UNIVERSITY OF NOVA GORICA
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PRESENT-DAY SPELEOGENETIC PROCESSES, FACTORS AND FEATURES IN THE EPIPHREATIC ZONE

DISSERTATION

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Nova Gorica, 2009

UNIVERZA V NOVI GORICI
FAKULTETA ZA PODIPLOMSKI ŠTUDIJ

DANAŠNJI
SPELEOGENETSKI PROCESI, DEJAVNIKI IN OBLIKE
V EPIFREATIČNI CONI

DOKTORSKA DISERTACIJA

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Nova Gorica, 2009

Izjavljam, da je doktorsko delo v celoti moje avtorsko delo.

Hereby I declare this thesis is entirely my author work.

Next to Mont Aigoual,
a small stream of water sinks underground and
seems to reappear 440 metres further and 90 metres deeper.

Everybody

assumes that these two streams are one and the same,

but E.A. Martel

demonstrates it irrevocably by
following the water upstream.
In his report of this experiment, he makes interesting remarks
regarding underground water circulation[1].

[1] *Schut P.-O., 2006 – E. A. Martel, the traveler who almost became an academician. Acta Carsologica 35/1: p. 153.*

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Present-day speleogenetic processes, factors and features in the epiphreatic zone

Abstract: The epiphreatic zone is one of the most interesting hydro-geomorphic zones in karst massifs, since it represent a place of development of many extensive cave systems which, furthermore, influence and control development of nearby underground and superficial drainage and geomorphogenesis. Easily accessible extensive cave systems in the epiphreatic zone also give us excellent opportunity to study geomorphic processes in, below or above the epiphreatic zone. Nevertheless, geomorphological studies in epiphreatic zones are most often restricted just to morphological studies – more rarely, processes and factors are taken into consideration.

This dissertation deals with the inseparable relationship between processes, key factors and resulting features. At the beginning of study, the main disadvantage was scarce and scattered data about speleogenetical processes. Therefore measurements of rates, horizontal, vertical and temporal distribution of corrosion and flowstone deposition was the first and the most important goal. Results were a source of information about factors that influence the processes. Results were interpreted with interdisciplinary approach; this takes into consideration all relevant hydrological, geomorphological, hydrogeological, climatic, meteorological and biological factors. Knowledge about rates and variability of processes and the partial influence of each factor gives us opportunity to evaluate visible results of processes in karst massif – development of speleogenetic features at least during the Holocene. Contradiction between present-day features and potential features, as a result of measured present-day processes, gives us an important hint on the age of present-day (existing) features in caves.

Eight-month-long measurements of corrosion and flowstone deposition rates gave us interesting and sometimes unexpected results. Moreover, high rate of processes enabled deeper investigation of processes and factors in cave system Križna jama-Križna jama 2 and in cave Lekinka. Investigations continued also at sites which are especially interesting from the viewpoint of geomorphic development of nearby non-karstic area or development within the karst massif (cave system Postojnska jama-Planinska jama, Škocjanske jame, Tkalca jama, Malni springs, Jelovička jama). The most intensive work was done in the cave system Križna jama-Križna jama 2, which gives excellent opportunity for studies of speleogenetical factors due to good preservation of cave and catchment area, long accessible horizontal passages and variable (rates of) processes.

Let us mention just one speleogenetical factor, which was recognized as the most important but mostly overlooked by other speleologists – winter ventilation of the cave. The latter reduces CO_2 concentration in the karst massif; it consequently influences rates and spatial distribution of intensive flowstone deposition and most probably reduces corrosion rates.

The rate of corrosion and flowstone deposition was determined with limestone tablets. This methodology is usually used to determine corrosion rates in soil but very rarely in underground streams. With important improvements of the methodology, testing in different speleogenetic environment, comparison with other methods for quantification of speleogenetic processes (e.g. micrometer) and measurements with limestone tablets made of different lithology, methodology of measurements with limestone tablets is convenient also to determine rates of speleogenetic processes in further measurements of present-day processes – especially at places with very low rates, where other methodologies for determining cumulative rates of processes become useless.

Key words: speleology, karst geomorphology, karst processes, corrosion, flowstone deposition, limestone tablets

Današnji speleogenetski procesi, dejavniki in oblike v epifreatični coni

Izvleček: Epifreatična cona spada med ene izmed najbolj zanimivih hidrološko-geomorfoloških con krasa, saj se v njej razvijajo mnogi največji jamski sistemi, ki velikokrat pogojujejo razvoj bližnjega podzemskega in nadzemskega kraškega hidrološko-geomorfološkega sistema, hkrati pa nudijo najbolj enostaven in pester vpogled v notranjost kraških masivov. Kljub pomembnosti pa so geomorfne raziskave v njej pogosto omejene le na proučevanje morfologije – precej redkeje sledimo študije procesov in dejavnikov.

V pričujoči doktorski disertaciji smo poskušali sedanje procese, dejavnike in oblike povezati v neločljivo celoto. Ključna ovira pri tem so zelo pomanjkljivi kvantitativni podatki o speleogenetskih procesih, zato smo se sprva podrobneje osredotočili na merjenje intenzitete korozije in odlaganja sige, njuno vertikalno in horizontalno razporeditev in časovno spremenljivost. Meritve speleogenetskih procesov so bila osnova za izpostavitev ključnih dejavnikov, ki jih pri tem najbolj očitno usmerjajo. Podatke smo razlagali v čim večji meri interdisciplinarno, torej tako z vidika hidroloških, geomorfoloških, hidrogeoloških, klimatskih, meteoroloških in bioloških dejavnikov. Časovna spremenljivost dejavnikov in njihov vpliv na procese nam da dober vpogled vsaj v holocenski potencialni količinski iznos korozije, torej tudi vpogled v nastanek potencialnih reliefnih oblik, njihova primerjava z obstoječimi speleološkimi oblikami pa tudi dober namig v recentnost oz. fosilnost obstoječih oblik v kraških jamah.

Po uvodnih 8-mesečnih meritvah kraških procesov smo spoznali, da nekatere jame nudijo možnost podrobnejšega vpogleda zaradi velike intenzitete procesov (sistem Križna jama-Križna jama 2, Lekinka), v nekaterih drugih pa so nadaljnje meritve smiselne zaradi pomena jam za geomorfni razvoj okoliškega reliefa in razvoj pod- ter nadzemne hidrološke mreže (sistem Postojnska jama-Planinska jama, Škocjanske jame, Tkalca jama, izviri v Malnih), nekatere jame pa v razvoj posameznih jamskih oblik (Jelovička jama). Glavnino raziskovalnega dela smo opravili v sistemu Križna jama-Križna jama 2, ki nam s svojo naravno ohranjenostjo, dolžino, pestrostjo, dostopnostjo in zanimivostjo kraških procesov nudi izjemen vpogled v manj poznane dejavnike, ki z različnim usmerjanjem procesov pogojujejo nastanek tako korozijskih kakor tudi kemično-sedimentnih oblik. Pri tem naj omenimo le vpliv zimskega prezračevanja

jame, ki posredno preko nižanja koncentracije CO_2 v jamskem zraku vpliva na intenziteto in prostorsko razporeditev intenzivnega odlaganja sige in šibke korozije.
Do rezultatov nikakor ne bi mogli priti brez meritev z apnenčastimi ploščicami. Le-ta metodologija mejenja procesov je bila običajno uporabljena pri meritvah kraških procesov v prsti, tokrat pa tudi v svetovnem merilu prvič v tako obsežnem merjenju procesov v kraških jamah. S pomembnimi izboljšavami metodologije, njenim testiranjem v različnih speleoloških pogojih in primerjavo z nekaterimi drugimi metodami (npr. mikrometrskimi meritvami) smo vzpostavili njeno uporabnost tudi pri potencialnih nadaljnjih meritvah, vendar pa nekatere specifike metode še naprej terjajo njeno nadaljnje preizkušanje. Glavna prednost metode (izjemna preciznost) kljub temu ostaja njena glavna uporabna prednost, saj je v večini proučevanih jam jakost recentnih kraških procesov izven dometa drugih klasičnih kumulativnih metod merjenja dogajanj v podzemlju (npr. meritev z mikrometrom).

Ključne besede: speleologija, geomorfologija krasa, kraški procesi, korozija, odlaganje sige, apnenčaste ploščice

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1 INTRODUCTION

1.1 Foreword

Nearly all present-day ideas related to the formation of caves in limestone areas were born already in the 19th century. At that time, the principal role of corrosion due to CO_2 from the soil was known, all important chemical reactions, general underground water flow and vertical zoning of karst massifs. Although an idea of dissolution gave an answer to many questions about cave origin and development, some speleologists (e.g. E.A. Martel in 1896) were already aware that "no theory about the origin of caves is universal" and "all of them are partly correct" (LOWE, 2000, 30). The latter belief that is valid even today was intensively studied during 20th century. Many karstological studies in 20th century brought deepened understanding of geomorphic evolution of karst surface and caves, hydrogeological functioning of karst aquifers, chemical and physical processes that take place on karst. General human development also expressed a need for deeper investigation in many karst regions and made possible deeper, longer, efficient and more scientifically supported cave exploration, especially due to improved technique in the last decades of 20th century. Although the latter activities brought also some new ideas about the cave development, some old ideas still wait for more comprehensive confirmation. Results of this Thesis are nothing but an additional contribution to the understanding of karst environment, which will, somewhere in the future together with much broader knowledge, lead to a clear and well-supported understanding of karst and cave genesis.

1.2 The background of the thesis

Cave systems are formed through the action of *speleogenetic agents* which, regarding to *factors*, through various *processes* produce *speleogenetic features* within *speleogenetic environment.*

The main **speleogenetic agent** in karst is water. Water in a karst system is a medium, which transfers dissolved or partly weathered rock through speleogenetic environment. Accordingly, water erodes, transport and accumulate material in/through caves as a part of water and rock cycle (NATEK, 1987, 75). Universal physical and chemical laws, in particular speleogenetic environment, define how much rock can be eroded/corroded, transported or deposited. At a particular location, physicochemical properties of water (e.g. CO_2 concentration, Ca^{2+} concentration, temperature, viscosity, density) and nearby conditions (e.g. velocity of flow, hydraulic head, type of rock, erosion base) are crucial for geomorphic action of water.

Speleogenetic processes are sequences of changes of a real object that occur by the action of agent in speleogenetic environment and may result in specific cave features/forms. The main, but not the only speleogenetic process is corrosion/dissolution and to it contrary process of solute deposition/precipitation. Without solution, formation of caves is not possible or at least very difficult and spatially limited. Theoretically, dissolution of carbonates is a complex series of ionic dissociations and reversible reactions, governed by their own activity constants and saturation equilibria (JENNINGS, 1985, 22). Generally speaking, the amount of carbonate dissolved in solution depends on the concentration of hydrogen ion. The latter is usually defined by CO_2 concentration in the air, with which the water is in contact.
The kinetics of the process is at least as important as the equilibrium. The highest rates are achieved when a concentration of individual ion is far from equilibrium (e.g. when water is highly undersaturated or supersaturated with respect to Ca^{2+}; FORD & WILLIAMS, 2007, 65). Final rate of corrosion/flowstone deposition depends on a rate-limiting process, which can be reaction on a crystal surface, conversion of CO_2 to H^+ and HCO_3^- (or *vice versa*) in the water or transport of ions by diffusion (DREYBRODT & EISENLOHR, 2000). Rate of reaction can be lower also 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 kinetics of reaction (JENNINGS, 1985, 23). Therefore, amount and rate of dissolution is controlled by many speleogenetic factors. Influence of some of them were studied theoretically and experimentally (DREYBRODT, 1988; DREYBRODT, 2004), but the variety and temporal variability of factors in natural environment is usually too wide to calculate and predict actual rates of processes. Therefore, several field techniques exist to measure corrosion 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 a contact with non-karstifiable rock (corrasion, sedimentation of allochtonous material) or close to cave entrances in occasionally colder climate (mechanical breakdown). The latter is a logical consequence of disequilibrium in a karst massif, which is established after the cave is 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 corrosion or deposition. All mentioned processes can be complementary or contrary to corrosion. Therefore, they can increase or decrease the volume of underground passages. Extend of final form (cave system or individual micro-feature) depends on the rate of processes and available time.

Speleogenetic processes are controlled by **speleogenetic factors**. They 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 geological, hydrological, meteorological to biological ones. Some of them are properties/characteristics of geological environment (e.g. degree of fracturization, chemical composition of rocks, texture and structure of rock), water bodies (e.g. CO_2 concentration, Ca^{2+} concentration, temperature, flow velocity, sediment load, presence of other ions), meteorological (e.g. number of days with transition of temperature under/over 0 °C, degree of ventilation, relative humidity) or biological (e.g. biodiversity, density of organisms and their metabolic processes) if they have influence on karst processes. Some factors increase solubility of carbonates or increase corrosion rates (e.g. small grains of calcite-micrites, low Ca^{2+} concentration, high CO_2 concentration in the water, high flow velocity, mixing of saturated waters with different CO_2 concentrations, transition from laminar to turbulent flow, presence of other acids (sulfuric acid, nitric acid), presence of sodium chloride, hydrogen sulfide, sulfates), some of them decrease solubility of carbonates or decrease corrosion rates or leads toward flowstone deposition (e.g. large crystals-sparites, high degree of rock impurities, presence of dolomite, small or reducing 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, presence of dissolved organic carbon) and the other has 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 were developed under the action of speleogenetical processes or within cave systems. They can be a result of one 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 subjective) genesis (GAMS, 1962, 3; NATEK, 1987), descriptive literature on features is the most numerous in speleology in comparison with speleogenetical processes or factors. Features that can be found in caves are numerous by type, genesis and individual morphology. A comprehensive study of cave rocky features is given by Slabe (1995). Nevertheless, genesis of some basic and most well-studied features is still not fully explained. For example, the genesis of scallops is generally attributed to corrosion process (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; PALMER A., 2007, personal comm.), while some authors attribute at least initiation to corrasion (RENAULT, 1968, 563 after SLABE, 1995, 20; HÄUSELMANN, 2002, 8), since they can be found also at almost insoluble rocks (e.g granite). Due to relatively fast water flow, small scallops should be characteristic for epiphreatic zone, although they can be larger in the zone that is restricted by downstream narrows, this is due to flooding (LAURITZEN & LUNDBERG, 2000, 411).

Speleogenetic environment is a three-dimensional space where the speleogenesis takes place. Usually, it is divided into several zones regarding to prevailing medium that fills the voids in karst massif (air or water; permanently, occasionally). Two main zones are put usually forward: *vadose and phreatic zone*. In the first one, water percolates downwards planary and has possibility to sufficiently get in 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 hydraulic head in a full pipe flow. Portion of overall corrosion in phreatic zone is estimated usually to 5-20 %, in rare cases up to 40 % (FORD & WILLIAMS, 2007, 94). Nevertheless, corrosion in the phreatic zone takes place at relatively small reaction surface; therefore, corrosion rates can be relatively high (GUNN, 1986, 382). Dissolution in the phreatic zone has also big geomorphological and hydrological importance since it makes possible drainage of extensive (karst and non-karstic) regions. Further division of phreatic (shallow, deep) is common.

Because of significant secondary porosity and fluctuation of boundary layer between vadose and phreatic zone, *epiphreatic zone* between vadose and phreatic zone is often enlightened. Epiphreatic zone (named also as epiphreas, floodwater zone, temporarily flooded zone) can be defined with the highest and the lowest piezometric water level in karst massif (GAMS, 2003, 46), this is 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 phreatic zone due to the most direct connection between ponor and spring 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), 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 phreatic zone (such (sub)horizontal flow can also take place in epiphreatic zone). Nevertheless, some researchers (e.g. JEANNIN ET AL., 2000, 345-346; HÄUSELMANN ET AL., 2003) agree with special suitability of epiphreatic zone for formation of (sub)horizontal but do not agree with relation of the (sub)horizontal caves in epiphreatic zone to high fracture density (and the your state model described in FORD & EWERS (1978), since some areas (Siebenhengste-Hohgant-Lake of Thun) exhibit also formation of passages around 200 m below the water level, although the rock is densely fractured.

Karst processes and factors (most commonly attributes of water) vary in short and long (geological) time scale. From the viewpoint of solution, high differences in corrosion rates are observed even within 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 formation of a substantial cave system. Dating of cave sediments confirms a very old age for several systems (see ZUPAN HAJNA ET AL., 2008 for details). During such a long period especially speleogenetic factors and related processes can change significantly. Change of climate is the most obvious one although some significant changes of catchment area, tectonic position of karst massif and position of inflow/outflow are possible. Therefore, present-day speleogenetical activity can be understood just as a moment during long-term evolution of cave system.

Which are nowadays the most important speleogenetic research areas? A purpose of geomorphology is the comprehension of the form of the ground surface and the processes which mould it (GOUDIE, 2000, 222) and as such much more than past descriptions of landscape. Transition of speleology was similar to transition of geomorphology in the past – with a shift in emphasizes from the general theories (e.g. water table controls) to investigations of underlying processes and mechanisms of cave development (WHITE, 2000). Second half of 20th century also brought greatly improved understanding of the chemical equilibrium and chemical kinetics of carbonate rock dissolution (WHITE, 2000). Quantification of speleogenetic phenomena made possible also computer modeling of karst aquifer development, which is in great progress nowadays. Therefore the trend of speleology goes toward good understanding of physical and chemical nature of karst processes and factors, modeling and testing them in a virtually defined environment. Even regional studies with field observations, which are conceptually and spatially bounded by realistic environment, often rely on physicochemical law valuable for karstic areas (PALMER, 2007). Gabrovšek (2005) states that for understanding of karst and its evolution one has to study and understand the basic processes behind it. Basically, there are two approaches to this: empirical (from large to small scales; knowledge comes from field observations) and analytical approach (from small to large scales; knowledge of basic principles of physics and chemistry results in understanding of complex cave system networks; GABROVŠEK, 2005).

