 2).

There are stream caves where the current prevailing sinter deposition rates are in contradiction with cave formation or with at least actual cross-sectional morphology. From such cases, where thickness of actual flowstone coating fits with potential thickness of flowstone coating if present-day sinter deposition rates are extended through the Holocene epoch, it is clear that an important change of direction and/or rates of chemical processes in cave streams were caused by climate change between the last Ice Age during the Pleistocene and Holocene[4]. This can be interpreted through the influence of temperature, length of vegetation season and soil microbial activity, partial pressure of CO_2 in the percolation water and consequential potential for the outgassing of CO_2 from autogenically recharged water. The decrease of CO_2 partial pressure in the water was recognized as an important factor for the downstream increase of SIC in Križna Jama and most probably also occurs in the Pivka River between its spring and ponor in the Postojna-Planina cave system. More intensive direct runoff from the surface due to partly frozen ground or different precipitation regime should result in lower hardness of water (Nanoščica River) and higher dissolution rates. In Lekinka, the biggest wall notch 75 cm from the bed of the channel and the current dissolution rates (-61.1 μm/a) suggest that the wall notch was formed during the Younger Dryas stadial when the climate was the coldest in the Late Pleistocene and the wall notch development can possibly be due to the protection of the bed of the channel during more intensive transport and accumulation of sediment.

Where the rates of chemical process are stronger, a high correlation was recognized between morphology and processes. The actual morphology of Škocjanske Jame that shows flowstone coating at the bottom of a channel, scallops 1.5 m higher and absence of scallops more than ~2 m above the bed of the channel, is concordant with average annual chemical processes in the Reka River and certain other factors (flooding, freezing in winter time). In Križna Jama in the first lake and downstream at Brzice (rapids), morphology in the bed of the channel also comports with the present direction and rates of processes.

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[4] *This phenomenon was already observed in the growth of stalagmites (Mihevc 2001) and tufa dams but it was rarely attributed to speleogenesis in stream caves in an epiphreatic (or shallow phreatic) zone.*

5
POVZETEK

5.1 Uvod

Sedanje poznavanje kraških oblik, dejavnikov in procesov temelji na več kot stoletje dolgem intenzivnem proučevanju kraških pojavov. Prva temeljna spoznanja in konceptualne ideje o kraških pojavih imajo korenine že v 19. stoletju, ko so bile poznane osnove raztapljanja karbonatov, vloga CO_2, osnovni mehanizmi pretakanja vode in vertikalna conacija kraških masivov. V 20. stoletju se je to znanje večinoma le še izpopolnjevalo, močno poglobilo, razvoj jamarske tehnike pa je omogočil tudi boljši vpogled v notranjost kraških masivov. Rezultati meritev podani v tej monografiji niso nič več kot le dodaten delček v mozaiku znanja o krasu, ki ga lahko z izboljšanimi metodami tudi vse bolj točno kvantificiramo, obenem relativiziramo, predvsem pa čedalje bolje objektivno spoznavamo.

Naslov monografije omejuje njeno dimenzijsko razsežnost, in sicer v času (današnji pojavi), vodilnemu predmetu (procesi) ter prostoru (vodne jame). Recentna dinamika je bila v slovenski geomorfologiji, pa tudi v svetovni speleologiji, vedno v senci drugih raziskav, ki so bile osredotočene na pretekli običajno zelo dolg razvoj jam (speleogenezo). To je povezano z željo po časovno čim celovitejšem proučevanju razvoja jam, ki v krasu običajno poteka več 10.000, 100.000 ali celo nekaj milijonov let. Recentna morfodinamika je zaradi tega precej slabše poznana, tudi v svetovnem merilu (Gunn 1986). Velik primanjkljaj je predvsem na nivoju poznavanja dinamike recentnih procesov, kar velja za celotno področje slovenske geomorfologije (Natek 1993; 48 po Natek 1983; 87). Načrti o meritvah geomorfne aktivnosti podzemnih voda sicer segajo že v 60. leta 20. stoletja, vendar niso bili načrti nikoli realizirani. Precej bolje so raziskani dejavniki, ki vplivajo na kraške procese, vendar ne nujno z geomorfološkega vidika (npr. fizikalno-kemijske analize voda, litološke litološke značilnosti kamnin). Pri naštetem se primanjkljaj kaže v geomorfološkem vrednotenju hidroloških in litoloških podatkov. Precej bolj pestro in široko je znanje o speleomorfologiji, ki je najbolj očiten in najlažje prepoznaven rezultat učinkovanja kraških procesov pod vplivom dejavnikov. Izstopa predvsem proučevanje morfologije večjih aktivnih in fosilnih jamskih rovov, ki nam pogosto ne poda le informacij o razvoju jame, ampak tudi o razvoju okolice, ki je močno vezana na jamo. Tudi v tej monografiji smo se osredotočili na proučevanje pomembnejših aktivnih vodnih jam, pri katerih smo si zastavili naslednje cilje:

- testiranje metode merjenja procesov z apnenčastimi ploščicami, uvesti izboljšave

na področju ustreznejše pritrditve in merske natančnosti ter metodo primerjati z drugimi razpoložljivimi metodami za ugotavljanje recentnega raztapljanja,
- ugotoviti smer in intenziteto recentnih speleogenetskih procesov v pomembnejših vodnih jamah slovenskega krasa ter opredeliti vodilne dejavnike, ki na procese vplivajo, in oblike, ki pri tem nastajajo,
- izboljšati vpogled v povezavo med speleogenetskimi procesi, dejavniki in oblikami,
- določiti potencialne speleogenetske oblike, ki z recentnimi procesi šele nastajajo, in jih primejati z aktualnimi oblikami v kraškem podzemlju, ki so lahko podedovane.

Običajno se je na recentne procese sklepalo iz podzemnih oblik, ki jih občasno dosega podzemna voda (Slika 1.1a na strani 12). Pri tem se je pogosto zavračalo dejstvo, da recentne oblike morda ne nastajajo več z recentnimi procesi, saj so se dejavniki v času spremenili (npr. sprememba klime, hidroloških razmer v porečju, tektonski premiki) in so zato lahko dediščina procesov v preteklosti. Pogoj za dolgoročno ohranjanje oblik je majhna intenziteta procesov, ki je bila že prepoznana v nekaterih študijah (Spate et al. 1985, Gams 1996). Zaradi tega smo za proučevanje recentne in pretekle morfodinamike uporabili drug pristop (Slika 1.1b), pri katerem smo ločili recentne procese z dejavniki od aktualne morfologije. Ločenost analize nam omogoča navzkrižno primerjavo med aktualno in potencialno morfologijo ter določitev preteklih dejavnikov, v kolikor je odstopanje očitno.