The idea of this PhD thesis is to contribute some more quantified data of speleogenetic processes, factors and features in epiphreatic zone based on field observations in Slovene caves.

1.3 Goals, objectives and approach

Title of this Thesis frames subject of this work in time, theme and space:

- **temporal framework** (actual, present-day activity),
- **thematic framework** (relation between speleogenetic processes, factors and features) and
- **spatial framework** (epiphreatic zone).

Contrary to studies of past features, which are more easily found in speleological literature, we decided to face with **present-day geomorphic activity**. The latter was mostly disregarded in the past due to prevailing interest on long-term geomorphic evolution. Evolutional studies base on interpretation of recent morphology and present-day connection between features, factors and relevant processes. Another cause is a strong wish of geomorphologists/speleologists to put together evolutional history of cave system or karstic area, which is related to long evolutional time. Present-day speleogenetical activity would not give us answers to the majority of these interests. But, it will give us good insight into the connection between processes, factors and forms and would show all complexity of geomorphic activity. Lack of consideration and unfamiliarity with this complexity led to several misinterpretations in the past.

The second reason for studying present-day **speleogenetical processes, factors and features** is weak knowledge about their values and relation in known cave systems. In the past, present-day processes and factors were mostly defined by study of cave morphology, where the connections between them were "obvious". But, can we really relate present-day morphology with present-day processes? Are they related or not? To answer these questions, good and numerous data from all mentioned aspects are needed. Here arises a big embarrassment since 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 the corrosion was recognized as the main process for cave formation, we still lack direct measurements of corrosion rates in caves. This deficiency is not characteristic just for Slovenia but also on a world scale (GUNN, 1986) and not just for karst studies but also for fluvio-denudational relief (NATEK, 1993, 48 after NATEK, 1983, 87). Since the corrosion rates are probably small, we tested and improved methodology for corrosion rate measurements in caves – limestone tablets.

Epiphreatic zone represents probably the most attractive and the easiest accessible zone. It often represents the biggest portion of underground water flow. In the epiphreatic zone, processes, factors and features seems to be quite homogeneous, if we compare this zone with vadose zone. The phreatic zone is accessible only to divers, while the epikarstic zone, where usually the majority of dissolution occurs, is inaccessible for humans. Where it is possible, we take into account the cave system instead of part of it because the whole system gives us more information about the integrity of speleogenetic environment (HÄUSELMANN, 2002).

Goals of PhD thesis can be summarized thus:

- testing of methodology of standard limestone tablets for process measurements, introducing some improvements,
    - correlation with micrometer measurements,
- measurements of corrosion and flowstone deposition rates over Slovene karst,
    - relation of results to factors and features,
- measurements of corrosion and flowstone deposition rates within smaller areas – cave systems (case studies):
    - finding out the most relevant factors for corrosion/flowstone deposition in epiphreatic zone,
    - finding out the most evident features that are developing with recent processes,
    - finding out the relationship between actual forms, processes and factors.

Usually, known relationship between morphology, processes and factors gives us opportunity to interpret relevant processes and factors from morphology. Such approach was and still is (LAURITZEN ET AL., 2000; Fig. 1.3.1a) common in geomorphology and speleology. It is very effective in environment, where the relations are clear, sometimes even visible and processes relatively fast. In caves, processes are usually slow and, since the rock is transformed into solution, also invisible but observable. Change of hydrological role of underground passages is also common (GOSPODARIČ, 1976; ŠUŠTERŠIČ ET AL., 2002). Additionally, connection of karst processes and climatic conditions (trough CO_2 concentration, temperature and amount of precipitation) makes the relationship even more complicated. Since connection between present-day features, factors and features seems to be questionable, we decided on a slightly different approach for interpretation, which is represented in Fig. 1.3.1b. The advantage of such approach is the separation of the study of morphology and processes (with factors), which seems to be problematic in study of temporally limited present-day phenomena. Measurement of present-day processes, which was often omitted in general speleogenetic studies, gives us also rough estimation of time, which is needed for feature formation. Usually, age of features was calculated from dated cave deposits that overlay or are in any other known temporal relation with features (BOSAK, 2002, 201).

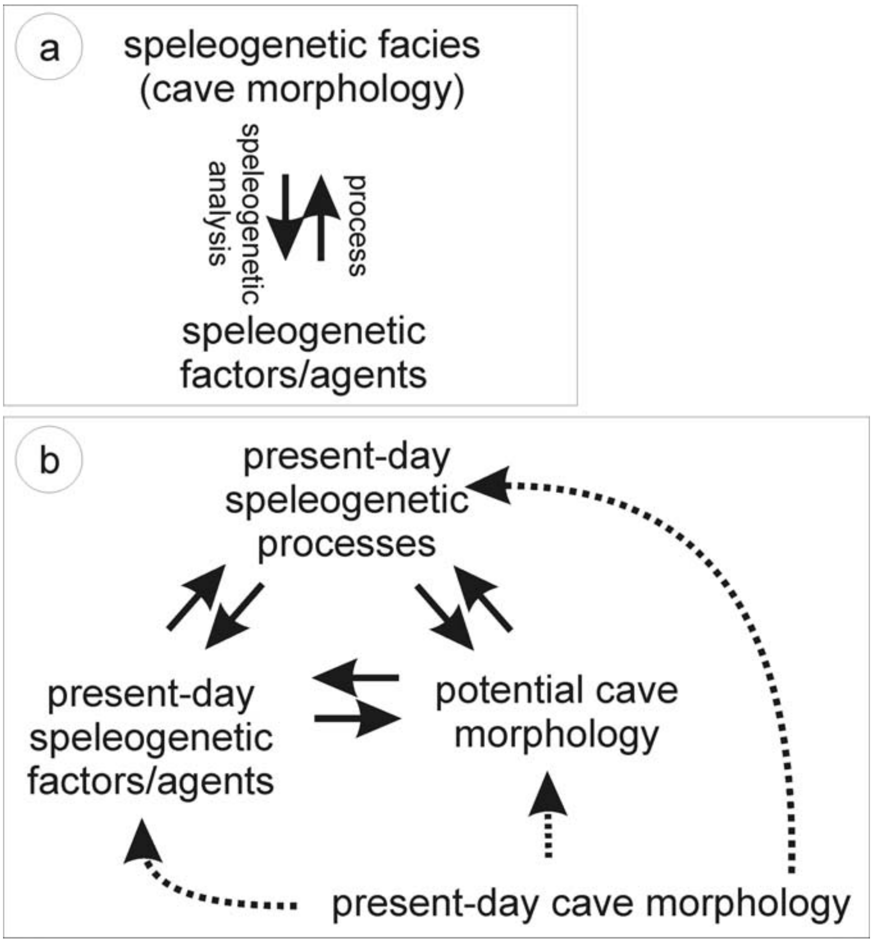


Figure 1.3.1: *Approach to "speleogenetic analysis" suggested by Lauritzen et al. (2000; a) and approach used in this PhD Thesis (b) to interpret speleogenetic relation between present-day processes, potential morphology, present-day factors/agents and their relation with present-day morphology.*

2 Research methods

Grouping of research methods is based on the thematic framework of this Thesis (Chapter 1.3). Since we are dealing with process, factors and feature measurements, research methods can be grouped into:

- measurement of processes (corrosion and flowstone deposition rates; defined with limestone tablets and micrometer measurements),
- measurements of factors (physicochemical properties of water/air):
  - analyses of water (SEC, pH, T measurements, determination of carbonate alkalinity, Ca^{2+} concentration, Mg^{2+} concentration, computation of SI_{Ca}),
  - measurements of air (CO_2 concentration, air temperature, ventilation of cave) and
- measurement of features (thematic geomorphological mapping, detailed observation of some features).

2.1 Measurement of processes

Measurements of speleogenetic processes are relatively sparse, since the processes are supposed to be low-intensive and also unrepresentative for longer time scales, and, if measurements exist, spread over many speleogenetical studies. More often, processes are calculated from datings of reliable sediments, which give us direction and average intensity or rate of the prevailing process. Sometimes, the prevailing process is recognized or analysed from (corrosional) features. In caves, present-day corrosion or flowstone deposition processes were usually measured with micrometer (i.e. HIGH & HANNA, 1970 after WHITE, 2000; SPATE ET AL., 1985; MIHEVC, 1993; MIHEVC, 1997; MIHEVC, 2001) and more rarely with limestone tablets (i.e. 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). Such measurements are highly site-specific. They were frequently used on surface bare rock but much more rarely in caves. The intensity of corrosion in the whole aquifer was usually calculated using hydrochemical data from karst springs (solute load and discharge; PULINA & SAURO, 1993; FORD & WILLIAMS, 2007).

The biggest disadvantage of measurements on karst is the low intensity of karst processes. Usually, measurements should last several years to be sure that results are really representative, while the processes on non-karstic areas are usually much more intensive. Therefore, a disadvantage is accuracy and also reliability of measurements. Using micrometer, accuracy amounts from usual 0.01 mm to up to 0.00001 mm (TRUDGILL, 1977, 253), but the amount of error, which is at low rates relatively higher, represents a serious problem (SPATE ET AL., 1985). Hydrochemical measurements offer us much better insight into the temporal variations of corrosion 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 can not obtain rate of passage enlargement since we lack many variables (i.e. reaction surface, rate of process in different part of an aquifer). These problems can be avoided if we are measuring the same parameters (solute load and discharge) between two measurement points between 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. Disadvantage of this method is also that we are unable to measure at high water level due to small changes in solute load and flooding in epiphreatic passages.

The biggest opportunity, which was rarely used in the past, is calculation of corrosion or flowstone deposition rate from weight loss of limestone tablets. Weight loss is relatively easy to measure with accuracy up to 0.000001 g and since we are dealing with quite high reaction surface, very precise data can be obtained. This finding led us to improve methodology of limestone tablets for measurements in caves and to use it as a basis for corrosion and flowstone deposition rates between 2005 and 2009.

Four years of measurements is very small in comparison with long speleogenesis of Slovene caves (i.e. nowadays active ponor cave Markov spodmol 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 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 influencing environment (i.e. changes of tectonic settings, changes in drainage basin, climate change, land cover…). Among all, the closest limitation seems to be climate change from Pleistocene to Holocene, which significantly changed temperatures, vegetation cover, CO_2 concentration and amount and distribution of precipitation. Accidentally or not, Kunaver (1978) found out that measurements with micrometer (from -0.02 to -0.1 mm/a) obtained in one year fit very well with average corrosion rates (from -0.015 to 0.08 mm/a), which were defined from pedestals formed after glacial retreat at the end of Pleistocene. Much better results can be obtained if the rates are measured frequently – from such results we have insight into temporal variability of processes and can get some crucial information on factors which are controlling the rates of processes.

Another problem is spatial extrapolation. Thus, to what extent can we interpolate and extrapolate rates of processes in space? Available micrometer 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 feature (i.e. doline, slope) can vary a lot. Similar level of variation in the soil was measured also by Trudgil et al. (1994; Crabtree & Trudgil, 1985), who exposed 240 limestone tablets transversally to slope in different depth. Similarly to temporal extrapolation, spatial extrapolation depends on variability of factors, which control rates of processes. Nevertheless, variability of factors along underground water flow in epiphreatic zone 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 done 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 due to mixing corrosion, at changes of water velocity, turbulency…). Measurements at several places and measurements of reliable factors give us important insight at least into magnitudes of spatial variability of processes.

2.1.1 Micrometer measurements

Micrometer, generally known also as micro-erosion meter (MEM) since we are usually measure erosion (but not always!), was quite extensively used in evaluation of chemical denudation rates on bare karst rock. It was developed already in 1960s (SPATE ET AL., 1985), for the first time used by High and Hanna (1970 after FORD & WILLIAMS, 2007) and later improved by several researchers. During our measurements, we used micrometer from Karst Research Institute ZRC SAZU, which was already used by Mihevc (1993, 1997, 2001) in some caves and on the surface. It consists of a micrometer gauge connected with an iron plate with 3 triangularly arranged legs, which locks precisely into stainless steel studs set into the rock surface. Micrometer gauge is moved for several millimeters from the center of equilateral triangle that is formed by three legs. Such arrangement of micrometer gauge enables us to make three different measurements at each measurement place. Accuracy depends considerably on micrometer gauge – the micrometer that we used has resolution about 0.01 mm. Nevertheless, accuracy depends also on some errors recognized and summarized by Spate et al. (1985):

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

Exact value or error depends on temperature changes, material, from which the micrometer is formed, softness of the rock, number of measurements and carefulness 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 could amount even more than 0.02 mm per reading (SPATE ET AL., 1985). Even more concerning is the fact that error of measurements and even standard deviation often exceed corrosion rates that were measured with micrometer. In Yarrangobilly cave (Australia), where erosion rates are from -0.000 to -0.137 mm/a (with median value -0.008 mm/a!), error was estimated to ±0.008 - ±0.022 mm (SPATE ET AL., 1985). Therefore, annually micrometer measurements are useless in streams, which show very low erosion/corrosion rates or where the errors can be high.

2.1.2 Hydrochemical method

Hydrochemical method was often used to observe chemical denudation rates with observation of discharge and concentration of solutes at the spring (WHITE, 2000, 151). The method bases on differences on solute load between input (surface) and output (resurgence) at known amount of water (or discharge). Input is often neglected due to low solute load in precipitations but if we are dealing with at least portion of allogenic input, consideration of the latter is of crucial importance. If an aquifer is recharged by primary infiltration, only discharge and solute concentrations are measured at the spring. Since measurements of specific electrical conductivity (SEC) are more easily obtained than chemical analysis of water samples with respect to calcite and SEC is relatively good approximation for total hardness ($CaCO_3$ 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). To check reliance of data (especially solute concentration), some laboratory analyses and discharge verifications are essential. Errors are complex and depend strongly on accuracy of discharge and solute concentration measurements.

Denudation rates are related to the whole catchment area but such measurements do not provide any information on spatial variability, which can vary considerably within the aquifer. Somewhere along water flow, chemical denudation rate can be calculated similarly to a whole catchment area if we take into account change in solute load between two measurement points, where confluences and diffluences are absent. In such a way, flowstone deposition rates were calculated in Križna jama.

2.1.3 Measurements with limestone tablets

The first observations of corrosion with limestone tablets (also known as limestone plates, limestone discs, rock tablets, micro-weighed tablets or weight-loss tablets) were done by Chevalier (1953 after GAMS, 1959) and later by Gams (1959). In 1960s, an extensive plan for corrosion measurements in Slovene caves was proposed by Društvo za raziskovanje jam Ljubljana (=Caving Society Ljubljana) most probably under the influence of Gams (POROČILO O…, 1959). This plan was never realized. Although the first measurements were done in underground water flows, later measurements with limestone tablets were dedicated to corrosion measurements in soil. The greatest expansion 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). Before (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), limestone tablets were used in many local studies, mostly to evaluate corrosion rates at the soil-rock contact. 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 difficultness with fixing.

Methodology of limestone tablets is based on weight-loss during exposure. If we know reaction surface (area of limestone tablet) we can transform weight-loss into metric units (i.e. mm/a). This simple calculation shows that we can measure corrosion or flowstone deposition rates very precisely in comparison with micrometer, if the accuracy of balance is better than 0.1 g. This reason led us to start with short-term measurements of corrosion and flowstone deposition rates over Slovene underground karst.

Limestone tablets used by Gams (1985) were made of borehole's cores from Lipica limestone quarry. We used the same. Limestone is of Senonian (Upper Cretaceous) age. It contains 97.7-98.7 % of $CaCO_3$, 0.21 % of MgO, less than 0.1 % of SiO_2, 0.05 % of Al_2O_3 and 0.05 % of S, 0.007 % of Fe_2O_3, (GAMS, 1985, 365). According to Folk's classification Lipica's limestone is micrite to biopelmicrite. According to Gams (1985, 365), density of limestone is 2,710 kg/m^3, while our measurements, based on weight and volume of 235 limestone tablets, showed a slightly lower value (2,688 kg/m^3). The latter value was used for transformation of units from grams to millimetres with Eq. 2.1.3.1.

$$C/D = \frac{\Delta m}{\rho \times A \times t}$$ **(Equation 2.1.3.1)**,

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

Diameter of limestone tablet is 41 mm, while the thickness ranges 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. Similar procedure was advised by Goudie et al. (1981, 143). Due to numerous measurements, we avoided such procedure by drying in chemical laboratory for 15 days. Instead of drying in oven, we implemented correction factor for amount of water which remained in the limestone tablets after 15 days of drying. Whole procedure from preparation to final weight of limestone tablets is represented in Fig. 2.1.3.1.

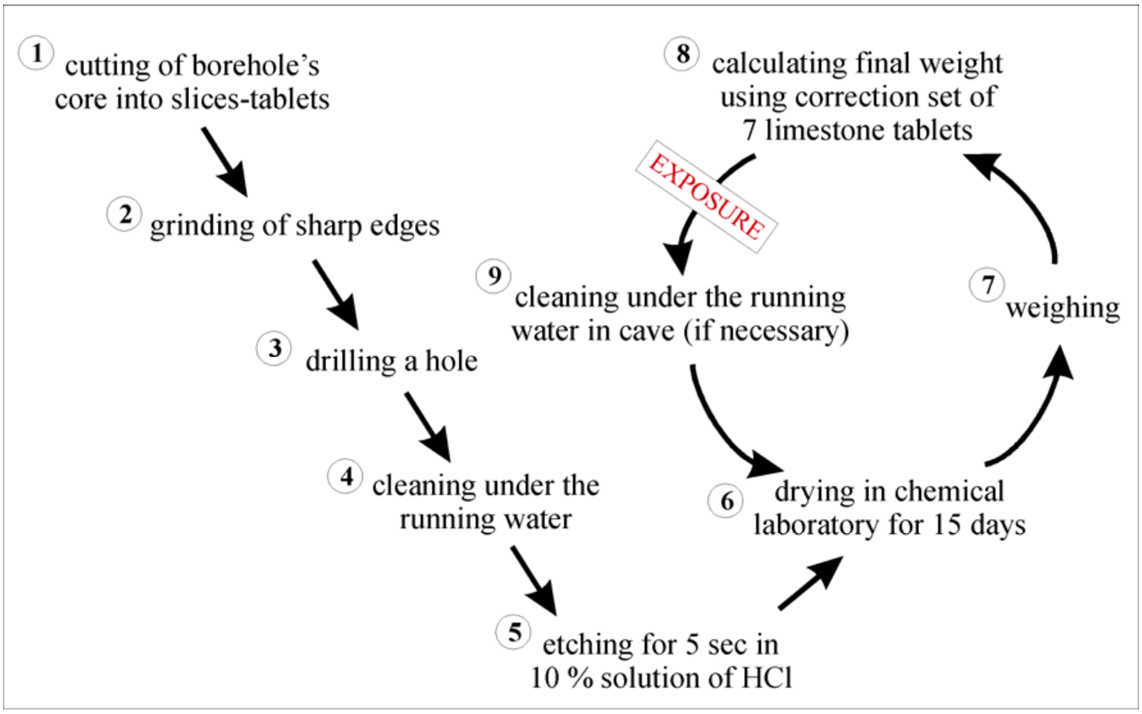


Figure 2.1.3.1: *Procedure from preparation to final weight calculation of limestone tablets and their treatment after exposure in this Thesis.*

With phase 1 (Fig. 2.1.3.1) core with diameter of 41 mm was cut into 5-8 mm slices. Probability of chipping at edges was reduced with phase 2. Drilling was done with a drilling machine under the water. Due to fragility of limestone, a small hole with 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. Final elimination of fine particles was achieved in phase 5, when the surface of limestone tablets was also partly naturalized. Afterwards, limestone tablets were dried in chemical laboratory for 15 days. In this period of time, the majority of water left the limestone tablets and the weight became quite stable. Weighing (phase 7) was done at the balance Sauter 404/13 with resolution 0.0001 g and accuracy about ±0.0003 g. Since the weight of limestone tablets depends on amount of water (and this phenomenon is the most closely related to air relative humidity), weight was calibrated according to Eq. 2.1.3.2 with correction set of 7 limestone tablets during phase 8 (described more in detail in following paragraph). With such procedure we prepared 739 limestone tablets. With phase 9 we gently cleaned limestone tablets after exposure if this was necessary. Cleaning was done usually in cave streams. If any dirtiness was not noticed in the cave, it was removed under the drinkable running water in chemical laboratory. This water comes from Malni springs – therefore no corrosion can be expected during cleaning (Chapter 4.6). Phases from 6 to 9 were applied when the limestone tablets were exposed to cave streams.

$$m_{corr} = m - m \times \frac{\overline{m_{7(x)}} - \overline{m_{7(initial)}}}{\overline{m_{7(initial)}}}$$ **(Equation 2.1.3.2)**,

where m_{coor} is corrected weight of individual limestone tablet, m is measured weight of limestone tablet, $\overline{m_{7(x)}}$ is average weight of 7 limestone tablets at the same time as m was measured and $\overline{m_{7(initial)}}$ is average weight of 7 limestone tablets defined at the beginning of measurement (16th March 2006; temperature 25 ºC; relative humidity ~38 %).

Since we avoided drying of limestone tablets in oven and cooling in silica gel performed by Gams (1985) and advised by Goudie et al. (1981, 143), usage of phase 8 is crucial to avoid error from changes in air relative humidity. Limestone is a porous rock and easily absorbs water from flowing streams and air. If we take into account that relative humidity was not stable in the chemical laboratory, change of weight of limestone tablets should be expected because of changes in relative humidity. This is clearly visible in Fig. 2.1.3.2, where seasonal change of average weight of correction set from 96 measurements is represented. Annual variability is seen in relative humidity and deviation of weight. Pearson product moment correlation coefficient is important and amount 0.73. Since the weight of limestone tablets is an important function of relative humidity, equation on Fig. 2.1.3.3 significantly describes the relationship between weight of limestone tablets and air relative humidity. Usage of correction factor (Equation 2.1.3.2) is therefore crucial to eliminate influence of changeable relative humidity.

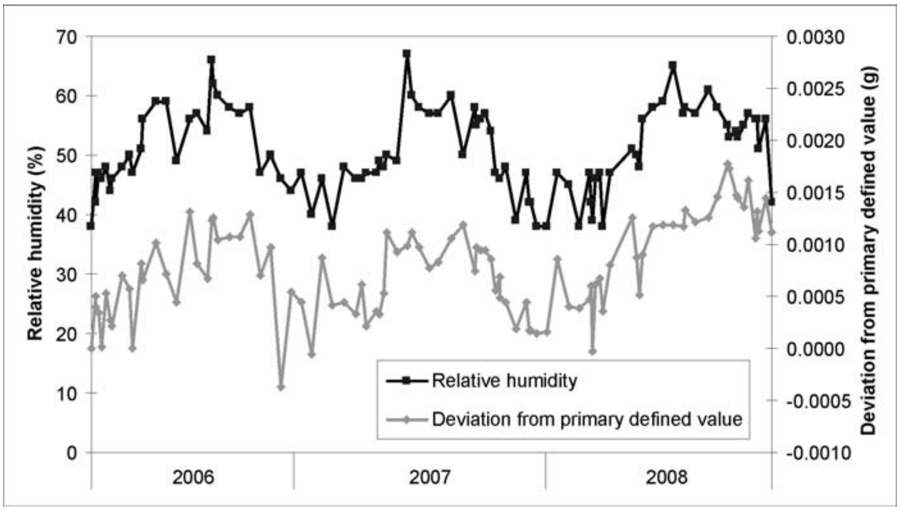


Figure 2.1.3.2: *Annual and subannual variation of relative humidity and deviation of weight from primary defined weight.*

Application of correction factor eliminates up to 0.0018 g high seasonal variation in weight of 20-25 g heavy limestone tablets. Although, some real values deviate from calculated weight regarding to equation in Fig. 2.1.3.3 averagely for ±0.0003 g (about ±0.00003 mm) to up to ±0.0011 g (about ±0.00012 mm), which is most probably a sum of the balance error, error of defining relative humidity and error of some measurements when humidity in the limestone tablets was not equilibrated with relative humidity in the air.

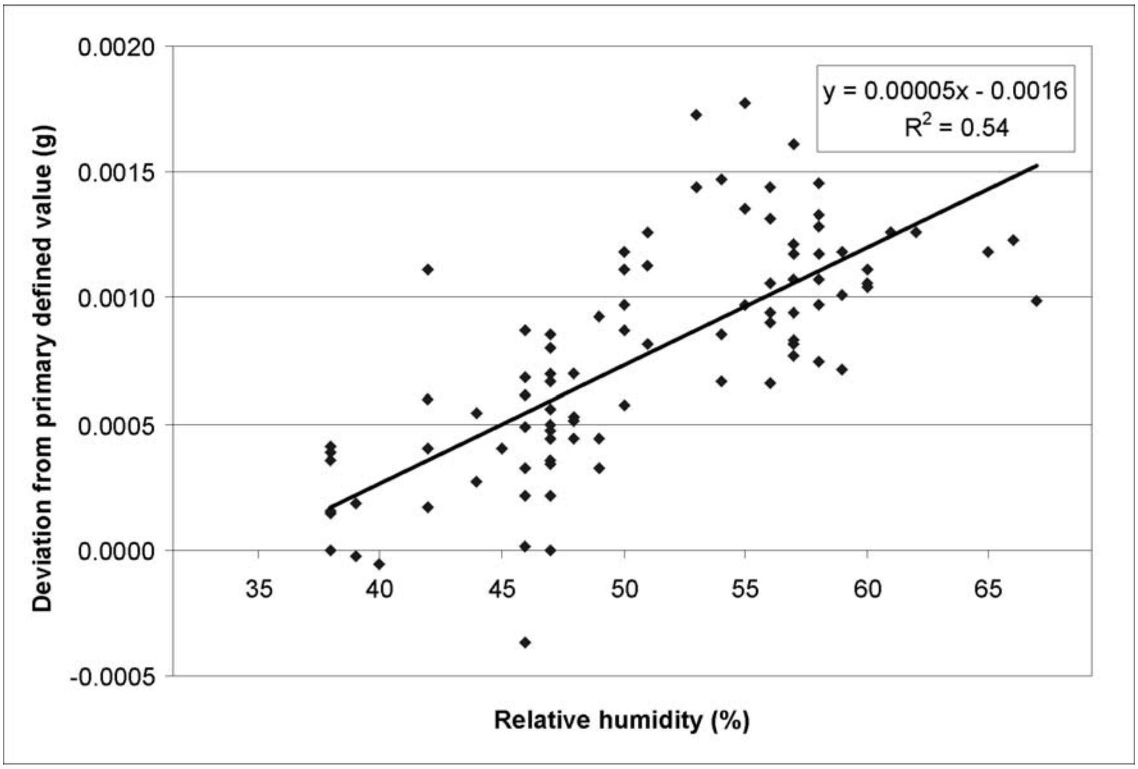


Figure 2.1.3.3: *Relation between relative humidity and deviation of weight from primary defined weight.*

Results obtained during measurements on case studies show that error can be much higher than ±0.00003 mm and that this error is not caused by changes in relative humidity. This kind or error can be calculated using differences in weights of limestone tablets, which were placed in Križna jama and Lekinka but not reached by water. Distribution of errors in Križna jama is nearly normal, in Lekinka is a little bit more flattened. Average is in both cases exactly at 0.0000 mm (Fig. 2.1.3.4), which means that procedure has no systematic errors. Standard deviation was calculated using Eq. 2.1.3.3 and amounts ±0.00013 mm in Križna jama and Lekinka.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}}$$ (***Equation 2.1.3.3***),

where σ is standard deviation, x_1 is individual deviation from average value, $\bar{x}$is average value and N is number of measurements ($N_{\text{Križna jama}}$=362, N_{Lekinka}=214).

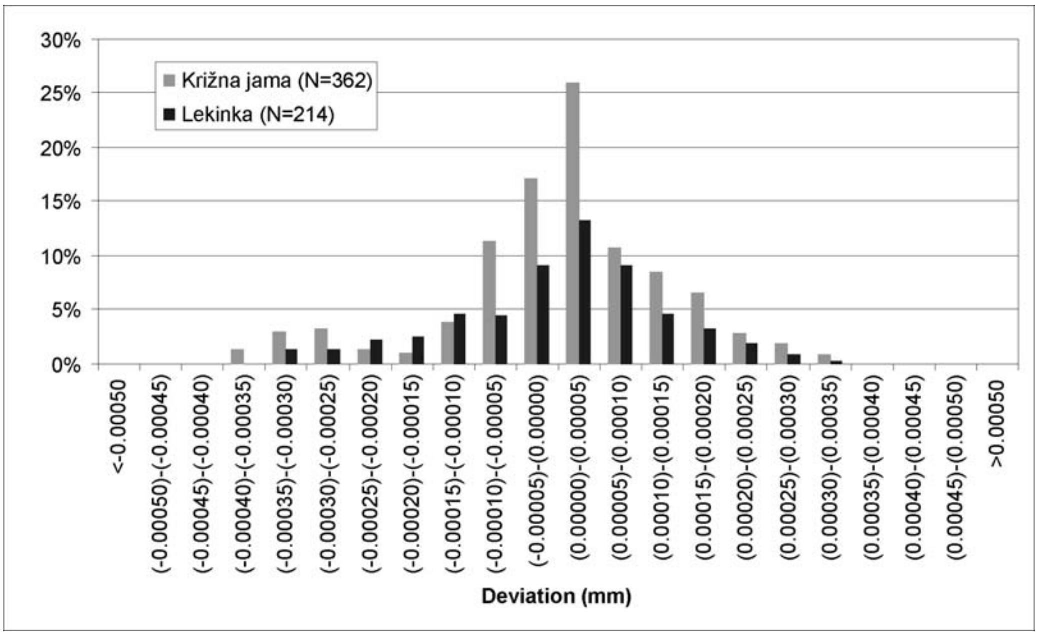


Figure 2.1.3.4: *Distribution of errors during measurement with limestone tablets in Križna jama and Lekinka.*

In extreme situation, we can expect up to ±0.0004 mm of deviation. These deviations are valid for 15-30 g limestone tablets – if they are lighter, deviation is expected to be higher due to smaller reaction surface. Errors can not be a result of other speleogenetical processes (i.e. condensation corrosion) or mechanical damage (since the average value is 0.0000 mm) and therefore represent a practical error of measurements with limestone tablets. During our research we could not find any appropriate reason for this type of error. Nevertheless, even maximal error obtained during measurements with limestone tablets is much lower than average error obtained with measurements with micrometer (Chapter 2.1.1). **On the basis of this finding, measurement with limestone tablets seems to be the most accurate methodology for low-intensive chemical karst processes.**

During measurements with limestone tablets we noticed that deviation described in the previous paragraph is not randomly distributed. Deviation there was calculated using all deviations together. If we cluster individual daily deviations from Križna jama and Lekinka (these are deviations which were obtained every 15 days regarding to measurement strategy – see measurements at KJ-2 in Chapter 4.1.2 and L-1 in Chapter 4.2.1) and calculate mean value with standard and maximum deviation for each cluster we notice that standard deviation within cluster is often much smaller than average value of deviation (Fig. 2.1.3.5). Therefore, we can distinguish between accuracy and precision of method as it is shown in Fig. 2.1.3.6. We notice that precision is much better than accuracy. This means that if we have limestone tablets, which were placed but not exposed to flowing water, and we subtract their deviation from exposed limestone tablets, we can achieve on average for ±0.00011 mm better results. **In this case, mean error (precision) of ±0.00005 mm is expected. Although this mean error is very low, we can sometimes expect much higher maximum error of ±0.0002 mm due to other reasons, especially in Križna jama (Fig. 2.1.3.5).** In spite of all that, this limit of error can be achieved if we have placed but not exposed limestone tablets together with exposed limestone tablets. Very high Pearson product moment correlation coefficient between deviations in Lekinka and Križna jama (+0.84) also indicates that we should use correction value for accuracy from any cave if the limestone tablets were collected and dried in the same period of time.

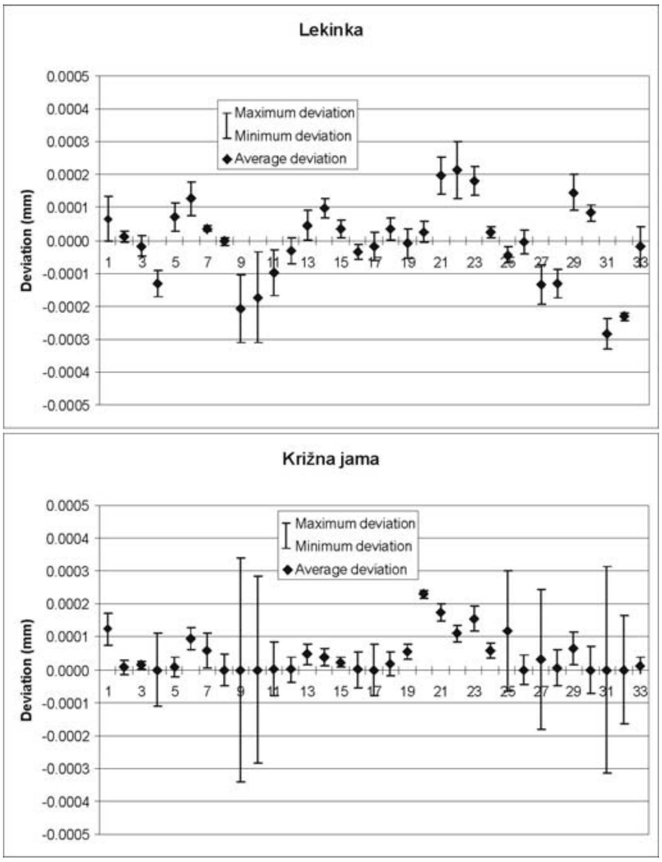


Figure 2.1.3.5: *Minimum, maximum and average deviations regarding to deviation of placed but not exposed limestone tablets from Lekinka.*

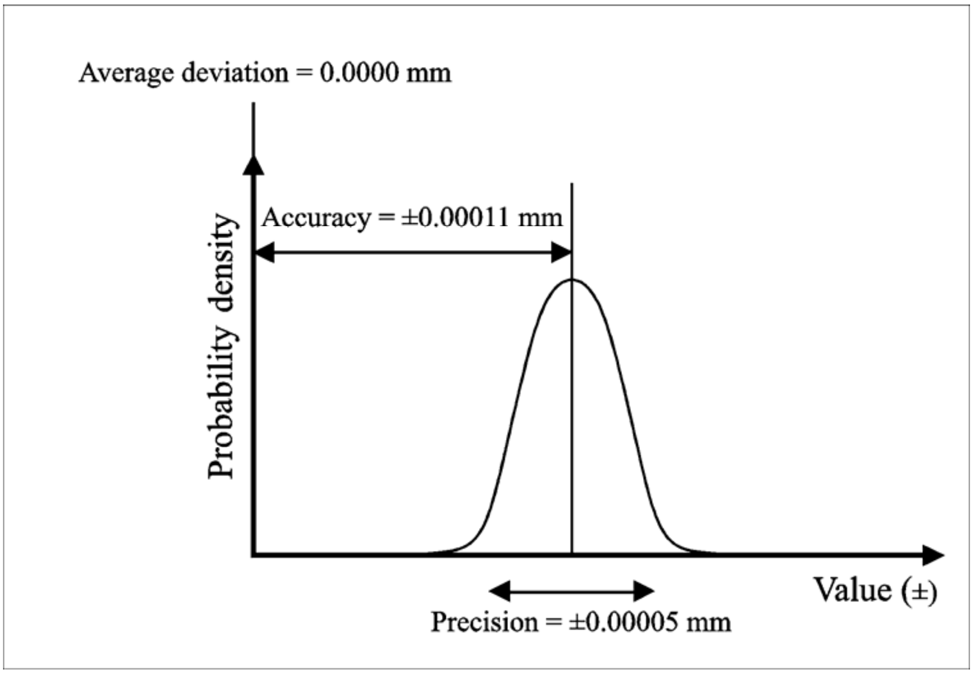


Figure 2.1.3.6: *Average precision and accuracy of measurements with limestone tablets regarding to deviation of placed but not exposed limestone tablets from Lekinka and from Križna jama.*

Our limestone tablets differ significantly from others because of the central hole for fixing. Other researchers, who were measuring corrosion 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. **The central hole in our limestone tablets was a key factor to succeed in measurements in underground water flows**. At the beginning, we used a 8 mm cave anchor with nut and a pair of felted washers to protect limestone tablets against abrasion. Since rusting of iron represent a big problem especially at low rates of processes, iron parts were later replaced with stainless steel, brass or plastic. Abrasion was avoided with firm fixing and protection of stainless steel washer with nonabrasive material – felt. The way of fixing can be seen in Fig. 2.1.3.7.