5.2 Raziskovalne metode

Za meritev recentnih procesov smo uporabili mikrometrske meritve, apnenčaste ploščice, v omejeni obliki pa tudi hidrokemično metodo. Mikrometrske meritve so najbolj uporabljena metodologija za ugotavljanje mehanskih (korazijskih) in kemičnih procesov na krasu (npr. High & Hanna 1970 po White 2000, Spate et al. 1985, Mihevc 1993, Mihevc 1997, Mihevc 2001), saj je metoda enostavna, meri se dejansko odmikanje (ali približevanje) jamske stene, omogoča več meritev na istem mestu ter izračun standardnih odklonov na posameznih vzorčevalnih ploskvah. Slabosti metode so relativno visoke napake meritev, katerih vpliv se veča s šibkostjo procesov (Spate et al. 1985). Hidrokemične meritve so se večinoma izvajale na izvirih z meritvami prevodnosti, s katero se določa celokupna trdota, in meritvami pretokov. Čeprav omogoča metoda tudi ugotavljanje raztapljanja oz. odlaganja sige med dvema točkama vzdolž podzemnega toka brez vmesnih pritokov, je slabost pri preračunavanju v metrične enote zlasti težko določljiva reakcijska površina. Rezultati prostorskih meritev vzdolž toka nam torej veliko bolje podajajo smer procesa (raztapljanje ali odlaganje) kot pa dejansko intenziteto le-tega.

V želji po čim bolj natančnih meritvah smo največ meritev opravili z metodo apnenčastih ploščic, ki smo jo pred (poglavje 2.2.2) in tekom meritev na posameznih izbranih primerih (poglavje 3) preizkušali ter jo tudi primerjali z mikrometrskimi meritvami. S strani raziskovalcev procesov na krasu so bile apnenčaste ploščice običajno uporabljene za meritve intenzitete raztapljanja v prsti (Trudgill 1975 po Gavrilović & Manojlović 1989, Jennings 1977 po Gavrilović & Manojlović 1989, Trudgill 1977, Day 1984 po Gavrilović & Manojlović 1989, Gavrilović 1986 po Gavrilović & Manojlović 1989, Sbai 1993, Trudgill et al. 1994, Urushibara-Yoshino 1999 po Ford & Williams 2007, Plan 2005), le redko tudi v jamah (Chevalier 1953 po Gams 1985, Gams 1959, Rebek 1964, Delannoy

1982 po Gams 1985, Gams 1996). Teoretično je lahko ta metoda veliko natančnejša od mikrometrske, saj izračunavamo tanjšanje ploščic iz dosti lažje določljive razlike v teži, vendar tudi njo spremlja več potencialnih napak. Prva je povezana z vplivom spreminjajoče se relativne vlažnosti pri tehtanju, ki so se jo v preteklosti ognili s sušenjem apnenčastih ploščic v pečici pri temperaturah nad 100 °C in v silica gelu (Gams 1985), kar pa pri večkratni uporabi taistih apnenčastih ploščic lahko pripelje do intenzivne migracije vode iz notranjosti na površino apnenčastih ploščic in neželenega otrdevanja površine (t.i. case hardening). Klasično sušenje več deset ploščic v 15-dnevnem zamiku preko več let bi bil tudi znaten tehničen zalogaj. Zaradi tega smo uvedli korekcijski faktor, ki izniči spremembo relativne vlage v kemijskem laboratoriju Inštituta za raziskovanje krasa ZRC SAZU, kjer so bile meritve opravljene (Slika 2.3 na strani 20). S tem korekcijskim faktorjem in ob odsotnosti drugih znanih vplivov smo vpliv napake pri 20-25 g težkih ploščicah zmanjšali na povprečno ±0,2 µm, največ pa ±0,4 µm napake. Le-to se da še nadalje zmanjšati s terensko uporabo korekcijskih ploščic, ki jih vodni tok ni dosegel, so pa bile postavljene, pobrane in sušene skupaj s ploščicami, ki jih je vodni tok dosegel. S tem pridobimo na točnosti, večjo preciznost pa dobimo z uporabo večjega števila apnenčastih ploščic na istem mestu (Slika 2.1.3.6; Slika 2.1.3.7). S tem se povprečna napaka zmanjša na ±0,05 µm, maksimalna pa na ±0,2 µm. Znatno napako pri merjenju lahko povzroči oksidacija železa, ki ga uporabljamo za pritrditev. Intenziteta zavajajočega raztapljanja, ki se pri tem pojavlja, je močno odvisna od lokacije in znaša od 0,0 do -2,4 µm v 30 dneh merjenja (slika 2.4 na strani 21). Zavajajočemu raztapljanju s strani železovega oksida se lahko izognemo s pritrditvijo ploščic na nerjaveč ali plastičen vijak. Med njimi bistvenih razlik ni opaziti. Del napake pri meritvah z apnenčastimi ploščicami je povezan tudi s sveže odrezano nepreperelo površino, ki se obnaša drugače od deloma preperele jamske stene. Zaradi drobnih deloma zdrobljenih kristalov na površini apnenčaste ploščice, lahko na začetku meritev pričakujemo do okoli 2 µm na 15 dni višjo intenziteto raztapljanja (Slika 2.6 na strani 23). Razlika izgine, ko je odstranjena okoli 25 µm debela plast apnenčaste ploščice. Še večja razlika se pojavlja pri odlaganju sige (Slika 2.7 na strani 24). Del variabilnosti izhaja tudi zaradi heterogenosti med apnenčastimi ploščicami, in sicer v povprečju ±0,5 µm na 15 dni (največ -1,3 ter 0,7 µm na 15 dni), vendar so razlike v daljšem časovnem obdobju povprečene, zato je topnost v daljšem obdobju praktično enaka (Slika 2.6 na strani 23). Največja odstopanja lahko izhajajo iz različne litološke sestave ploščic. V kolikor merimo z apnenčastimi ploščicami, odstopanja niso velika (do 20 %; Slika 2.8 na strani 26). Če pa merimo v jamskih rovih izoblikovanih v dolomitu, je lahko hitrost raztapljanja zlasti ob precejšnji nenasičenosti vode (Gerstenhauer & Pfeiffer 66 po Sweeting 1972; 28-29, Chou et al. 1989 po Dreybrodt 2004; 297-298) do 90 % nižja. Precejšen del napake lahko izhaja tudi iz poškodb pri transportu, vendar se ji lahko v celoti ognemo s prenašanjem ploščic v posebej za ta namen izdelanem nosilcu (Slika 2.5 na strani 22). Primerjava med metodo apnenčastih ploščic in mikrometrom pokaže, da sta raztapljanje in odlaganje sige izmerjeni z mikrometrom običajno intenzivnejši v primerjavi z meritvami z apnenčastimi ploščicami (Slika 2.9 in 2.10 na strani 27). Ni nujno, da napaka izhaja le zaradi uporabe apnenčastih ploščic, saj lahko tudi uporaba mikrometra pripelje do nekaj µm velikih napak (npr. velike temperaturne razlike med posamičnimi meritvami, abrazija z mikrometrsko konico). Čeprav obe meritvi izkazujeta enako magnitudo procesov, so lahko odstopanja precejšnja in terjajo nadaljnje proučevanje.