Figure 2.1.3.7: *The way of fixing of limestone tablet (example from KJ-3, Križna jama, during very low water level).*

Rusting of iron anchor, washers and nuts and contact of rust with limestone can represent a significant problem at corrosion and flowstone deposition rate measurements. We found that at some places rust accelerates corrosion rates, possibly via formation of siderite ($FeCO_3$), which enhances acidity (FORD &WILLIAMS, 2007, 58). If the flowstone deposition rates are very small, rusting sometimes turns small flowstone deposition rates to misleading corrosion. Accelerated corrosion, as a result of rust, can be seen under the magnifier as a circular entrenchment at the surface of limestone tablet especially below edge of washers or as incomplete solution over all area of limestone tablets located under the felted washers. Influence of rusting was found out relatively early (after 8-month measurements) but the real importance of the problem was recognized much later (in summer 2007 in Križna jama 2, when we compared results of monthly and half-year measurements at the same measurement point). For this reason, some low or even medium corrosion rates, especially rates determined during 8-month-long measurements, should be taken cautiously.

Rusting, and its influence to corrosion rates, is not expressed equally at all measurement points. In Križna jama and Križna jama 2, comparison with tablets fixed on stainless steel screws shows that rates of misleading corrosion can amount from -0.0001 to -0.0024 mm/30 days. The lowest average and the lowest maximum misleading corrosion (up to -0.0001 mm/30 days) was detected in Pisani rov near Kalvarija and at Brzice (=Rapids) downstream of 1st lake. The highest maximum misleading corrosion was detected in the upstream part of Jezerski rov, where amounts up to -0.0024 mm/30 days. In Križna jama 2, maximum misleading corrosion is smaller in comparison with Križna jama (up to -0.0010 mm/30 days) but the average can be much higher (from -0.0003 to -0.0006 mm/30 days). These values are so high that they surpass flowstone deposition rates, at least in Križna jama 2! Limestone tablets fixed on plastic or brass screw, washers and nut do not show any important deviation from limestone tablets fixed on stainless steel parts. Therefore, only usage of iron for fixing sometimes leads to lower flowstone deposition rates or higher corrosion rates. Synchronous measurements with limestone tablets fixed on stainless steel screws and plastic screws, which were done in Križna jama 2, show no differences.

Damage of limestone tablets were avoided with usage of specially designed **transporter** (Fig. 2.1.3.8). In transporter, limestone tablets were arranged in several layers. Each limestone tablet within each layer was distanced from another limestone tablet with at least 5 mm distance. 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 limestone tablet, since they were not directly signed. Damages during transport never occurred during 4 years of usage.

According to some warnings (ŠUŠTERŠIČ-personal comm.), **freshly cut surface can have some influence on corrosion rates.** Gams (1985, 372) found out that corrosion rates are due to fresh cut surface lower in first year and remain constant during second and third year of measurements. A contradictory phenomenon was observed by Trudgil et al. (1994) – in first 2 years corrosion rates were for a magnitude higher in comparison with observations that lasted 10 years. Decrease of corrosion 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 cleaning process. In addition, it is possible that the dryer years in the second period of observation could decrease rates of corrosion. Our study, which was carried out in Lekinka, showed decrease in corrosion rates, since the highest corrosion rates were observed at freshly exposed limestone tablets, while the other was exposed before for about 540 days (Fig. 2.1.3.9). The highest difference between limestone tablets was observed at the beginning of measurements (difference amounted more than 0.0020 mm/15 days). When corrosion removed 0.025 mm of surface, limestone tablets indicated similar corrosion rates. This is a result of reaction surface, which is enlarged with unnatural cut into the crystal lattice. After corrosion of many small crystals with high specific area, the reaction at the surface is much smaller since corrosion has to remove much bigger crystals. At the latter surface of crystals, corrosion "passes from one atomic layer to the next, much like unraveling successive rows of knitting" (FORD & WILLIAMS, 2007, 66).

Figure 2.1.3.8: *A way of protection of limestone tablets to prevent tablets from damage during transport (photo: Alojz Troha, DLKJ).*

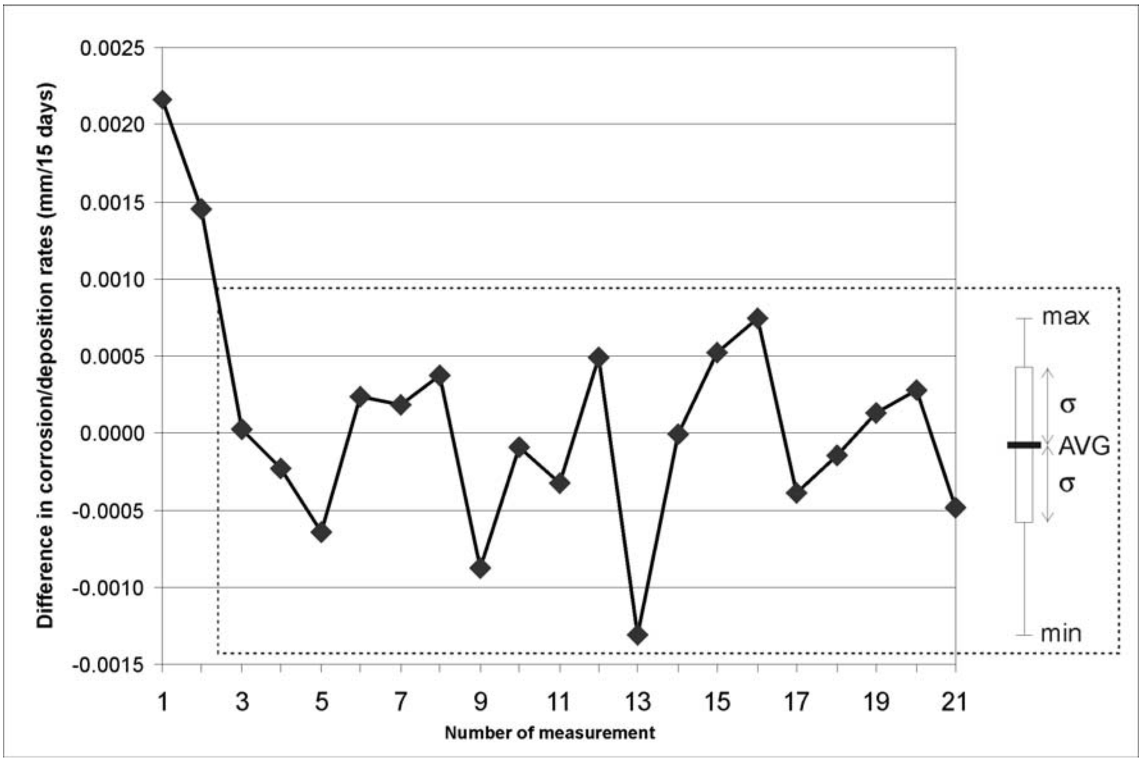


Figure 2.1.3.9: *Differences in corrosion rates due to freshly cut surface and due to heterogeneity of limestone tablets (positive deviation shows higher corrosion rates on fresh limestone tablet and vice versa).*

Influence of freshly cut surface on flowstone deposition rates was studied at and next to measurement point KJ-6 (downstream ending of Pisani rov, Križna jama; Chapter 4.1.5). Measurements with old limestone tablets started on 16th August 2006. Measurements with new limestone tablets started few centimeters beside old ones on 18th December 2007. Between these two dates, 0.0210 mm of flowstone was already deposited on old limestone tablets. On-going synchronous measurements point out that difference in flowstone deposition rates exist only at the beginning of measurements until ~0.03 mm of flowstone is deposited (Fig. 2.1.3.10). Differences are not reduced gradually but rather in steps from 62 % to less than 5 %. Later, flowstone deposition is nearly equal to or at least close to maximum error of measurement (±0.0004 mm).

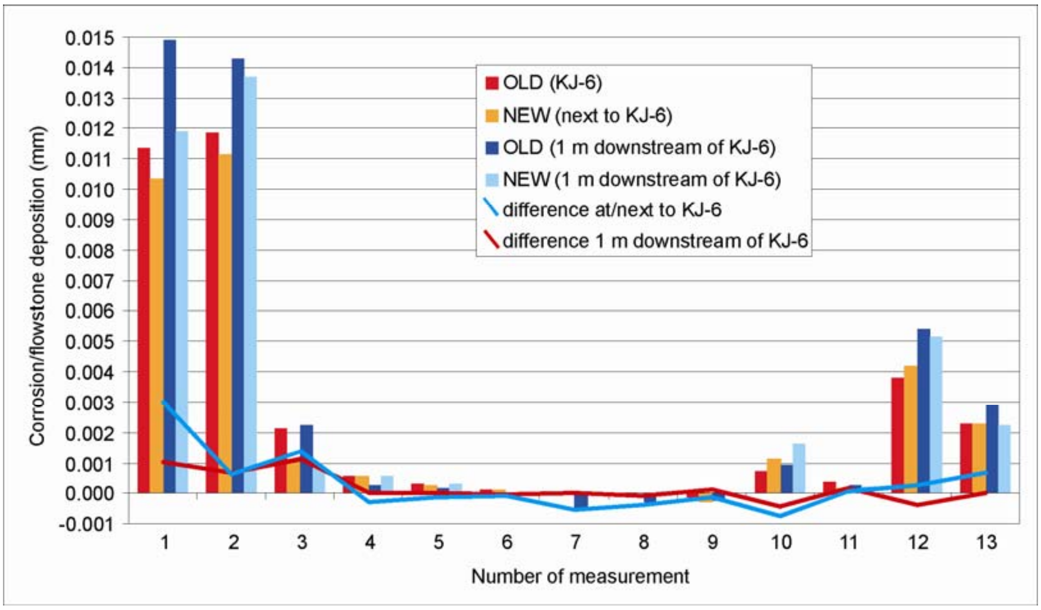


Figure 2.1.3.10: *Influence of freshly cut surface on flowstone deposition rates.*

Although limestone tablets are made of the same type of limestone, they show a certain degree of **heterogeneity**. Gams (1985) did not devote any special attention to this problem although he visually recognized heterogeneity of limestones, from which the tablets were prepared. Like Crabtree & Trudgill (1985), he avoided this problem by using similar limestones, if possible from the same stratigraphic horizon. According to our observation, even limestone from the same stratigraphic horizon consists of different portion and composition of allochems (biogenetic remnants-shells, peloids and intraclasts) and different portion of micrite with different degree of recristalization. Since sparites and other coarse grained rocks are less soluble than pure micrite, we should expect different corrosion rates. Many studies have found that micrites and biomicrites are soluble faster and that rate of dissolution decreases substantially where sparite becomes grater than 40-50 % by volume (SWEETING & SWEETING, 1969 after FORD & WILLIAMS, 2007, 28; MAIRE, 1990 after FORD & WILLIAMS, 2007, 28). Corrosion rates increase also with heterogeneity of grain size since differences in grain size results in greater roughness (reaction surface) at reaction surface – this is the reason for smaller corrosion rates in pure micrite (FORD & WILLIAMS, 2007). Although Lipica limestone seems to be quite homogeneous, we should expect some differences in corrosion rates. In Fig. 2.1.3.9 we can see that differences in corrosion rates are sometimes higher than maximum error calculated from tablets fixed in caves but not exposed to flowing water (±0.0004 mm). This deviation probably derives from heterogenic limestone tablets and can amount on average ±0.0005 mm/15 days. Maximum observed deviation amounts -0.0013 and 0.0007 mm/15 days. Nonetheless, both limestone tablets indicate similar average corrosion rates (difference is only -0.0001 mm/15 days; Fig. 2.1.3.9).

If we apply measured corrosion rates to different caves, we have to be sure that corrosion rates at limestone tablets made of Lipica limestone are equal to corrosion rates, which are valid for rock in which the cave is formed. Therefore, measurements of corrosion rates on **different lithology** have to be made to apply measurements with limestone tablets made of Lipica to development of individual cave. Gams (1966b, 1980) states that hardness of waters from dolomites do not differ much from that one, which flows through the limestones. This would show similar corrosion and was recognized also by Sweeting (1972, 29), who interpreted similarities with sufficient residence time of water to reach equilibrium (SWEETING, 1972, 29) and higher degree of fracturization in dolomites, which enhances dissolution with bigger reaction surface. But since the major role in corrosion rates is kinetics of dissolution, which is without no doubt slower in dolomites (GERSTENHAUER & PFEIFFER, 66 after SWEETING 1972, 28-29; CHOU ET AL., 1989 after DREYBRODT, 2004, 297-298) due to bigger crystals and stronger bonds between $MgCO_3$ molecules (FORD & WILLIAMS, 2007, 71), differences appear in corrosion rates between limestones and dolomites (DREYBRODT, 1988, 179). Differences are evident especially at low saturation (up to 50-60 %), while at higher degree of saturation differences seem to decrease (DREYBRODT, 1988, 179; DREYBRODT & EISENLOHR, 2000, 145). Differences in corrosion rates appear also within limestones, since they contain different amount of "impurities", different type and amount of allochemical graines, different cement (micrite/sparite) and different primary porosity. Regarding to some examinations, Sweeting (1968, 229) states that limestones which have a percentage of sparry calcite, may be less soluble than micrites, most probably because of larger crystals. To apply corrosion rates measured with limestone tablets made of Lipica limestone, comparison of corrosion rates between several carbonate rocks was done in Lekinka. Some limestones were taken from caves, where we measured corrosion rates (Križna jama, Lekinka, Postojnska jama), while some other were taken randomly usually from Dolenjska region (J_1, J_2). Results represented in Fig. 2.1.3.11 show that limestones of different age and also composition demonstrate similar corrosion rates. Deviation from Lipica limestone (K_2^3) is rather small and amounts up to 20 %. Lower corrosion rates were observed with marble from Pohorje mountain, with dolomite from Dolenjska region (J_2_dol) and especially with Middle-Lower Jurassic, Lower Jurasic and Upper Triassic dolomites sampled in or near Križna jama. The latter dissolves up 90 % slower than Lipica limestone! Higher corrosion rates were observed at fractured limestones (K_2^2_lim (fractured; POST) – most probably due to higher reaction surface. Deviation within each carbonate group is relatively small – on average it amounts to 7.7 %.