Metodologija merjenja procesov z apnenčastimi ploščicami je bila preizkušena na 85 lokacijah večinoma po slovenskem krasu v 8-mesečnem merilnem obdobju. Rezultate meritev temeljiteje analizira Prelovšek (2009) v svoji doktorski disertaciji. Na tem mestu naj opozorimo le na ugotovljeno nizko intenziteto kemičnih procesov v vodnih jamah (večina med -1 in -10 µm/a, povprečje -7.4 µm/a, mediana -1,5 µm/a), večkrat prevladujočo smerjo odlaganja sige namesto raztapljanja ter znatno večjega raztapljanja na izvirih v primerjavi z jamami v zaledju zaradi vpliva biokorozije. Pri meritvah je potrebno predvsem na alogenih vodotokih upoštevati tudi pojav korazije. Regionalne in lokalne razlike so lahko majhne ali izredno velike; med največjimi so med Postojnsko jamo in Lekinko, ki sta oddaljeni le kilometer, v samih rovih pa na intenziteto procesov vpliva tudi višina merjenjav jamskem rovu.

Fizikalno-kemične lastnosti vode smo ugotavljali z meritvami v laboratoriju in na terenu. Koncentracija Ca^{2+} je bila ugotovljena s kompleksometrično titracijo z 0,01 M EDTA, koncentracija Mg^{2+} pa z odštevkom koncentracije Ca^{2+} od celokupne trdote vode. Alkalnost je bila ugotovljena s titracijo z 0,02 M HCl pri končnem pH = 4,5. Obe koncentraciji sta nam omogočili izračun razmerja Ca/Mg. Specifična elektroprevodnost (SEP) kot vsota vseh raztopljenih snovi, pH kot koncentracija H^+ ionov in temperatura so bili izmerjeni z merilcem WTW Multiline P4 in ustreznimi sondami na terenu. Indeks nasičenosti glede na kalcij (SI_C) je bil ob pridobljenih koncentracijah Ca^{2+}, Mg^{2+}, alkalnosti, T, SEP in pH izračunan s programom WATEQ4F (Ball & Nordstrom 1991). Pretok vode smo merili z injektiranjem vodne raztopine NaCl v vodotok ter dolvodnim merjenjem SEP v znanem časovnem intervalu (Käss 1998) ter določeni pretočni krivulji (Križna jama in Lekinka). Vodostaj smo ugotavljali bodisi vizualno bodisi z digitalnim registratorjem vodnega nivoja Schlumberger TD-Diver. Med marcem in oktobrom 2007 smo v Križni jami za meritve vodostaja, temperature in SEP uporabljali Gealog S.

Karakteristike zraka smo ugotavljali predvsem z vidika gibanja (intenziteta, smer) ter koncentracije CO_2. Prostorske meritve ter meritve v 20 do 12 dni dolgem časovnem razponu smo izvajali s prenosnim merilcem CO_2 Vaisala GM70 z pripadajočo sondo GMP222 z maksimalno koncentracijo 3.000 ppm.

5.3 Izbrani primeri s slovenskega krasa

Jamski sistem Križna jama-Križna jama 2

Sistem obeh Križnih jam leži v sredini trikotnika med Cerkniškim poljem, Loškim poljem in Bloško planoto. Preko 9.688 m dolg in pretežno vodoraven jamski sistem je razvit v tektonsko slabo pretrtih spodnje jurskih apnencih. Skrajni gorvodni deli Blat ležijo že v spodnje jurskem zrnatem dolomitu. Jamski sistem sestavlja v grobem en glavni vodni rov, ki se gorvodno od Kalvarije (Križna jama) razcepi v rov Blata in južneje ležeči Pisani rov. Vsi rovi prevajajo preniklo vodo, le ob višjih vodostajih se ji pridruži tudi tok z Bloške planote (Kogovšek et al. 2008). Zaradi tega ima voda visoko celokupno trdoto, relativno stabilno letno temperaturo in ima visok parcialni tlak CO_2. Pretok znaša od 0 do nekaj m^3/s (običajno okoli 0,1 m^3/s). Križna jama je izredno dobro prevetrena, zlasti ko zunanja temperatura znatno odstopa od jamske (8 °C). Pozimi je prepih usmerjen skozi glavni vhod v jamo, poleti pa priteka jamski zrak skozi glavni vhod na površje. Križna jama 2 je prevetrena v znatno manjši meri, predvsem zaradi majhnega in verjetno edinega večjega vhoda. Glede na meritve Mihevca (1997) je prevladujoč geomorfni proces v Križni jami odlaganje sige s hitrostjo 128 µm na leto.

S podrobnejšimi meritvami smo pričeli februarja 2006 in končali aprila 2009. Izvajali smo jih na 14 merilnih mestih v Križni jami in na 6 merilnih mestih v Križni jami 2 (Slika 3.1.6 na strani 40). Interval meritev je bil odvisen od dostopnosti merilnih mest in je segal od 15 dni do več kot pol leta. Meritve procesov smo izvajali z apnenčastimi ploščicami, mikrometrom ter hidrokemično metodo, za ugotavljanje fizikalno-kemičnih lastnosti vode smo uporabljali merilec prevodnosti, pH, temperature in vodostaja. Za meritve v zraku smo uporabljali prenosni merilec koncentracije CO_2.

15-dnevna merjenja kraških procesov 10 m dolvodno od 1. jezera (merilno mesto KJ-1) v večinoma stalno zaliti coni so pokazala, da je prevladujoč proces odlaganje sige. Intenziteta le-te prvenstveno ni odvisna od vodostaja, temveč od intenzitete in dolgotrajnosti prepiha v jamo pozimi (Slika 3.1.11 na strani 45). Največje odlaganje sige smo zabeležili ob dolgotrajnem intenzivnem prepihu v jamo, ki običajno nastane, ko ostane zunanja temperatura preko dneva pod -2 °C. V taki meteorološki situaciji so pogoji za izhajanje CO_2 iz vode dovolj ustrezni za znatno zvišanje SI_C ter s tem za znatno odlaganje sige. Tako se v nekaj dneh odloži praktično vsa letna količina sige. Količina letno odložene sige je prvenstveno odvisna od intenzitete in trajanja zimskega prepiha v jamo in lahko znaša do 17 µm/15 dni. V preostalem delu leta je intenziteta kraških procesov nizka (manj kot ±0,5 µm/15 dni). Korazije kljub evidentiranemu prenosu suspendiranega materiala tudi ob visokih vodostajih nismo zasledili.