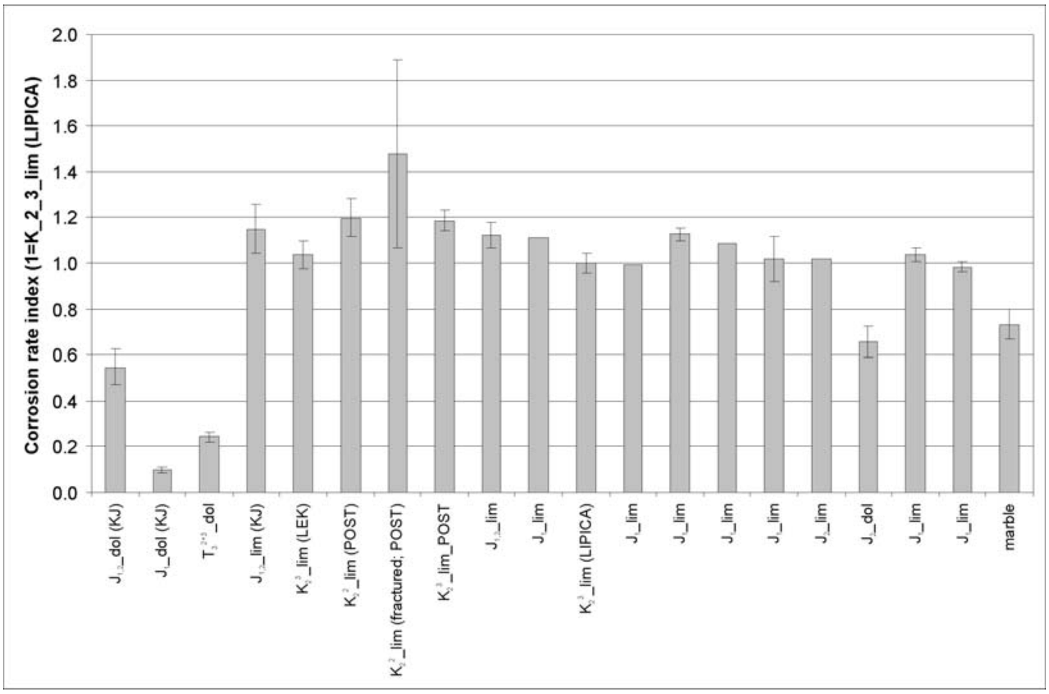


Figure 2.1.3.11: *Corrosion rates at tablets of different lithology (lim-limestone; dol-dolomite; KJ-Križna jama; LEK-Lekinka; POST-Postojnska jama).*

Comparison with micrometer measurements was done in Lekinka for corrosion rates and in Križna jama for flowstone deposition rates. According to Jennings (1981 after SPATE ET AL., 1985), good agreement between limestone tablet experiments (-0.017 mm/a) and micrometer measurements (-0.021 mm/a) in absolute terms was achieved. Our comparison, done in Lekinka cave on the same place with micrometer (9 values per measurement period) and limestone tablets (3 values per measurement period; Fig. 2.1.3.12), shows considerably higher differences. Only during the 1st measurement period, was corrosion higher in the case of measurements with limestone tablets. Further on, all measurement periods show higher corrosion rates measured with micrometer, although some minimal values measured with micrometer can be equal to average values measured with limestone tablets. The highest discrepancy (1:0.41) was observed during the 3rd measurement period, in which limestone tablets were partly buried under the bed load material. Nevertheless, the 2nd and 4th measurement periods indicate that, even the hydrological conditions are the equal, average corrosion rate measured with limestone tablets is for about 33 % lower in comparison with average corrosion rate measured by micrometer. Similar deviation in the same direction was found by Jennings (19 %; 1981 after SPATE ET AL., 1985). On the basis of recent results it hard to find appropriate reason for higher corrosion observed with micrometer. It could be related to overestimated "corrosion" due to probe erosion, which can bring more than 0.02 mm higher "corrosion" rate per reading – especially during first observation even on hard limestones (SPATE ET AL., 1985, 431). Since we were measuring on wet surface, higher probe erosion is possible. Nevertheless, it is hard to say which method gives more reliable results.

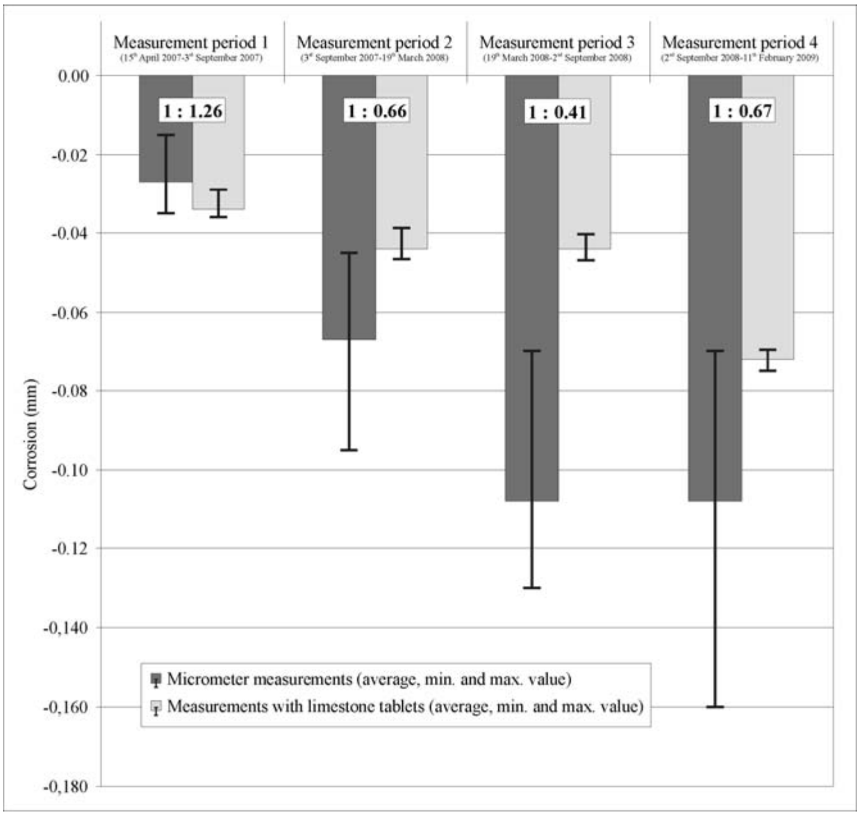


Figure 2.1.3.12: *Differences in corrosion between micrometer measurements and limestone tablets recorded in Lekinka.*

Fig. 2.1.3.12 gives us also good insight into the maximum deviation of measurements using micrometer or limestone tablets. Average standard deviation and maximum deviation using limestone tablets is at least 5 times smaller in comparison with micrometer measurements. This difference arises from microlocal differences in corrosion, which are averaged using limestone tablets since the corrosion rates are calculated from weight loss and reaction surface. Using micrometer, differences reflect real differences in corrosion at several measurement points at the rock surface due to heterogeneity of the rock.

Comparison of flowstone deposition between micrometer measurements and measurements using limestone tablets also reflects quite high differences (Fig. 2.1.3.12). The highest difference was observed during the 1st measurement period (using limestone tablets we detected only 8 % of flowstone deposition measured with micrometer). Later, differences are lower (during the 2nd measurement period, using limestone tablets we detected 50 % of flowstone deposition measured with micrometer). Differences can arise from roughness of the rock surface, which influences thickness of diffusion boundary layer.

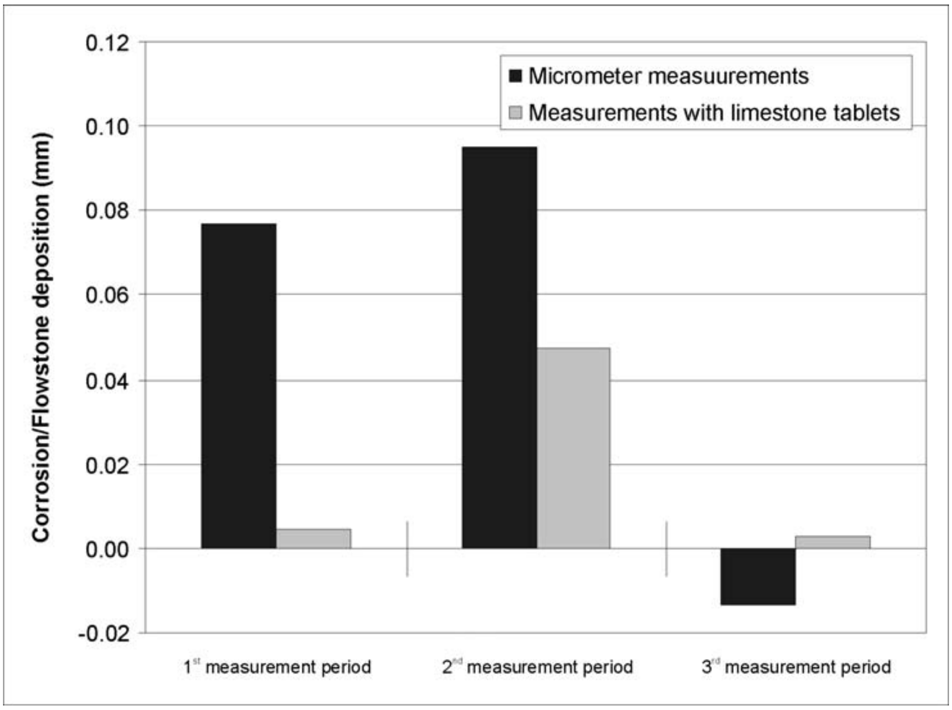


***Figure 2.1.3.13:** Comparison of corrosion/flowstone deposition rates between micrometer measurements and measurements with limestone tablets recorded at Brzice (Križna jama).*

Total error of measurement done by measurement with limestone tablets depends on a number of errors and on possibility of using correction factors. The following deviations from expected values (errors) were recognized during measurements (values are valid for 17-25 g limestone tablets):

- E_1 – deviation due to different water content in limestone tablets related to relative humidity (average: ±0.00003 mm; maximum: ±0.00012 mm),
- E_2 – deviation due to unknown reason (average: ±0.00013 mm; maximum: ±0.0004 mm); it can be reduced with placed but not exposed limestone tablets (average: ±0.00005 mm; maximum: ±0.0002 mm),
- E_3 – deviation toward higher corrosion rates due to rusting of iron parts used for fixation (from 0.0000 to 0.0024 mm/30 days),
- E_4 – deviation toward higher corrosion rates due to freshly cut surface (at the beginning less than -0.0020 mm/15 days, then diminishes below -0.0005 mm/15 days when about 0.0025 mm of rock is removed); – deviation toward slower flowstone deposition (at the beginning is relatively small, then diminishes below ±0.0004 mm when about 0.03 mm of flowstone is deposited),
- E_5 – deviation due to heterogeneity of Lipica limestone (on average: ±0.0005 mm/15 days; maximum: -0.0013 mm/15 days and 0.0007 mm/15 days; in longer period of measuring is most probably averaged and therefore lower),
- E_6 – deviation due to differences of Lipica limestone with cave’s host rock (depends on type of cave’s host rock; limestones are usually up to 1.2 times more soluble than Lipica limestone; dolomites are from 1.4 to 10 times less soluble).

2.2 Measurements of water characteristics

Water samples were collected in 0.5 L bottles, stored, as suggested by Cryer & Trudgill (1981, 185), at temperature between 5 and 10 °C and analyzed within 2 days for **total hardness (Ca^{2+} and Mg^{2+}) and Ca^{2+} concentration.** Concentrations were determined by complexometric titration with 0.01 M EDTA in chemical laboratory at Karst Research Institute ZRC SAZU, Postojna. Due to relatively pure Ca-Mg-CO_3 waters, **Mg^{2+} concentration** was determined as difference between total hardness and calcium hardness. Analyses were done by laboratory assistant, Mateja Zadel. Carbonate alkalinity (usually HCO_3^-) 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 be in pure carbonate water solutions good approximation of dissolved load (Ca^{2+} and Mg^{2+} concentrations; WHITE, 2000, 145). Consequently, its change during water course reflects degree of interaction with soluble rock or degree of flowstone deposition. For defining spatial and temporal changes of dissolved load we used WTW Multiline P4 and SEC probe. Resolution was 1 µS/cm, accuracy is estimated to ±2 µS/cm. SEC was measured *in situ*.

pH measurements show 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 solution. In the past, accurate measurements of pH represented one of the gravest analytical problem (FORD & WILLIAMS, 2007, 64). Since the influence of H^+ concentration to saturation indexes is high, its accurate measurements are crucial for proper determination of carbonate balance. If we miss right pH value for 0.1, saturation index with respect to calcite will be wrong for nearly the same value, this is 0.1 (SASOWSKY & DALTON, 2005, 127).

pH measurements were done using WTW Multiline P4 and plastic body pH probe. *In situ* measurements were taken in calm or slowly flowing water. Calibration of pH meter was done in chemical laboratory with pH = 7 and pH = 10 buffer solutions. Due to many measurements and complicated calibration in caves we practiced calibration in laboratory instead of proposed calibration on each measurement point. Resolution was 0.01 of pH value. Accuracy was estimated to ±0.05.

Water temperature was determined with WTW Multiline P4 and SEC probe, which supports also temperature measurements. Resolution and precision was 0.1 °C, accuracy is probably a little smaller (±0.2 °C).

Saturation index with respect to calcite (SI_{Ca}) indicates aggressiveness of water with respect to calcite. It 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 solution (FORD & WILLIAMS, 2007, 48-49; MEADOWS, 2000, 68). If is lower than -0.1, water will dissolve carbonate rock 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_{Ca} was calculated with computer program WATEQ4F (BALL & NORDSTROM, 1991). Input parameters were SEC, T, pH (defined *in situ*), concentration of Ca^{2+}, concentration of Mg^{2+} and carbonate alkalinity (defined in chemical laboratory).

Discharge was measured with salt-dilution method (KÄSS, 1998). It involves preparation of solute (usually sodium chloride-NaCl), injecting of solute to flow and determining its dilution at downstream measuring point. Time dependant NaCl concentration curve defined with SEC meter (WTW Multiline P4) and stopwatch at downstream point, where the solute becomes uniformly mixed with stream water, gives us information about discharge. For a given volume or rate of injection, greater stream discharges will result in greater tracer dilution and lower concentrations measured at the downstream site and *vice versa*. Several discharge measurements at different discharges and observation of water level enable us to define stage-discharge curve, where discharges are easily determined using water level.

Height of water level and related discharge was obtained either with periodical visual observations of water gauges or with digital level loggers. Between 18th January 2008 and 17th February 2009, Schlumberger TD-Diver was used in Lekinka for determining water level and temperature. Sample interval was set to 15 min. Due to high errors (up to ~20 cm), data were recognized as useless for small flood events but accurate enough to observe big flood events.

Between 21st March 2007 and 17th 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 measurements done by 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 stage-discharge curve defined with salt-dilution method.

2.3 Measurements of air characteristics

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, minimal accuracy was 105 ppm at 3,000 ppm. Better results were obtained with longer measurements at individual measurement point and calculation of an average.

2.4 Measurement of features

Caves are result of long-term speleogenesis under the influence of factors that only partly correspond to present-day situation. Therefore, taking into consideration macrofeatures and mesofeatures and relating them to present-day or recent processes seems to be an inappropriate approach, recognized also for nowadays fluvio-denudational relief (NATEK, 1993). Extrapolation of present-day processes measured in mm/a into mm/ka or even mm/Ma is not acceptable or even extremely hazardous (GUNN, 1986; TRUDGILL, 1986, 499; TRUDGILL, 1994, 113; WHITE, 2000). Therefore we take into account only several centimetres big (micro)features, which should be related to present-day processes and factors.

Lots of information about features were taken from the **literature** since many speleological studies were dedicated to cave morphology (SLABE, 1992; SLABE, 1995; LAURITZEN & LUNDBERG, 2000) or individual features (for details see SLABE, 1995). If necessary, **observation** and **thematic mapping** of was used to represent spatial distribution and special characteristics of features. Usually, the official UIS symbol list (HÄUSELMANN, 2002) was used for mapping of speleological features. Cross-sections were measured with ordinary cave survey equipment (digital meter, inclinometer and compass). Since we were studying mostly in historically and speleologically important caves, accurate cave maps were already done for all caves of interest.

3 8-month-long measurements of corrosion/flowstone deposition rates

Although caves are solutionally enlarged geological features and the object of numerous speleological researches, little is known about the actual corrosion rates that take place locally or even on a world scale (GUNN, 1986, 386). In Slovenia, the situation is similar since we know the rates of corrosion for a very limited number of caves (Ponikve v Odolini-MIHEVC, 1993; Škocjanske jame-MIHEVC, 2001; Postojnska jama (without values)-GAMS, 1996). Much more is known about net solutional denudation, but the latter values are more characteristic for solution in subcutaneous and epikarst zone rather than for epiphreatic and phreatic zone, where corrosion rates are thought to be smaller. Nevertheless, corrosion rates can be higher in conduits in comparison with the rate of surface lowering, since the quantity of water is much bigger and the reaction surface much smaller (GUNN, 1986, 382).

Quite a good estimation of corrosion rates in the caves that are fed by an allogenic stream can be acquired from the hardness of sinking superficial streams and their ability to corrode. In such a way, corrosion was estimated by Gams (1962, 1966b). Estimation of relative corrosion rates is possible if actual hardness is compared with hardness at equilibrium. Nevertheless, using this method we deny the influence of other substances (e.g. organic acids, sulphates, phosphates), which influence hardness at equilibrium (DREYBRODT, 1988; DREYBRODT, 2000), influence of increased CO_2 concentration under the surface and the influence of mixing, which can raise water hardness at equilibrium. Nevertheless, nothing can be said about corrosion rates in caves with autogenic recharge. In the latter, corrosion rate is more or less defined by water hardness and CO_2 concentration (in the water and in the air) and their attitude to saturation.

Therefore, the main purposes of this 8-month-long measurements of corrosion rates were the following:

- to test the accuracy and applicability of methodology of corrosion measurement with limestone tablets,
- to get approximate corrosion rates over the Slovenian part of (Dinaric) karst,
- to get insight into the spatial variability of corrosion rates,
- to find out the most relevant factors that control the rate of corrosion,
- to define places for additional more detailed measurements.

Methodology

Limestone tablets were prepared for the methodology represented in Fig. 2.1.3.1 (Chapter 2.1.3). Since we did not pay any attention to deviation due to relative humidity at that time, no correction factor can be defined. Nevertheless, measurement point 57 (Kozja luknja; Appendix I), which was not reached by water, suggests that accuracy (as defined in Fig. 2.1.3.6 (Chapter 2.1.3) is as good as ±0.0001 mm/a. Such a low deviation is most probably a consequence of weighing of limestone tablets at similar conditions with respect to relative humidity.

At one measurement point, only one limestone tablet was placed. It was fixed on an iron screw with nut and felted washers (Fig. 3.1). Due to iron parts, misleading corrosion due to iron oxide was noticed at several measurement points. Since it occurs very randomly without noticeable logical explanation, it can not be predicted or quantified. Regarding measurements in Križna jama 2, where the corrosion rates due to iron oxide seem to be quite high, corrosion due to iron oxide were from 0 to up to -0.0024 mm/30 days (up to -0.0192 mm/8 months!). Therefore at places where misleading corrosion was observed, actual corrosion rates are smaller.

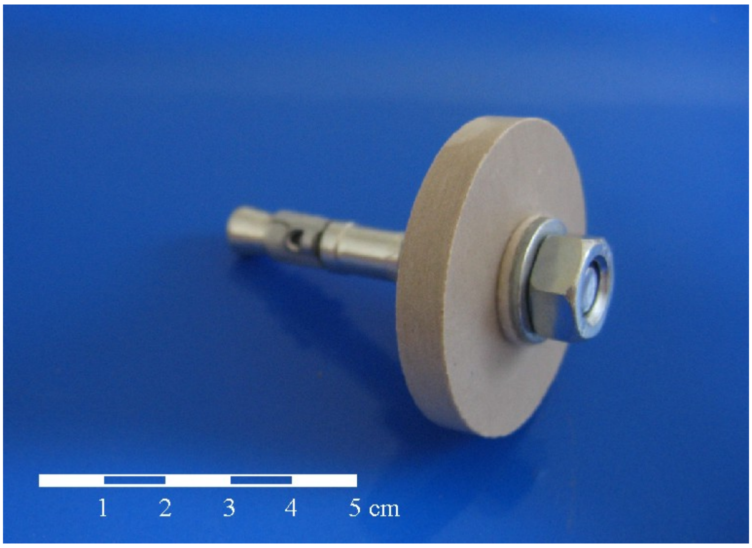
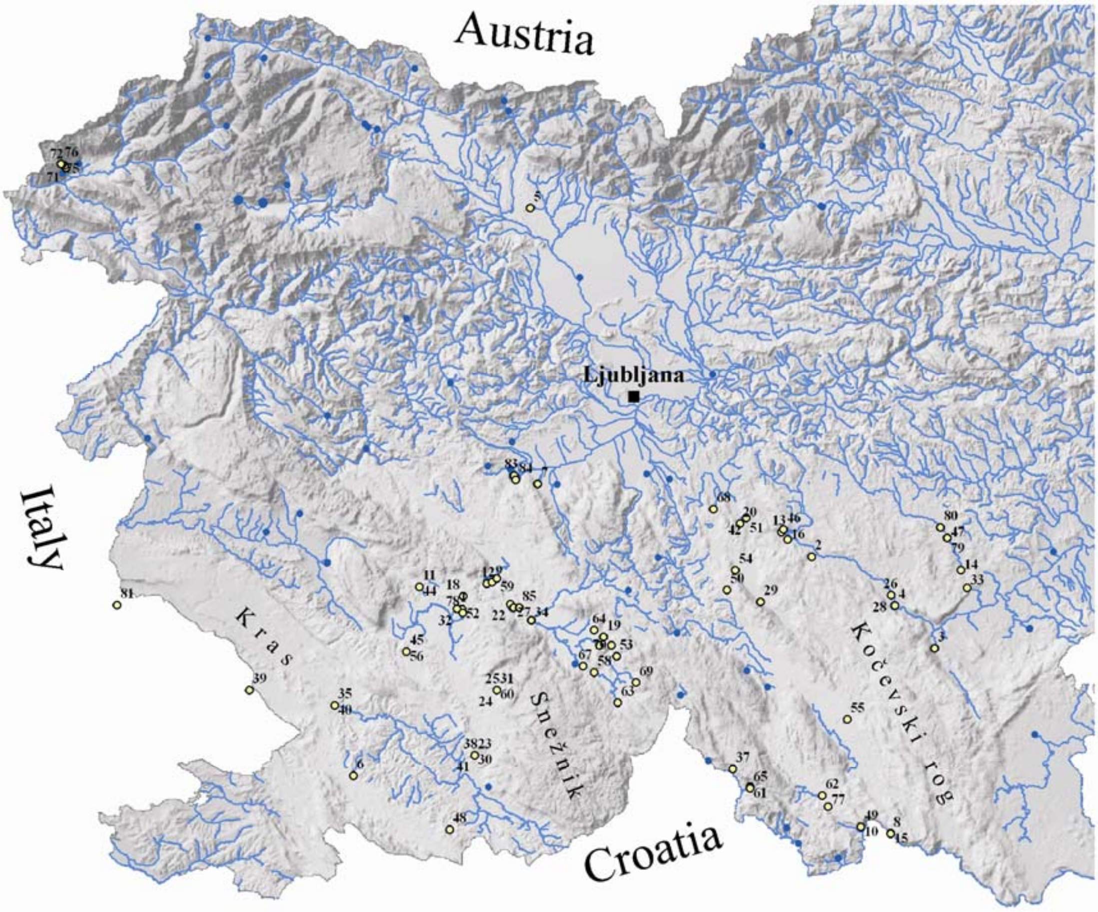


***Figure 3.1:** Limestone tablet fixed on iron screw (right photo was taken in Lekinka).*

Eight month long measurement started at the end of October 2005 or in the beginning of November 2005 and finished in the middle of July 2006 (~8 months). In Škocjanske jame, measurements ended on 17th April 2007. The beginning and end of the measurements were defined with low discharges, when the measurement points were accessible. Since the low summer discharges were excluded from measurements and corrosion rates extrapolated from 8 months to one year, actual corrosion rates can be smaller and flowstone deposition rates higher – if they predominantly depend on discharge.

Location of measurements

Measurements took place at 85 locations mainly on the High and Low Dinaric karst of Slovenia (Fig. 3.2). Nevertheless, some measurements were done also in Alpine karst (Mala Boka), Subalpine karst (Velika Lebinca, Turkova jama) and across the border, where such measurements were reasonable (Labodnica-Abisso di Trebiciano, Timava-Timavo). Limestone tablets were placed in all major caves that lie in the epiphreatic zone. Where the caves were not accessible, measurements took place at springs with supposition that corrosion rates at the springs correspond to corrosion rates in the underground passages behind them. With widespread locations of measurement points, we tried to get insight into regional differences in corrosion rates. On the other hand, with several measurement points in the same cave (e.g. Postojnska jama, Škocjanske jame, Lekinka, Kozja luknja, Matijeva jama, Mala Boka) we tried to get insight into micro-local differences in corrosion rates. To observe differences along uniform superficial and underground water flow, several measurements points were located at ponors, in caves and at springs (e.g. eastern branch of Ljubljanica river, Temenica/Prečna river, underground Reka river). The main characteristics of all measurement points are represented in Appendix I.



Measurement point	Location	Measurement point	Location
1	Lekinka (entrance part; location 1-lower part of passage)	44	Predjama (entrance part; location 2-upper part of passage)
2	Globočec (spring)	45	Markov spodmol (entrance part; location 1-at the 1^{st} lake)
3	Radešcica (spring)	46	Krška jama (entrance part)
4	Tominčev izvir (spring)	47	Temenica (Zijalo/Jama Jezero pod Zijalom; location 2-upper part of passage)
5	Velika Lebinca (entrance part of a cave)	48	Račiške ponikve (central part)
6	Ponikve v Odolini (entrance part of a cave)	49	Jelovička jama (entrance part of a cave; location 2-upper part of passage)
7	Bistra (Galetovi izviri; spring)	50	Podstenska/Finkova jama (entrance part-upper part of passage)
8	Kolpa (few m upstream from confluence with Bilpa)	51	Viršnica (central part of a cave; location 2-upper part of passage)
9	Malni (spring)	52	Postojnska jama (Veliki dom; location 2-upper part of passage)
10	Jelovička jama (entrance part of a cave; location 1-lower part of passage)	53	Mrzla jama pri Ložu
11	Predjama (entrance part; location 1-lower part of passage)	54	Podpeška jama
12	Planinska jama (entrance part)	55	Želnjske jame (Velika dvorana)
13	Poltarica (spring)	56	Markov spodmol (entrance part; location 2-upstream of the 1^{st} lake)
14	Temenica (Goriška vas-ponor)	57	Kozja luknja (location 6-in front of the cave)
15	Bilpa (spring)	58	Golobina (entrance part)
16	Lipovka (spring)	59	Škratovka (entrance part)
17	Postojnska jama (Spodnji Tartar; location 3)	60	Matijeva jama (location 3-entrance part of a cave)
18	Postojnska jama (Pivka jama; location 4)	61	Jama 1 v Kotlu (entrance part)
19	Mrzla jama pri Bločicah	62	Reški/Mokri potok (ponor)
20	Šica (Racna; spring)	63	Mali Obrh (spring)
21	Podstenjšek (spring)	64	Žerovniščica (spring)
22	Rakov Škocjan (Veliki naravni most)	65	Izvir pri zajetju za HE Belica (spring)
23	Kozja luknja (location 2)	66	Podštebršcica (spring)
24	Matijeva jama (at the sump; location 1)	67	Cemun (spring)
25	Matijeva jama (at the sump; location 3-in the ceiling pocket)	68	Podlomšcica (spring)
26	Bruhalnik za Javornikovo žago (spring; location 1-upper part of passage)	69	Veliki Obrh (spring)
27	Kotliči (spring)	70	Križna jama (between 1^{st} lake and Ponor)
28	Bruhalnik za Javornikovo žago (spring; location 2-lower part of passage)	71	Mala Boka (Jelinciceva dvorana; location 1-lower part of a passage)
29	Kompoljska jama (entrance part)	72	Mala Boka (Jelinciceva dvorana; location 2-lower part of a passage)
30	Kozja luknja (location 1-the lowest part of passage)	73	Mala Boka (kanjon Akob; location 3-middle part of passage)
31	Matijeva jama (at the sump; location 2)	74	Mala Boka (kanjon Akob; location 4-upper part of passage)
32	Lekinka (entrance part; location 2-middle part of passage)	75	Mala Boka (Freatika: location 5-upper part of passage)
33	Prečna/Temenica (spring)	76	Mala Boka (Freatika; location 6-lower part of passage)
34	Velika Karlovica (entrance part)	77	Mošenik (ponor)
35	Škocjanske jame (Swidovo razgledišce; location 1)	78	Postojnska jama (Veliki dom; location 1-lower part of passage)
36	Kozja luknja (location 3)	79	Temenica (Zijalo/Jama Jezero pod Zijalom; location 1-lower part of passage)
37	Šratlova luknja (entrance part)	80	Temenica (Rupa 1 na Zemljancevem travniku/Rupa 1 sv. Ane)
38	Kozja luknja (location 5-near the entrance)	81	Timava (srednji izvir)
39	Labodnica (Lindnerjeva dvorana)	82	Turkova jama
40	Škocjanske jame (Swidovo razgledišce; location 2)	83	Velik Mocilnik (izvir)
41	Kozja luknja (location 4)	84	Veliko Okence (izvir)
42	Viršnica (central part of a cave; location 1-lower part of passage)	85	Zelške jame (vhodni del)
43	Lekinka (entrance part; location 3-upper part of passage)		

***Figure 3.2:** Location of measurements.*

Hydrological conditions during time of measurements

Measurement of corrosion rates took place mostly within 5 catchment areas: catchment area of Ljubljanica river, Krka river, Kolpa river, Prečna/Temenica river and Reka river. All catchment areas are equipped with several hydrological stations, where discharges have been measured at least once per day for several decades. Therefore, evaluation of hydrological conditions in the years 2005, 2006 and 2007 and comparison with average conditions during 1971-2000 is possible (Fig. 3.3).

In general, **average annual discharges** in the time of measurement corresponded to the average discharges in the period 1971-2000 (DISCHARGE DATA FOR PERIOD 1971-2000). Slightly higher discharges (up to 17 %) were recorded in southeastern Slovenia (catchment area of Kolpa river, Krka river and Prečna river), while discharges in southwestern Slovenia were slightly lower (up to 14 %) in comparison with the average 1971-2000. In southeastern and central part of Slovenia, unusually high discharges were a consequence of higher amount of precipitation and snow melting in March 2006 and in December 2005. In Ljubljanica catchment area, the highest negative deviation from average discharges occurred at the beginning and at the end of measurement, when discharges were significantly lower than average 1971-2000. In southwestern Slovenia (catchment area of Reka river), the highest negative deviation is characteristic for the autumn 2006, which was one of the driest autumn ever recorded. Relatively higher discharges were characteristic for February 2007, when the amount of precipitation reached up to 200 % of average February amount in catchment area of Reka river. Precipitations were more or less equally distributed over February without any exceptionally high flood event.

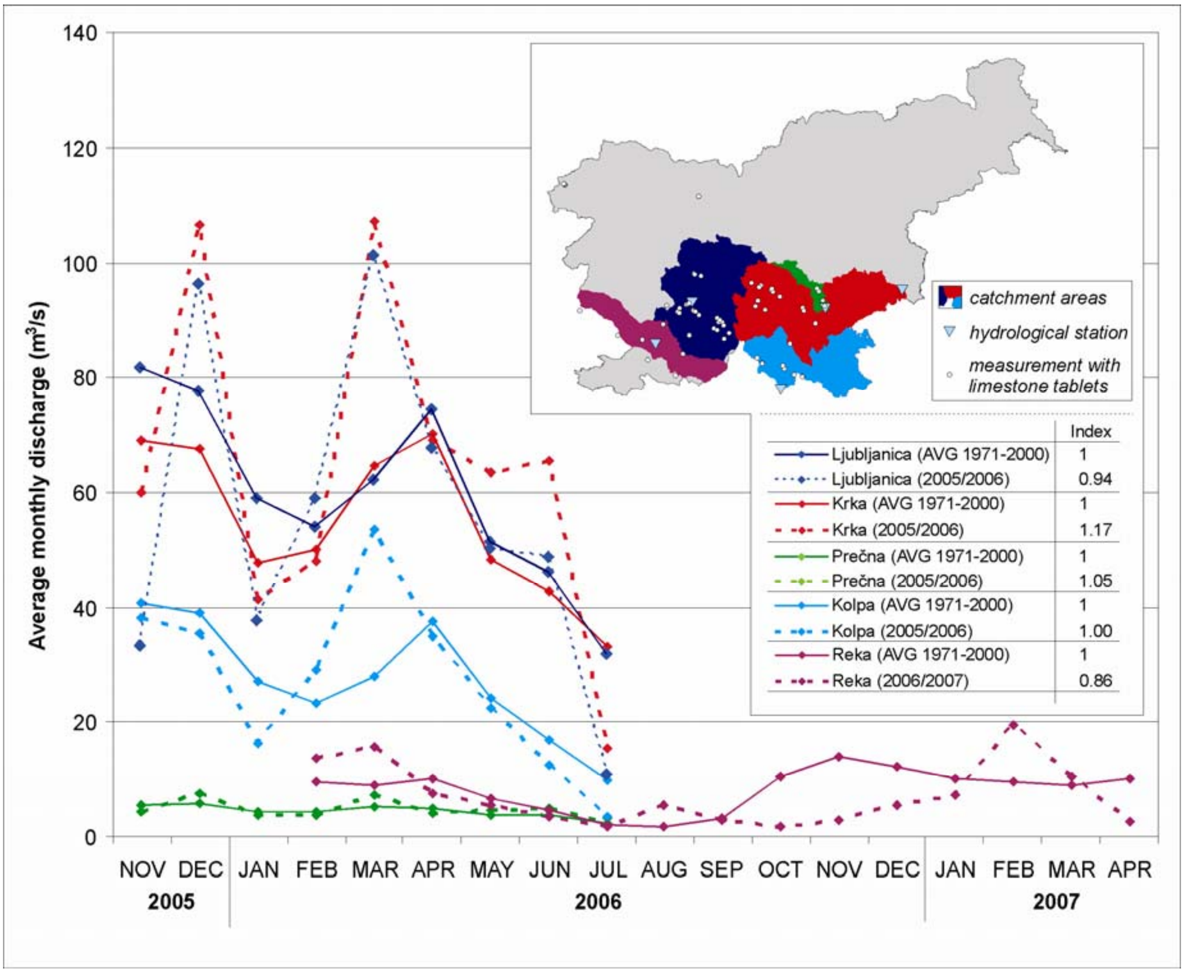


Figure 3.3: *Hydrological conditions during 8-month-long measurement in comparison with period 1971-2000 at measurement stations Moste (Ljubljanica river), Podbočje (Krka river), Prečna (Prečna/Temenica river), Petrina (Kolpa river) and Cerkvenikov mlin (Reka river) (source of data:* DISCHARGE DATA FOR PERIOD *1971-2007).*

Relatively high **daily and weekly discharges** were characteristic for southwestern and central part of Slovenia for the end of November 2005 and beginning of December 2005, when the amount of precipitation during 2 rainy days exceeded 10-year recurrence interval. In March 2006, discharges were constantly higher due to snow melting without any relatively high daily discharges. In catchment area of Reka river, relatively high discharges were absent. High monthly discharge in February 2007 is a consequence of long-term higher discharge, while the highest discharge did not exceed 100 m^3/s. The only relatively high discharge in catchment area of Reka river is characteristic for the end of May 2006, when discharge reached 100 m^3/s. Nevertheless, such discharges happen usually at least once per year.

To conclude, discharges at measurement periods were in the time of measurement more or less characteristic for the period 1971-2000. In southeastern Slovenia, unusually high monthly discharges were characteristic for the November/December 2005 and for March 2006, while the highest daily or weakly discharges were characteristic only for November/December 2005. In southwestern Slovenia, monthly, daily or weekly discharges were lower in comparison with average values in 1971-2000. Therefore, results of measurements with limestone tablets relevantly represent geomorphic processes at measurement points, at least from a hydrological point of view. In Reka river, it is possible that corrosion rates are underestimated due to lack of very high daily discharges (above ~100 m^3/s) during measurement period.