Z meritvami na merilnem mestu KJ-2 smo poskušali dobiti vpogled v intenziteto raztapljanja, saj smo 21 apnenčastih ploščic razvrstili navpično v območje najpogostejšega nihanja vodne gladine v 1. jezeru. Zgornje ploščice, ki so bile izpostavljene zgolj visoki vodi, v skoraj 3 letih merjenja niso povsem zanesljivo pokazale na raztapljanje. Spodnje ploščice, ki so bile izpostavljene tako odlaganju sige kakor tudi potencialnemu raztapljanju, so pokazale daleč prevladujoč proces odlaganja sige, kljub temu pa precej manj kot na brzicah pod 1. jezerom (merilno mesto KJ-1). Intenziteta odlaganja je bila na obeh merilnih mestih enaka v času nizkih odlaganj sige, glavne razlike pa so nastajale v času visokih zimskih prirastkov sige, ki so pogojeni s prepihom v jamo. V kolikor intenzivnega in dolgotrajnega prepiha ne bi bilo, bi bile razlike v odlaganju sige med brzicami in jezerom odsotne, s tem pa tako dolga jezera v Križni jami sploh ne bi mogla nastati. Domnevamo, da gre pri povezavi odlaganja sige s prepihom tudi za povratno zanko – z zviševanjem sigovih pregrad se zračni prehod med jezersko gladino in stropom niža, s tem se manjša stopnja prezračevanja jame v zimskem času, ki povratno vpliva na manjše odlaganje sige na pregradah in v jezerih. Hitrost odlaganja sige se tako sčasoma zmanjšuje.

Z meritvami prostorskih zakonitosti odlaganja sige med Brzicami pod 1. jezerom in Kalvarijo smo ugotovili, da se intenziteta odlaganja sige gorvodno znižuje (Slika 3.1.16 na strani 51). To je povezano z naraščajočim SI_C pod sotočjem potoka iz Pisanega rova s potokom iz rova Blata. Pri mešanju voda sicer ne prihaja do intenzivne korozije mešanice, vseeno pa se odlaganje sige pod sotočjem močno zmanjša. V kolikor je zimski prepih premalo intenziven, na gorvodnih sigovih pregradah do odlaganja sige sploh ne prihaja. Morfološki rezultat tega pojava je viden v tanjšanju sigove prevleke na stenah jezer od 1. jezera do Kalvarije in pa predvsem v upočasnjeni rasti gorvodnih sigovih pregrad v primerjavi z dolvodnimi. Le-to pripelje do poplavljanja gorvodno ležečih pregrad s strani dolvodnih ter daljšanje jezer od 1. jezera proti Kalvariji (Slika 3.1.18 na strani 54). Meritve na Kalvariji so pokazale tudi na sezonsko pogojenost kemičnih procesov (Slika 3.1.20 na strani 57); v poletnih in jesenskih mesecih prihaja do skromnega raztapljanja (okoli -0.3 µm/30 dni), v zimskih in spomladanskih pa do odlaganja sige (okoli 0.6 µm/30 dni).

Sezonski potek kraških procesov v Pisanem rovu v grobem ustreza razmeram v rovu med 1. jezerom in Kalvarijo. Tudi tu prihaja zaradi močnega prepiha do odlaganja sige izključno v zimskem in zgodnjem spomladanskem času. Odlaganje sige se gorvodno po Pisanem rovu zmanjšuje (Slika 3.1.21 na strani 59).

V rovu Blata so geomorfne razmere precej bolj zapletene, saj se srečujemo z več dotoki, ki popolnoma ustavijo odlaganje sige (primer je na Sliki 3.1.23 na strani 63), vendar se le-to po nekaj sto metrih toka znova okrepi. Kljub temu je odlaganje sige v rovu Blata precej manjše v primerjavi z odlaganjem v Pisanem rovu ter med 1. jezerom in Kalvarijo, vendar precej bolj sezonsko in zvezno. Glavnina odlaganja sige je sezonsko pogojena in se tudi tu zgodi v spomladanskih mesecih, nato sledimo upad odlaganja sige ter celo prehod v raztapljanje, v zimskem času pa skromno raztapljanje zopet preide v skromno odlaganje sige. Ta prehod je opazen skozi vso Križno jamo in Križno jamo 2, vendar je marsikje manj razpoznaven zaradi intenzivnega odlaganja sige ob intenzivnih prepihih. Edina povezava raztapljanja z visoko vodo je bila ugotovljena na pritoku v rov Blata (KJ-12), kjer so visoki zimski pretoki, najverjetneje tudi s strani podzemeljske Bloščice in Farovščice, povzročili raztapljanje intenzivnejše od napake merjenja (-0,4 µm).

V Križni jami 2 sledimo podoben potek odlaganja sige in raztapljanja kot v rovu Blata (Slika 3.1.24 na strani 65). Sezonski impulz se torej prenaša preko celotnega jamskega sistema. Tudi količina letno odložene sige je v Križni jami 2 (0,6 µm na leto) enaka rovu Blata zaradi visokih koncentracij CO_2 preko zime (Slika 3.1.25 na strani 66), kar se pozna tudi pri konstantnem pH preko celotne jame (Slika 3.1.27 na strani 69). Dolvodno se količina odložene sige sicer poveča (na 2 µm na leto; Slika 3.1.26 na strani 68), vendar je povečevanje zaradi višjega CO_2 dosti manjše v primerjavi s tistim, zabeleženim v Pisanem rovu ali med 1. jezerom in Kalvarijo.

Prevladujoč proces odlaganja sige se ujema z morfološko izraženimi sigovimi pregradami in sigovimi prevlekami v jezerih. Ob sedanji hitrosti rasti se začetek intenzivnega odlaganja sige umešča na prehod iz pleistocena v holocen (12.000 B.P.). Odstopanja med ugotovljenim, a morfološko neizraženim odlaganjem sige sledimo v Križni jami 2, kjer smo zasledili prevladujoč skromen proces odlaganja sige in odsotnost sigovih prevlek. Zaradi nizke intenzitete odlaganja sige je možno, da plasti sproti odstranjuje korazija ali pa mikroorganizmi. Podoben razkorak med procesi in oblikami sledimo tudi pri fasetah, ki so dobro ohranjene povsod po jamskem sistemu, vendar je raztapljanje izjemno skromno. Tudi ker velikost faset marsikje ne ustreza današnjih hidrodinamičnim razmeram v jamskem sistemu ocenjujemo, da so fasete fosilne/podedovane in se danes ne oblikujejo več. Dosti boljše razmere za njihovo rast so bile v hladnejših obdobjih pleistocena, ko je sta bila trdota vode in koncentracija CO_2 nižja zlasti ob visokem vodostaju. To je ugodneje vplivalo na razvoj faset kot razmere v današjem času.