Results

Results of measurements are represented in Appendix I and summarized in histogram of distribution (Fig. 3.4). The latter shows a roughly log-normal distribution with only one peak that is situated below zero, which demonstrates prevailing corrosion. The prevailing corrosion is proved also with median (-0.0015 mm/a) and arithmetic mean (-0.0074 mm/a). Relatively high positive kurtosis (16.1) and negative skewness (-2.4) points out that distribution is peaked and skewed toward negative values (corrosion). Therefore, data are strongly concentrated near the arithmetic mean in the class between -0.01 and 0.001 mm/a. More intense corrosion rates are relatively rare, while the slighter corrosion rates or flowstone/tufa deposition rates are more numerous. High difference between arithmetic mean and median shows some relatively high outstanding values, which raise the arithmetic mean. The highest corrosion rates are under -0.1 mm/a and the highest flowstone/tufa deposition rates over 0.1 mm/a. Nevertheless, they are very rare (Fig. 3.4) and related to outstanding factors that favour high corrosion or flowstone/tufa deposition rates.

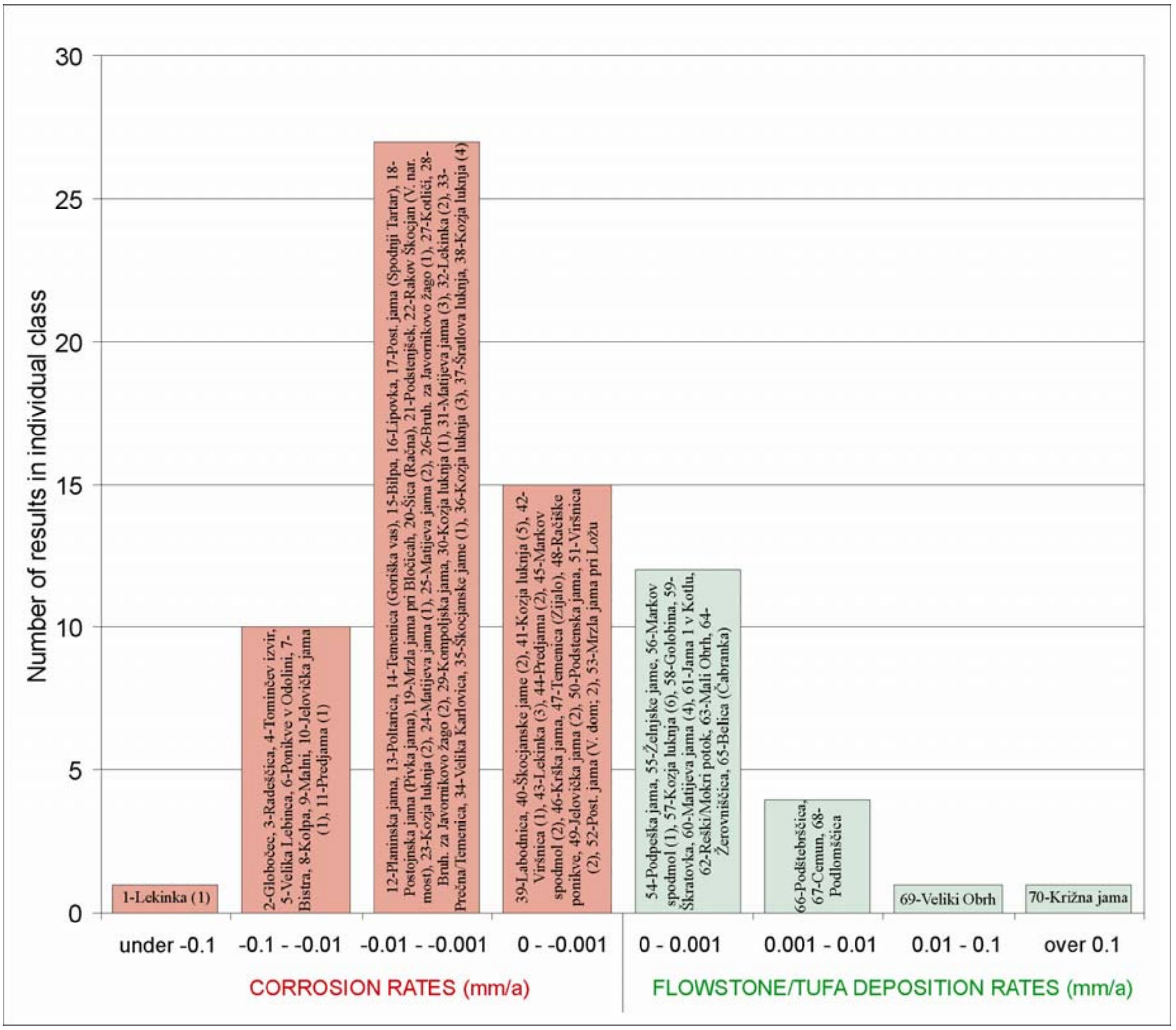


Figure 3.4: *Histogram of corrosion or flowstone/tufa deposition rates.*

The highest corrosion rates (under -0.01 mm/a) are characteristic for Lekinka (1), lower right tributaries of Krka river (Globočec, Radeščica, Tominčev izvir), Velika Lebinca, Ponikve v Odolini, Bistra spring, Kolpa river, Malni springs, Jelovička jama (1) and Predjama (1). The last two measurement points and the limestone tablet in Kolpa river were slightly damaged by corrasion; therefore, actual corrosion rates are lower. For the other measurement points, lack of one common outstanding factor that should be responsible for high corrosion rates at all measurement points is characteristic – high corrosion rates are characteristic for springs and ponors, for dark and lighted locations and for very different type of recharge (allogenic, concentrated and diffuse autogenic). Nevertheless, visual observation of limestone tablets after exposure and individual evaluation of each location shows some leading factors, which are responsible for high corrosion rates.

The first one is **availability of light** at some measurement locations (Globočec, Radeščica, Tominčev izvir, Bistra spring, Kolpa river), which is responsible for high rates of **biocorrosion**. The latter can be recognized from relatively deep hollows that are produced most probably by algae only at the illuminated part of limestone tablets. The rates of biocorrosion are still mainly unstudied but often recognized on the surface (e.g. PERNA & SAURO, 1979, 97; FORD & WILLIAMS, 2007, 61). Due to very low chemical corrosion[1], which is proved by well-preserved traces of sawing that disappear at rates between -0.0385 and -0.0109 mm/a, rough estimation of biocorrosion rates is possible. For example, at spring Tominčev izvir (measurement point 4), total corrosion rate is -0.0788 mm/a. To get minimum biocorrosion rate, we have to subtract -0.0385 mm/a and multiply the result by 2, since the biocorrosion takes place only at illuminated part of limestone tablets. Therefore, minimum biocorrosion rate is -0.0806 mm/a. To get maximum biocorrosion rate, one has to subtract -0.0109 mm/a and multiply result by 2. Regarding this procedure, maximum corrosion rate is -0.1358 mm/a at spring Tominčev izvir. Moreover, traces of sawing can be observed also at rates, which are lower than -0.0109 mm/a. If we take the most probable chemical corrosion rates at spring Tominčev izvir, which were recorded at nearby spring Bruhalnik za Javornikovo žago (measurement point 26 and 28) that is fed by nearly the same catchment area, biocorrosion rate can even higher (-0.1522 mm/a) due to lower chemical corrosion rates (~ -0.0027 mm/a). Similar calculation can be made also for the other measurement points, where biocorrosion was noticed (Tab. 3.1).
Biocorrosion can be a very intensive process, especially at lower right tributaries along Krka river. At other locations, biocorrosion rates are much smaller and at some places similar to average chemical corrosion rates (e.g. Temenica (Goriška vas), Bilpa (spring), Podstenjšek (spring), Kotliči (spring), Prečna/Temenica (spring). The intensity of biocorrosion most probably strongly relates to degree of illumination but also to regional location and length of measurements (biocorrosion is most probably the

[1] Term chemical corrosion is used to describe corrosion that is predominantly not caused by organisms although we know that organisms can remove carbonates mechanically or chemically. Contrary, chemical corrosion in caves is predominantly caused by chemical processes without action of organisms although we know that carbonates can be partly removed also biologically.

weakest at the beginning, when an algae population is not yet fully developed on freshly cut limestone tablets). Nonetheless, measurements of total corrosion rates with limestone tablets or micrometer at the illuminated springs do not reflect corrosion rates behind the spring, where the corrosion can be much smaller, at least at measurement points with ascertainable high biocorrosion rates.

Table 3.1: *Biocorrosion rates at measurement points, where biocorrosion was observed.*

Measurement point	Location	Calculation from disappearance of sawing traces		Biocorrosion rates calculated from (chemical) corrosion at Bruhalnik za Javornikov žago (measurement points 26 and 18)
		Minimum biocorrosion rate (mm/a)	Maximum biocorrosion rate (mm/a)	
2	Globočec (spring)	-0,0951	-0,1503	-0,1667
3	Radeščica (spring)	-0,0886	-0,1438	-0,1602
4	Tominčev izvir (spring)	-0,0806	-0,1358	-0,1522
7	Bistra (Galetovi izviri; spring)	0,0000	-0,0223	/
8	Kolpa (few m upstream from confluence with Bilpa)*	0,0000	-0,0109	/
9	Malni (spring)	0,0000	-0,0080	/
14	Temenica (Goriška vas-ponor)	0,0000	0,0000	/
15	Bilpa (spring)	0,0000	0,0000	/
16	Lipovka (spring)	0,0000	0,0000	/
20	Šica (Račna; spring)	0,0000	0,0000	/
21	Podstenjšek (spring)	0,0000	0,0000	/
27	Kotliči (spring)	0,0000	0,0000	/
33	Prečna/Temenica (spring)	0,0000	0,0000	/

**biocorrosion rates are actually smaller if we take into account also corrasion rates*

Another factor that leads to high corrosion rates is **low total hardness of allogenic water**, which was already measured by Gams (1962, 1966b), Gospodarič & Habič (1966), Kranjc (1989) and Mihevc (1991) at dealing measurement sites-ponors (Lekinka, Ponikve v Odolini, Predjama). All three ponors have catchment areas on impervious flisch rocks that are poor in carbonates. Therefore, low total hardness can be expected and was confirmed by chemical analysis of water and measurements of specific electrical conductivity. For Lekinka, typical total hardness corresponds to 111 mg of $CaCO_3$/L (GOSPODARIČ & HABIČ, 1966, 17). At low discharge, it can rise to 230 mg of $CaCO_3$/L (GOSPODARIČ & HABIČ, 1966, 17). In Ponikve v Odolini, total hardness corresponds to 104 (GAMS, 1962, 282) or 111 mg of $CaCO_3$/L (MIHEVC, 1991, 61). At measurement point Predjama (ponor of Lokva brook), total hardness corresponds to 111 (GAMS, 1962, 267) or ~65 mg of $CaCO_3$/L (KRANJC, 1989, 75). Nonetheless, the majority of these values are quite high and exceed amount of $CaCO_3$, which can be dissolved at CO_2 concentration characteristic for general atmosphere (80-90 mg $CaCO_3$/l; GAMS, 1966B, 56). Such waters could be capable of corrosion at the measurement points only if they contain humic acids, higher CO_2 concentration or some other dissolved ions that raise potential total hardness at equilibrium. Increased aggressiveness of water is expected also at high water levels, which were not observed by mentioned researchers. In spite of this, time of exposure can be so low that corrosion rates are much smaller than should be expected from aggressiveness of water (e.g. measurement point 32 (Lekinka-2) and 43 (Lekinka-3), which were located several decimeters above measurement point 1 (Lekinka-1).

It is not the case that caves with allogenic recharge are characterized by high corrosion rates. This is proved with measurement points 48 (Račiške ponikve), 45 and 56 (Markov spodmol), 50 (Podstenska/Finkova jama)[1] and 55 (Želnjske jame). The latter has catchment area on Miocene and Pliocene sediments that are rich with sulfates (GAMS, 2003, 377), which generally increases solubility (DREYBRODT, 1988, 34) due to formation of ion pairs $CaSO_4^0$, which reduce concentration of Ca^{2+} in solution. Nevertheless, corrosion potential is most probably lost in carbonate rich soils in the catchment area, which leads to corrosional inactivity of sinking stream. In Račiške ponikve, the catchment area lies on flisch rocks that are rich with carbonates (GAMS, 1962, 291) and potential for corrosion is already "lost" in the superficial catchment area. The same can be expected in the catchment area of Markov spodmol, which is composed of flisch rocks (ZUPAN HAJNA ET AL., 2008, 192). Therefore, corrosional potential is "lost" in the catchment area and the water at the ponor has too high total hardness (154 mg $CaCO_3$/l at Račiške ponikve; GAMS, 1966b, 291) to cause any corrosion rates. Results of our measurements show that conditions are not substantially changed even at high water level.

If we take into account total hardness of water that was measured by Gams (1962, 1966b; Appendix I) and compare these values with corrosion or flowstone/tufa deposition rates obtained by our measurements, Pearson product moment correlation coefficient shows almost no correlation (0.16; R^2=0.02; Fig. 3.5-a). This means that total hardness of water is not the main characteristic of water that influences the rate of corrosion or deposition. One of the most important processes, which importantly lowers correlation coefficient, is biocorrosion, since the Pearson product moment correlation coefficient increases to 0.62 (R^2=0.39; Fig. 3.5-b) if we exclude measurement points with observed biocorrosion (see Appendix I). In the case of our measurement points, measurements with biocorrosion can be nicely excluded with ellipse, for which

[1] Limestone tablet in Podstenska/Finkova jama was most probably not reached by water and therefore does not represent actual corrosion rates at ponor.

relatively high corrosion rates are characteristics for relatively high total hardness (Fig. 3.5).

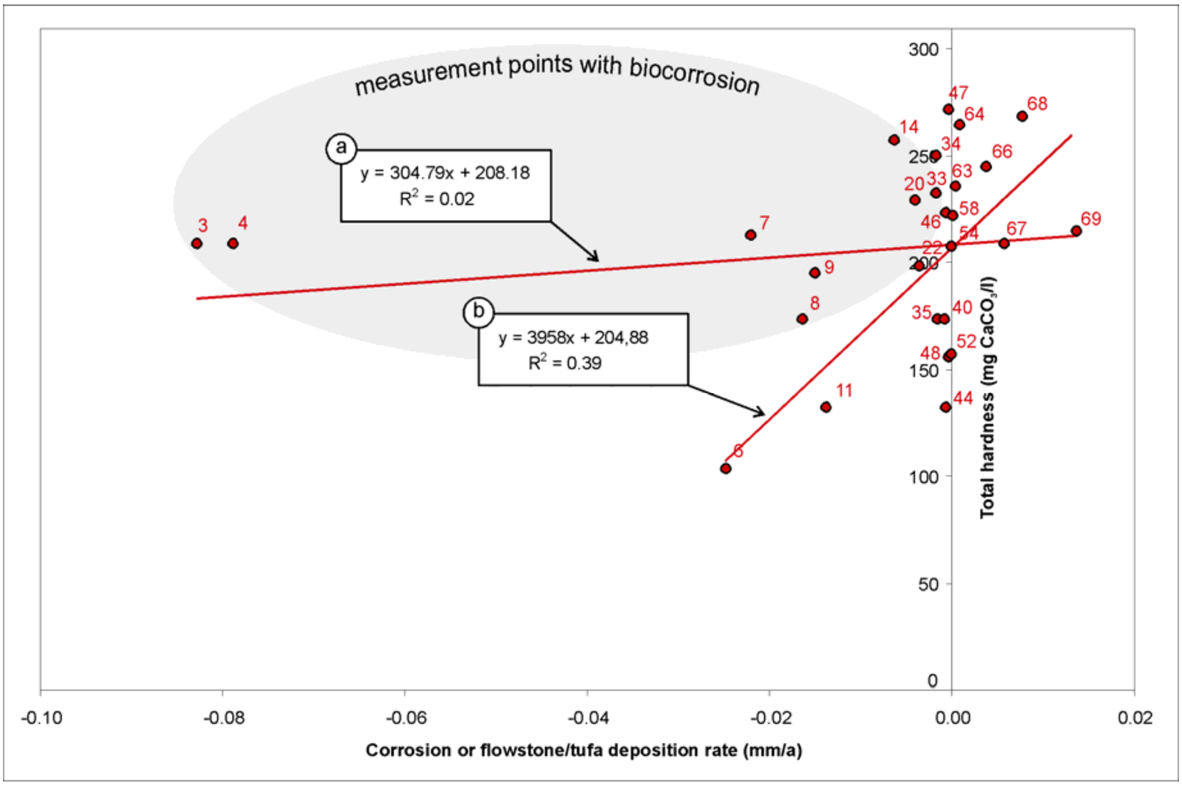


Figure 3.5: *Correlation between total hardness (after* G*AMS, 1962 and* G*AMS, 1966b) and corrosion or flowstone/tufa deposition rates. In correlation a, all values are taken into account. In correlation b, measurement points with substantial biocorrosion (3, 4, 7, 8, 9, 14, 20 and 33) are excluded.*

If we take into account all measurement points where biocorrosion was not predominant, relatively high Pearson product moment correlation coefficient shows that total hardness is one of the most important characteristic of water that controls the rate of corrosion and deposition. The relation between total hardness and corrosion or flowstone/tufa deposition rate can be described with Eq. 3.1. Nevertheless, deviation between calculated and real values can be quite high and therefore corrosion/flowstone deposition rates, which are calculated using this equation, relatively far from real ones.

$$C/D = \frac{tH - 204.88}{3958}$$ **(Equation 3.1)**,

where C/D is corrosion of flowstone/tufa deposition rate in mm/a and tH average total hardness expressed in mg $CaCO_3$/l.