Lekinka

Lekinka je tipična ponorna jama na severovzhodnem robu Pivške kotline 1 km severozahodno od ponora Pivke v Postojnsko jamo. Iz približno 1 km^2 velikega porečja na pleistocenski terasi Nanoščice in Pivke (Gospodarič & Habič 1966) odvaja vodo Črnega potoka (Slika 3.2.1 na strani 76). Zaradi nizkih reliefnih amplitud v porečju Črni potok prenaša malo talnega materiala, je pa zaradi močvirnih razmer v porečju toliko bolj izrazita nizka vsebnost karbonatov in vsebnost organskih snovi v vodi. V Lekinki lahko v dolžini 790 m spremljamo podzemni tok Črnega potoka, preden se ta pridruži podzemeljski Pivki v Otoški jami. Le-ta ob visokem vodostaju vpliva na retrogradno poplavljanje tudi v Lekinki, ob izredno visokih vodostajih Pivke in Nanoščice pa slednja tudi vdre v porečje Črnega potoka in za vsaj 8 m poplavi Lekinko (Slika 3.2.2 na strani 78). Take poplave zgolj s strani Črnega potoka niso možne, saj imajo rovi Lekinke dovoljšen prečni presek za prevajanje nekaj m^3/s vode. Ob običajnem vodostaju teče v Lekinko 0.05 m^3/s. Zaradi drugega vhoda, najverjetneje skozi Otoško jamo, je Lekinka dobro prevetrena.

Meritve intenzitet kraških procesov v več vodnih jamah v 8-mesečnem obdobju so pokazale na razmeroma visoko intenziteto raztapljanja, ki je lahko intenzivnejša od -100 µm na leto. Nadaljnje meritve na merilnem mesti

L-1 med septembrom 2006 in aprilom 2009 so visoke vrednosti potrdile, vendar kljub temu niso presegle -80 µm/a (Slika 3.2.6 na strani 82). Meritve na L-1, ki so bile opravljene z 15-dnevnim intervalom merjenja, so pokazale na razmeroma močno odvisnost intenzitete raztapljanja od količine padavin v 15 dnevnem obdobju ($R^2 = 0{,}55$). Korelacija intenzitete raztapljanja z maksimalno višino vode v 15-dnevnem obdobju je nižja ($R^2 = 0{,}31$), predvsem zaradi nekaj visokih vodostajev, ki se zaradi kratkotrajnosti poplav niso izrazili v najvišjih vrednostih raztapljanja v 15-dnevnem obdobju. V opazovanem obdobju nismo zasledili nobenega izrazitega sezonskega vpliva (Slika 3.2.8 na strani 84), ki bi bil povezan s sezonskim nihanjem temperature vode, koncentracije organskih snovi (kislin) v vodi ali koncentracijo CO_2 v vodi (kot posledica temperature vode ali biološke produkcije v tleh).

Na merilnem mestu L-1 smo z 11 apnenčastimi ploščicami opazovali višinsko spremenljivost raztapljanja (Slika 3.2.10 na strani 87). V skladu s pričakovanji je bila največja intenziteta zabeležena v spodnjem delu jamskega rova, sledil pa je izjemno hiter upad raztapljanja navzgor. To pomeni, da je voda zmožna raztapljanja tudi ob nizkem vodostaju, najbolj efektivno pa raztaplja ob srednjem vodostaju, ki se pojavlja najpogosteje. Največjo agresivnost doseže voda ob najvišjem vodostaju, vendar so ti tako redki in časovno zelo omejeni, tako da je raztapljanje v višjih delih jamskega rova precej manjše, jamski rov pa se tam najmanj spreminja. Velik upad raztapljanja z višino, dokaj nizka variabilnost vodostaja in zaščitenost skalnega dna s talnim materialom so izjemno ugodni pogoji za razvoj stenskih zajed. V tem primeru se rov širi bočno levo in desno, poglabljanje pa le navzdol, pa še tod lahko stalni dotok talnega materiala ščiti dno jamskega rova. V kolikor ga ne, sledimo bodisi epifreatično širjenje in poglabljanje v osnovi freatičnih rovov bodisi vrezovanje vadoznega meandra. Le-ta lahko ohranja širino le v ravnotežni spodnji obliki, ki jo v zgornjem delu sestavljata vzporedni steni, v spodnjem delu pa dno v obliki črke U. Pri tem je nujno, da ob srednjem vodostaju vodna gladina s stenami pod vodo tvori ostri kot. Le v tem primeru se lahko meander z enako mero poglablja kakor tudi širi v obe smeri. Tako obliko meandra v Lekinki dejansko opazujemo (Slika 3.2.12 na strani 89).

Meritve raztapljanja vzdolž podzemnega toka med ponorom in odtočnim sifonom (Slika 4.2.5) so pokazale dva dolžinska območja raztapljanja. V prvem dolgem 250 m sledimo hiter eksponenten upad raztapljanja (za 54 %), nato pa se upadanje raztapljanja praktično ustavi. Tako smo 790 m od ponora zabeležili še vedno 50 % raztapljanja značilnega za ponor. Pričakovali bi, da je upad raztapljanja rezultat čedalje bolj nasičene vode, vendar se glavna odvisnost kaže od parcialnega tlaka CO_2 v vodi (Covington et al., v tisku). Na intenziteto raztapljanja vplivajo še drugi dejavniki, npr. dotoki avtigene vode, razpad organskih snovi in sedimentacija ilovice, zato upad raztapljanja od ponora do Končnega sifona ni zvezen. Zabeležili smo vpliv hitrosti toka, ki vpliva na raztapljanje preko debeline difuzijske plasti – ko se prične retrogradno poplavljanje s strani podzemeljske Pivke, intenziteta raztapljanja v Lekinki ne narašča več. Na intenziteto raztapljanja na koncu jame vpliva tudi hitrost vodnega toka – ob višjem vodostaju je hitrost pretoka hitrejša, raztapljanje pa dolvodno tudi počasneje usiha.

Ponor Lekinke leži približno 1 m nižje od ponora Pivke v Postojnsko jamo. Hitro poglabljanje Lekinke in praktično nično poglabljanje Pivke bo sčasoma v porečju Črnega potoka ustvarilo močan gradient, ki ga bodo vse pogosteje izkoristile vode Nanoščice. Le-te se že sedaj ob zelo visokih vodah prelivajo preko razvodnice. Meritve raztapljanja ob takih situacijah kažejo, da Nanoščica zavre intenzivno raztapljanje v Lekinki. V kolikor bo prišlo do stalne pretočitve Nanoščice v Lekinko (ta vodna smer je pravzaprav bližnica v Otoško jamo), bo Lekinka doživela znatne spremembe v preoblikovanju s strani raztapljanja. Predvsem lahko pričakujemo znaten upad raztapljanja, prenehanje nastajanja meandra ter bolj freatičen način širjenja jamskih rovov zaradi večjega nihanja vodostaja in majhne (oz. odsotne) agresivnosti vode ob srednjih in nizkih vodostajih. Take spremembe so se verjetno v preteklosti že dogajale v Postojnski jami, ko vanjo morda ni vtekala Pivka.

Škocjanske jame

Škocjanske jame spadajo na UNSECO seznam svetovne dediščine predvsem zaradi zgodovine odkrivanja podzemnega toka Reke ter nadpovprečno bogato razvitega kontaktnega krasa. Podzemni tok Reke poteka večinoma v obliki podzemnega vintgarja, globokega do okoli 90 m. Navpične stene brez stenskih zajed kažejo, da je vrezovanje potekalo enakomerno navzdol. Proces vrezovanja je na nekaj točkah meril Mihevc (2001) z mikrometrom. Ugotovil je, da je korazija razmeroma močan proces (od -160 do -40 μm/a), medtem ko je raztapljanje precej šibkejše (okoli -10 μm na leto, kar je v območju napake merjenja z mikrometrom). Korazija je povezana z okoli 350 km^2 velikim porečjem, katerega 60-75 % (Kranjc 1986; 112, Habič et al. 1989; 10, Kranjc & Mihevc 1988 po Mihevc 1991) leži na nepropustnih silikatnih kamninah. Kljub temu je celokupna trdota razmeroma visoka (10,3 °NT; Gams 1962; 278), kar prispeva k majhni intenziteti raztapljanja že na kontaktu fliš-apnenec. Z natančnejšimi meritvami smo hoteli ugotoviti, kakšna je odvisnost raztapljanja od pretoka Reke ter kolikšna je višinska ter dolžinska spremenljivost raztapljanja.

Rezultati z merilnih mest S-1 in S-2 (Slika 3.3.1 na strani 103) kažejo, da ob srednjem in nizkem vodostaju prevlada odlaganje sige, medtem ko meritve raztapljanja ob visokem vodostaju ovira korazija. Le-ta je bila na srečo odsotna (ali vsaj močno zmanjšana) na spodnjih merilnih mestih pri Martelovem jezeru. Rezultati tam kažejo, da v spodnjem višinskem metru struge prevladuje odlaganje sige (0,5 μm/a), ki se očitno odlaga ob srednjem in nizkem vodostaju, visoke vode pa ga z raztapljanjem ne uspejo povsem odstraniti. To potrjuje tudi dokaj majhna največja zabeležena intenziteta raztapljanja, ki znaša okoli -0,4 μm/a približno 6 m nad dnom podzemne struge (Slika 3.3.6). Nižje je celokupno raztapljanje manjše zaradi odlaganja sige ob srednjem-visokem vodostaju, navzgor pa zaradi krajšega časa izpostavitve ob poplavi. Tudi pretok nad 200 m^3/s decembra 2008 in kasneje v zadnjem merilnem obdobju se ni odrazil v bistveni intenziteti raztapljanja. Prevlada raztapljanja nad odlaganjem sige se zgodi, ko ima Reka pretok okoli 20 m^3/s. Ker začne Reka ob nekoliko višjem pretoku že retrogradno poplavljati, je »okno« za skalne oblike hitrega toka (npr. faset) s strani raztapljanja izredno ozko. To se odraža tudi v morfologiji, saj se fasete nad 2 m nad dnom struge ne pojavljajo več, odsotne pa so tudi v spodnjem 1,5 m visokem delu struge (Slika 3.3.7 na strani 109). V tem delu namreč prevladuje odlaganje sige v obliki sigovih prevlek, ki jih v najnižjih delih struge lahko opazujemo v debelini okoli 6 mm. Glede na ta dejstva bi le-te lahko nastale v holocenu.

Dolžinske meritve intenzitete raztapljanja od prestopa Reke iz silikatnih na karbonatne kamnine pa vse do končnega sifona (Ledeni dihnik) kažejo, da je raztapljanje odstotno že ob prestopu na karbonatne kamnine (Slika 3.3.8 na strani 111). To je skladno z ugotovitvami Gamsa (1962; 278) o precejšnji karbonatni trdoti Reke, s čemer se zmanjša tudi možnost raztapljanja. Razmere se vzdolž površinskega in podzemnega toka ne spreminjajo bistveno – neto odlaganje sige znaša med 0,3 do 0,9 μm/a. Visoko celokupno trdoto Reke lahko pripišemo številnim desnim kraškim pritokom Reke, ki odvajajo razpršeno infiltrirano vodo z območja Snežnika in Zgornje Pivke, ter deloma karbonatnemu vezivu fliša. Levi pritoki s fliša kljub nizki trdoti visoke trdote v glavni strugi ne uspejo znižati do te mere, da bi se voda v Škocjanskih jamah odrazila z raztapljanjem.

Jamski sistem med Postojnsko kotlino in Planinskim poljem

Jamski sistem med Postojnsko kotlino in Planinskim poljem (jamski sistem Postojnske jame in Planinska jama) je hidrološko in geomorfološko izjemno pomemben splet rovov, saj v višinski razliki ~56 m povezuje Postojnsko kotlino s Planinskim poljem. Skupaj tvori kar 27.226 m rovov, od katerih je več kot 10 km vodnih. Dostopnost rovov tako s postojnske kakor tudi s planinske smeri nam nudi izjemen vpogled v dinamiko procesov, dejavnikov in oblik vzdolž podzemnega vodnega toka, hkrati pa omogoča tudi vpogled v eno izmed največjih podzemnih sotočij na svetu – sotočje Pivke in Raka v Planinski jami.

Meritve časovne in vertikalne spremenljivosti procesov smo izvajali v Velikem domu v vhodnem delu Postojnske jame (merilno mesto P-1; Slika 3.4.1 na strani 114). Rezultati kažejo, da so v obdobju od septembra 2007 do marca 2009 apnenčaste ploščice pridobile na teži, kasneje pa izgubile (Slika 3.4.4 na strani 119). Čeprav del prirastka teže odpade na odlaganje organskih snovi iz deloma onesnažene vode, rezultati kažejo na zanemarljivo intenziteto raztapljanja. Na spodnjih apnenčastih ploščicah smo vseskozi zabeležili odlaganje (do 1 µm/a), medtem ko smo raztapljanje na višje ležečih ploščicah zabeležili le v dveh merilnih obdobjih, čeprav so bile ploščice poplavljene v vseh štirih merilnih obdobjih. Pojav raztapljanja je povezan z visokimi vodami Nanoščice, ki se lahko odrazijo v raztapljanju le ob ustrezno nizki Pivki (Slika 3.4.5 na strani 120). Kljub temu so povprečne vrednosti raztapljanja zelo skromne (največ -0,6 µm/a). Zaradi visokega deleža Pivke se niso agresivno obnašale niti izredno visoke vode, ki so 12. decembra 2008 dvignile nivo Pivke v Velikem domu za kar 8 m (Slika 3.4.6 na strani 121). Raztapljanje smo zaznali ob znatno nižjem vodostaju, ko je bila Nanoščica višja in Pivka nizka.

Na nizu merilnih mest med ponorom v Postojnsko jamo in izvirom v Planinsko jamo smo vseskozi beležili odlaganje (Slika 3.4.7 na strani 123). Najmanjše vrednosti smo zabeležili v Pivki jami, medtem ko se odlaganje dolvodno in gorvodno povečuje. Razlike med merilnimi mesti so kljub temu majhne; še največje so v vhodnem delu Postojnske jame, najverjetneje zaradi največjega dolvodnega upadanja odlaganja organskih snovi iz vode. Pritoki bistveno ne vplivajo na intenziteto raztapljanja ali odlaganja vzdolž Pivke, tudi Rak v Planinski jami ne, saj tudi pri njem ne opažamo prevladujočega raztapljanja, na sotočju pa korozija mešanice ne prevlada nad izhajanjem CO_2 iz vode in posledičnim skromnim odlaganjem sige. Na nekaterih merilnih mestih smo zabeležili korazijo, kar kaže na intenziven prenos talnega materiala vzdolž podzemeljske Pivke. Čeprav bi se lahko odlaganje odrazilo v sigovih prevlekah, tega nismo nikjer opazili. Je pa tudi res, da nekatere tipične oblike raztapljanja (npr. fasete) kljub prisotnosti vzdolž podzemeljske Pivke ne kažejo recentne rasti (robovi med fasetami so obrušeni s strani korazije, na delu faset se pojavlja mrežasta struktura kalcitnih žil (t.i. boxwork). Vse to kaže, da je bila Pivka v preteklosti bolj agresivna, ni pa raztapljanja zaznati danes (izjema so zgornji deli rovov, ki so v dosegu poplavnih voda).

5.4 Splošni zaključki, diskusija in možnost nadaljnjih raziskav

Metodologija

Meritve kraških procesov zahtevajo uporabo posebnih metod merjenja, med katerimi velja izpostaviti predvsem naslednje: mikrometrske meritve, hidrokemična metoda in uporaba apnenčastih ploščic. Intenziteta kraških procesov je običajno izredno nizka, zato je glavna prednost uporabe apnenčastih ploščic v izjemni preciznosti (do ±0,05 µm) in točnosti metode (v povprečju ±0,2 µm, največje odstopanje ±0,4 µm). Ne glede na preciznost in natančnost, uporabo apnenčastih ploščic za meritve raztapljanja ali odlaganja sige spremljajo tudi nekatere pomanjkljivosti, ki se tičejo predvsem različnosti v litološki sestavi apnenčastih ploščic v primerjavi s kamnino, kjer se jama razvija (hitrost raztapljanja dolomita je lahko tudi 10-krat manjša v primerjavi z lipiškim apnencem), ter sveže odrezano površino, ki je v tem pogledu precej različna od deloma preperele stene jamskih rovov. Kratek interval meritev tudi zmanjšuje vpliv mikroorganizmov, ki imajo lahko ključno vlogo pri hitrosti procesov zlasti takrat, ko je hitrost kraških procesov nizka. S pogosto menjavo apnenčastih ploščic njihov vpliv znatno zmanjšamo. Pri apnenčastih ploščicah, ki so pritrjene z železnim vijakom, lahko pričakujemo tudi znaten vpliv raztapljanja s strani rje, zato je v izogib temu problemu nujna uporaba nerjavečega jekla ali plastike. Za točnejšo opredelitev uporabnosti metode apnenčastih ploščic bi bile zelo koristne podobne meritve v drugih podzemskih okoljih.

Primerjava meritev z mikrometrom in apnenčastimi ploščicami kaže, da je magnituda procesov v obeh primerih enaka, vendar je razlika v nekaterih primerih, npr. na začetku meritev, pri velikem odstopanju hrapavosti naravne podlage od gladkosti apnenčastih ploščic in pri intenzivnejši rasti sige, kljub temu precej velika. Ne glede na to se resne napake lahko pojavljajo v obeh primerih, tako da zaenkrat ne moremo trditi, katera metoda je bolj reprezentativna. Za katero izmed njih se bomo odločili je odvisno od hitrosti procesov (uporaba mikrometra je primerna le za jame z večjo intenziteto procesov, teh pa je razmeroma malo), pojava korazije (apnenčaste ploščice so neuporabne pri pojavu zmernemočne korazije) in dostopnosti do merilnih mest (apnenčaste ploščice so zaradi enostavnejše uporabe primernejše za težje dostopna mesta).

V izbranih primerih vodnih jam je hitrost kraških kemijskih procesov običajno tako nizka, da je uporaba apnenčastih ploščic nujna, v kolikor želimo v nekaj letih dobiti statistično pomembne rezultate. Kljub temu svetujemo nadaljnjo pozornost pri uporabi apnenčastih ploščic, saj se lahko pojavijo zaenkrat nepoznana odstopanja od dejanske hitrosti kraških kemijskih procesov. Več pozornosti bi kazalo posvetiti nadaljnji primerjavi obeh metodologij in boljšemu poznavanju razlik, ki se med metodologijama pojavljajo.

Intenziteta raztapljanja oziroma odlaganja sige

Na splošno je intenziteta kraških kemijskih procesov nizka, kar ustreza dolgotrajnemu razvoju kraških jam. Vzdolž naših največjih podzemnih vodnih tokov lahko pričakujemo na dnu rovov odlaganje sige, višje navzgor pa raztapljanje nekaj desetink μm na leto. Take hitrosti so značilne tako za jame, ki jih napaja razpršen ali koncentriran dotok kraške vode (Križna jama, Križna jama 2), in celo za jame, ki odvajajo vodo z nepropustnih kamnin (v kolikor je vodozbirno območje sestavljeno iz deloma karbonatnih kamnin; Škocjanske jame), ter za jame, ki jih napaja kombiniran dotok kraške in nekraške vode (Postojnska jama). Največja intenziteta raztapljanja in njena prostorska variabilnost je značilna za območja, kjer prihaja do izrazitih neravnovesij v koncentraciji CO_2 (npr. v Križni jami) ali neravnovesij v koncentraciji Ca^{2+} ionov (npr. v jami Lekinka). Tudi v takih primerih je raztapljanje lahko intenzivnejše od -100 μm na leto, medtem ko se v jamah z odlaganjem sige iz jamskih potokov odloži več kot 100 μm sige na leto. Za podzemne vodne tokove, ki povezujejo kraška polja ali planote, je poleg majhne intenzitete kraških procesov značilno majhno spreminjanje procesov vzdolž podzemnega toka. To je najverjetneje posldeica velikega pretoka, ki ne omogoča intenzivnega kontakta s povečano koncentracijo CO_2 značilne za jamski zrak. Taki podzemni vodni tokovi so običajno (pre)nasičeni s kalcitom že na ponorih, zato je zanje značilna celo majhna intenziteta odlaganja sige (okoli 0,6 μm na leto). Izredno majhna intenziteta raztapljanja je značilna celo za visoke vode ali pa najbolj intenzivno raztapljanje niti ni značilno za najvišje pretoke. Zato ni presenetljivo, da so nekateri raziskovalci v nastanek jam z raztapljanjem dvomili (npr. Melik 1955), nekateri so to celo dokazali (npr. Oertly).

Presenetljivo je, da v raztapljanje ni dvomil Gams, čeprav ga velikokrat ni mogel dokazati ali pa je bilo izredno šibko. Zato v njegovih člankih sledimo tendenco od trdne prepričanosti v raztapljanje jamskih vodotokov v 60-ih letih do postopnega nagibanja k neaktivnosti jamskih vodotokov v 90-ih letih 20. stoletja. Majhna intenziteta raztapljanja v epifreatični coni potrjuje dejstvo, da se daleč največja količina karbonatov raztopi v epikraški in vadozni coni. Odnos med obema intenzitetama je z našimi meritvami tudi kvantitativno dokazan. Pogost pojav v jamah je, da prezračevanje zmanjšuje koncentracijo CO_2 v jamskem zraku (posledično tudi v vodi), s tem pa povečuje odlaganje sige celo iz jamskih vodotokov.

Pri intenziteti kraških procesov je zelo slabo poznana vloga podzemskih mikroorganizmov, ki se jo lahko enostavno proučuje z različno pogostnostjo meritev v jamskih rovih. V kolikor so naša predvidevanja pravilna, je intenzivnejše raztapljanje pričakovati pri nekajletnih izpostavitvah apnenčastih ploščic v primerjavi z vsoto meritev v krajših merilnih obdobjih.

Razmerje med današnjimi procesi, dejavniki in oblikami

Eno izmed največjih presenečenj tekom meritev je prevladujoče (sicer po intenziteti majhno) odlaganje sige v nekaterih hidrološko pomembnih slovenskih jamah (Postojnski jami, Planinski jami, Škocjanskih jamah, Križni jami 2), medtem ko je v primeru Križne jame odlaganje sige lahko zelo intenzivno. To se ne ujema z nastankom jam z raztapljanjem in z nekaterimi značilnimi oblikami raztapljanja vzdolž podzemnega toka (npr. fasetami). To pomeni, da so oblike raztapljanja bolj ali manj fosilne/podedovane, saj jih današnji vodni tok ne more več oblikovati – marsikje se celo izredno visoke vode s povratno dobo nekaj deset let niso obnašale prepričljivo agresivno. Vsesplošno prevladujoč proces odlaganja sige v vodnih jamah in debelina sigovih prevlek v Križni jami in Škocjanskih jamah kaže na pomembne spremembe v intenziteti kraških procesov in njihovi prevladujoči smeri (raztapljanje-odlaganje sige) na prehodu pleistocena v holocen. V hladnih obdobjih pleistocena lahko tako pričakujemo manjše (ali celo odsotno) odlaganje sige ter intenzivnejše raztapljanje. Vzrok v preobratu podzemnih geomorfnih procesov lahko najdemo v znatni spremembi temperature, ki je spremenila vegetacijo, s tem produkcijo CO_2 v prsti, manjšo koncentracijo CO_2 v prenikli vodi in posledično manjšo intenziteto raztapljanja v vadozni coni. Zmanjša se tudi možnost izhajanja CO_2 iz prenikle vode v dobro prezračenih vodnih rovih. Nižja celokupna trdota in manjša koncentracija CO_2 v prenikli vodi nujno privedeta do znižanja odlaganje sige ter pripeljeta k manjši verjetnosti odlaganja sige v jamskih rovih. Te povezave so bile v preteklosti pogosto opazovane pri rasti kapnikov in lehnjakovih pragov, zelo redko pa so mu pripisovali močnejšo vlogo pri širjenju jamskih rovov. Če posplošimo, bi moralo biti intenzivnejše raztapljanje značilno za glaciale, manjše (oz. odlaganje sige) pa za interglaciale. To domnevo bi bilo lahko testirati v današnjih subpolarnih razmerah. Kljub vsemu je potrebno opozoriti, da nižanje letne temperature ne pripelje vedno do povišanega raztapljanja, npr. na ponorih visoko agresivne alogene vode.

Presenetljivo je, da v jamskem sistemu Križna jama-Križna jama 2, ki se napaja s preniklo vodo, nihanje pretoka nima odločilne vloge pri intenziteti odlaganja sige in raztapljanja, ampak nanju bolj vplivajo sezonske spremembe v prepihu. Ključno vlogo pri smeri in intenziteti kraških procesov ima prezračevanje jame, ki v zimskem in spomladanskem času niža koncentracijo CO_2 v kraškem masivu (s tem povzroča prenasičenost vode in posledično odlaganje sige), v poletnem in jesenskem času pa inverzni prepih ohranja visoko koncentracijo CO_2 v jamskem zraku, ki je značilna za celoten kraški masiv. Slednje pripelje do izredno nizkega odlaganja sige ali celo do skromnega raztapljanja. Pomembno bi bilo preveriti domnevo, da je tovrsten pojav značilen tudi za druge rove v epifreatični coni z razpršenim avtogenim napajanjem.

6

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