Relation between total hardness and corrosion or flowstone/tufa deposition rates shows that (generally!) water becomes inactive when total hardness amounts ~205 mg $CaCO_3$/l. This value is significantly higher than solubility of calcite or dolomite proposed by Gams (80-90 mg $CaCO_3$/l; 1966b, 56) or Ford & Williams (50-60 mg $CaCO_3$/l; 2007, 40), which shows on higher CO_2 concentration in the water or presence of other ions in natural karst waters that influence solubility. Higher CO_2 concentration is definitely responsible for relatively high deviation between real and expected corrosion or flowstone/tufa deposition rates (up to 0.0177 mm/a or on average 0.0081 mm/a; Fig. 3.5-b) at some springs (e.g. measurement point 47 (Temenica-Zijalo/Jezero pod Zijalom-2), 64 (Žerovniščica), 63 (Mali Obrh), 66 (Podštebrščica), 68 (Podlomščica) and 46 (Krška jama). In some cases, higher than expected real corrosion rates are related to measurement points, which were relatively rarely flooded (e.g. measurement point 44 (Predjama-2), 47 (Temenica-Zijalo/Jezero pod Zijalom-2).

The majority of results lie close to -0.001 mm/a or slightly below 0.001 mm/a (Fig. 3.6). Measurement points within this range are characterized by different and sometimes complex allogenic-diffuse autogenic-concentrated autogenic recharge and very different position within the local karst area. Within this group, some very hydrologically and historically important and big caves (locations) are placed: Planinska jama, Postojnska jama, Rakov Škocjan, Velika Karlovica, Krška jama, Viršnica, Krška jama, Želnjske jame, Markov spodmol, Golobina, Labodnica and Škocjanske jame. Therefore we can say that quite **low corrosion rates** are typical for the most important caves (in Slovene part) of Dinaric region. Nevertheless, low corrosion rates should be expected since we are dealing with very old caves, where the sediments can be more than 0.78 Ma old (ZUPAN HAJNA ET AL., 2008). Low corrosion rates characteristic for present-day climatic conditions also point out that the karst massifs are relatively poorly karstified in the epiphreatic (and shallow phreatic) zone and that the water should take more or less the same routes underground for several 100,000s of years instead of formation of new passages.

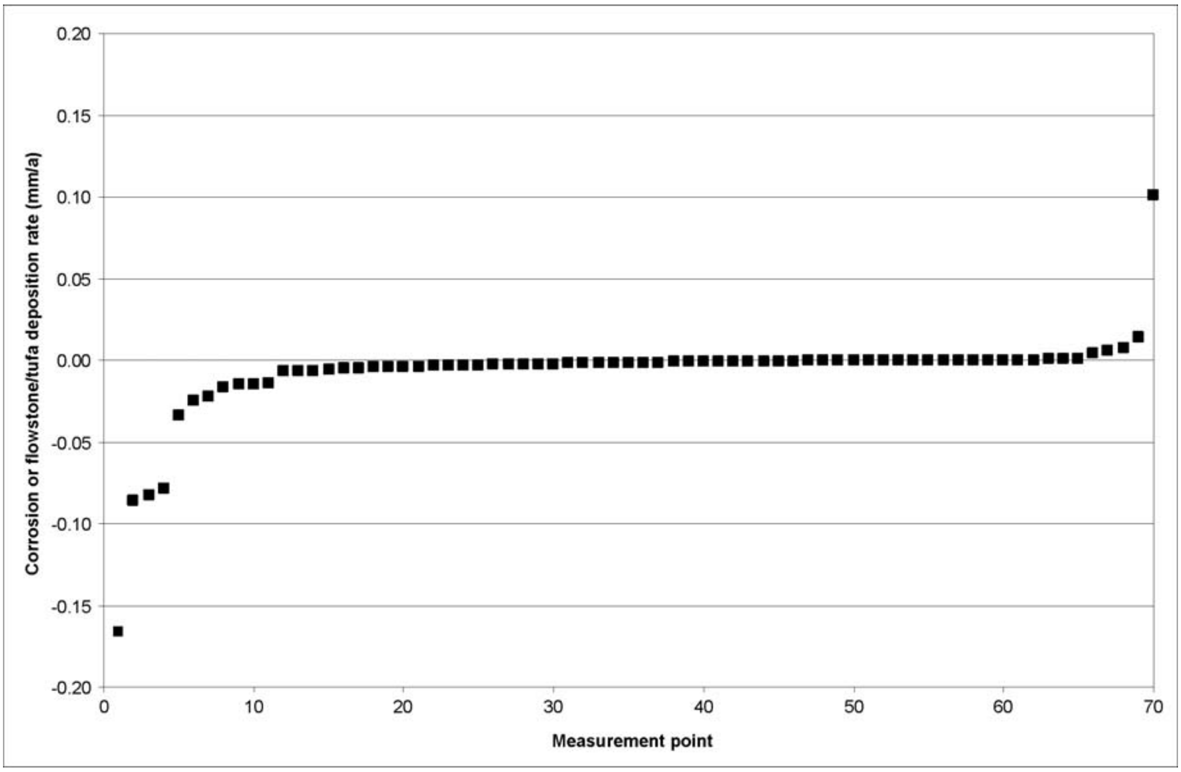


Figure 3.6: *Corrosion or flowstone/tufa deposition rates at all measurement points (numbers of measurement points refer to Fig. 3.2, Fig. 3.4, Fig. 3.5 and Appendix I).*

Low corrosion rates are a result of many **factors**. The majority of caves are fed by concentrated autogenic recharge, where the water from karst springs prevails. Originally, such water derives from diffuse autogenic recharge, for which intensive reaction in the subsoil and epikarst is characteristic. At springs, such water can be slightly aggressive (e.g. Matijeva jama, Kozja luknja). Further downstream, outgassing of CO_2 from the water leads to (over)saturation of water, which is unable to cause any high corrosion rate at the ponor, even at high water level (e.g. superficial stream between Šica (Račna) and Viršnica (1).

Along underground water courses, corrosion rates remain nearly equal (e.g. Postojnska jama (Spodnji Tartar)-Postojnska jama (Pivka jama) or even higher (e.g. in Postojnska jama-Planinska jama cave system). Increase of corrosion rates between the ponor and spring can be a result of mixing corrosion, underground tributaries with higher corrosion rates or a result of higher CO_2 concentration in the cave atmosphere, which decreases (over)saturation or increases undersaturation.

Several measurement points show **flowstone/tufa deposition**. By far the highest flowstone deposition was observed in Križna jama, where flowstone deposition slightly exceeded 0.1 mm/a. Slightly higher values were obtained by Mihevc (0.128 mm/a; 1997 & personal communication[1]). Regarding to Gams (2003, 325), high flowstone deposition rate is a consequence of high magnesium (magnesium hardness correspond to 98 mg of $CaCO_3$/l), calcium hardness (142 mg of $CaCO_3$/l) and most probably outgassing of CO_2. Tufa deposition is characteristic also for nearby springs (Veliki Obrh, Podšteberščica and Cemun) and for Podlomščica, where the reason can be similar (high total hardness). More- over, outgassing of CO_2, which is faster in superficial streams due to lower CO_2 concentration in the atmosphere, can result in increased (over)saturation. The latter phenomenon is even more characteristic for water courses downstream of springs.

Locally very different factors result in **regionally very different corrosion rates**, which can be seen in Fig. 3.7. In extreme case, corrosion rates in Lekinka are 36-times higher than corrosion rates in Postojnska jama (Spodnji Tartar), although they lie only a kilometre apart. The main cause is different types of recharge. High differences can be observed even along the same massif – on the SW slope of Brkini hills, different amounts of calcite in impervious catchment area is reflected in different corrosion rates at the ponors. In Ponikve v Odolini, corrosion rate is 70-times higher than corrosion rate in Račiške ponikve, although both catchment areas lie on Brkini hills.

Another very important factor of corrosion rates is related to **vertical microlocation** in the underground passage. In Lekinka, corrosion rates strongly decrease with height, although they were all flooded but for very different amount of time. The same phenomenon (with lower vertical differences) was observed in Kozja luknja, Viršnica, Jelovička jama and Predjama. In the last two and in Škocjanske jame, microlocation of measurements also strongly influenced corrasion rates.

[1] The rate mentioned in the article (0.256 mm/a; MIHEVC, 1997) has to be divided with 2 since the rates of flowstone deposition were measured during 2 years.

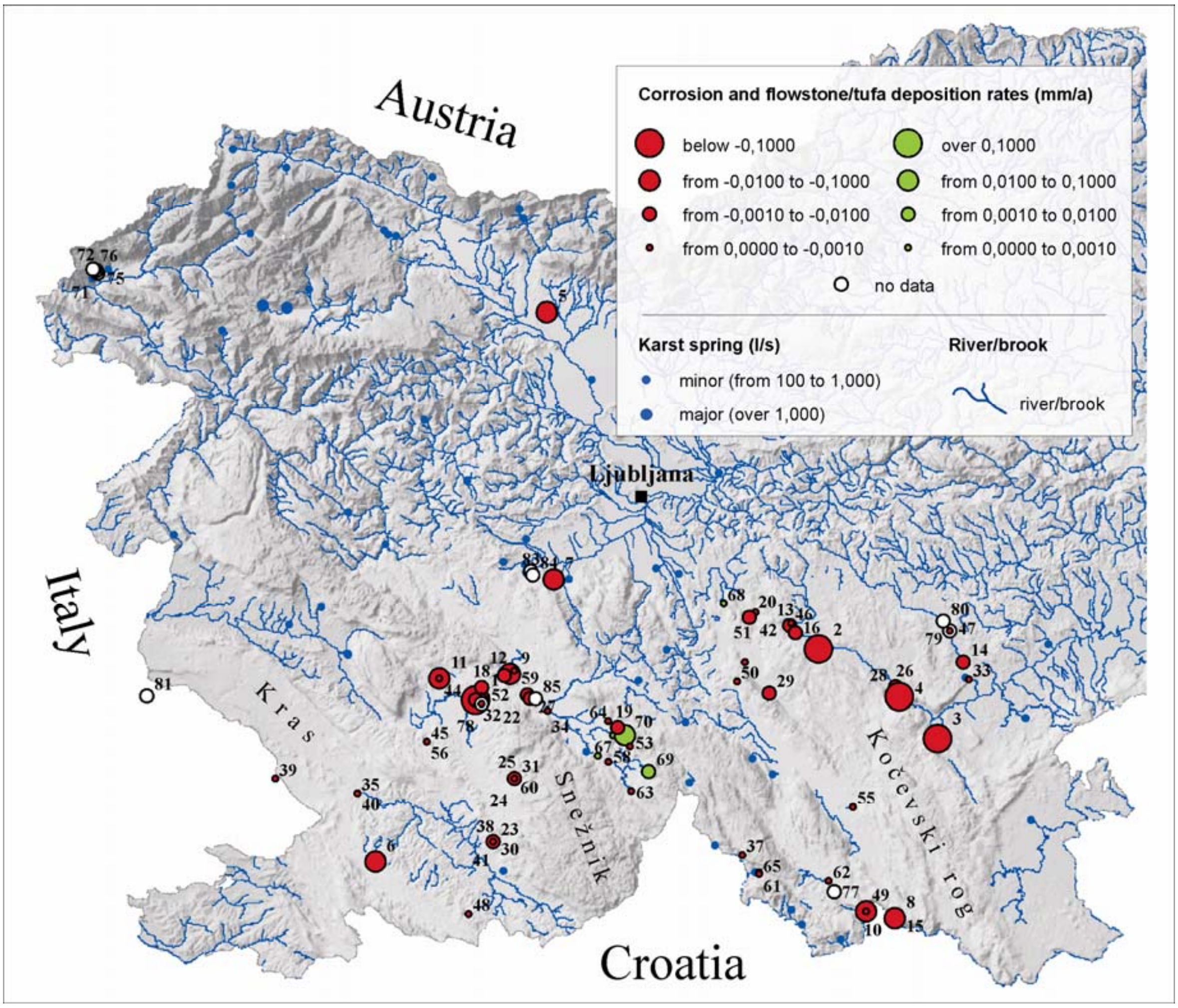


Figure 3.7: *Spatial distribution of corrosion and flowstone/tufa deposition rates.*

Nevertheless, some regions show **similar rates of karst processes**. In upstream part of eastern branch of Ljubljanica river, several measurement points show flowstone/tufa deposition. Flowstone/tufa deposition is related to springs and ponors. Since we know that dolomites occupy the area east from Idrija fault zone, so called Notranjsko podolje (=Notranjska lowland), increased corrosion during diffuse recharge, which leads to high total hardness and (over)saturation in the karst massif and at the springs, seems to be the main widespread factor that leads to flowstone/tufa deposition at several measurement points. At some places, water is so close to equilibrium that we detected slight corrosion or slight flowstone/tufa deposition rates (between -0.001 and 0.001 mm/a).

Another area of similar rates is lower right tributaries of Krka river, where high corrosion rates are result of fast biocorrosion. In this area, biocorrosion seems to take place at similar rates – most probably around -0.15 to -0.16 mm/a (Tab. 3.1).

Similar corrosion rates were observed also along some karst rivers (e.g. Pivka river in Postojnska jama, Rak/Kotliči in Rakov Škocjan). Nevertheless, measurement points are too sparse to conclude to what extent the corrosion or flowstone/tufa deposition rates are the same.

Application of corrosion or flowstone/tufa deposition rates to **morphology** is uncertain to some degree since the relation to other methods of measurement (e.g. micrometer) is quite poorly understood, the influence of misleading corrosion due to iron oxide can not be exactly quantified and long-term stability of karst processes questionable. Moreover, corrosion rates on dolomites can be up to 10 times lower in comparison with measurements with limestone tablets made of Lipica limestone (Fig. 2.1.3.11 in Chapter 2.1.3). Nonetheless, some conclusions can be made on supposition that rates nearly correspond to wall retreat in the Holocene, when a climatic, hydrological and vegetational conditions were more or less constant. Much higher differences are characteristic for Ice Ages, when at least climatic and vegetation pattern was much more different.

Transition between Pleistocene and Holocene is set to ~11,000 years BP (GOUDIE, 2000, 247) or 10,000 BP (PARKER, 2000, 377). The same values were recognized also for Slovene karst, although increased oversaturation of percolating water was recognized already 16,000 years BP at some places in western part of Slovene Low Dinaric Karst (MIHEVC, 2001). If we take into account similar rates of processes in 11,000 years, about 135 mm of corrosion can be expected on average. The highest corrosion (1.8 m) is characteristic for Lekinka, which indicates well developed corrosional features (scallops, wall notches, vadose meanders). Nearly the same corrosion can be expected from the side of biocorrosion at lower right tributaries of Krka river. At other locations, corrosion is much lower. In the group of corrosion rates between -0.01 and -0.001 mm/a, where the majority of measurement points are situated (Fig. 3.6), we can expect between 110 and 11 mm of corrosion. The latter values are high enough for formation of microfeatures that appear in the epiphreatic zone, such as scallops, small ceiling pockets and flutes. Formation of bigger features (e.g. wall notches, bigger ceiling pockets, bigger meanders) requires longer time or higher corrosion rates.

Much easier for evaluation is deposition, since we can observe thickness of flowstone cover, which can be easily compared with potential deposition within defined time-span. Using the same time-span as was used in corrosion, on average, thickness of flowstone coating is much smaller (9 mm) than corrosion since the peak in corrosion rates is in a group between 0 and 0.001 mm/a. In superficial streams, mechanical weathering and biocorrosion of tufa is probably much higher than tufa deposition rate and therefore such thickness can not be easily observed in superficial streams. Much different climatic conditions are found several tens of meters deep in the caves, where mechanical weathering is much lower. Therefore, deposited flowstone can be preserved. The thickest flowstone deposits can be expected in Križna jama (~1.1 m). The latter value corresponds to visual estimation of flowstone thickness at measurement point. During Pleistocene, flowstone deposition rate has to be much lower or even absent; otherwise the flowstone thickness would be much higher. The same phenomenon but at much lower rates, can be observed in Jama 1 v Kotlu (measurement point 61), where thickness of flowstone cover corresponds to measured flowstone deposition rates during Holocene (~3 mm).

Morphology at several measurement points indicates corrosion, while the measured rates show slight flowstone deposition (often close to measurement error). Such a situation can be observed at least in Podpeška jama, Markov spodmol, Golobina and in Matijeva jama (4). In Podpeška jama, water is practically inactive and could not form any corrosional feature even in 11.000 years. On contrary, the passage shows corrosion since it is covered with well developed scallops. Nevertheless, closer observation points out that they can be fossil, since the transition between them are rounded (see SLABE, 1995, 24). Markov spodmol is well known example of cave with extensively developed corrosional features. Nevertheless, present-day process near measurement points shows flowstone deposition, especially in lakes (see ZUPAN HAJNA ET AL., 2008, 192). Due to discrepancy between present-day and expected morphology, changes of water chemistry from corrosion toward flowstone deposition can be expected in these caves. It is interesting that none of measurement points reflect the opposite process, this is from flowstone deposition toward corrosion.

Conclusion

Measurements with limestone tablets seems to be an appropriate **methodology** to measure cumulative corrosion or flowstone/tufa deposition rates in caves, since the resistance to fast flows and precision is extremely good. Among 85 measurement points, limestone tablets were broken at 2 locations. Limestone tablets were very resistant also to water courses, which transports a lot of bed load material. Nevertheless, corrasion is very site specific and corrasion of limestone tablets does not reflects actual corrasion rates, since the rate of corrasion strongly depends on the shape of limestone tablets. Another problem is misleading corrosion due to iron oxide, which is characteristic for some measurement points. The problem can be avoided with usage of stainless steel or plastic screws, nuts and washers.
The majority of measurement points reflect small corrosion rates, which can be hardly measured with micrometer. If we exclude measurement points with biocorrosion, where the corrosion is unevenly distributed at the surface, yearly rates of corrosion or flowstone/tufa deposition can be detected with micrometer with accuracy 0.01 mm only in Lekinka, Velika Lebinca, Ponikve v Odolini, Križna jama, Veliki Obrh and maybe in Jelovička jama and Predjama (9-12 % of measurement points). At all other locations, small rates require longer measurements. At 44 % measurement points, rates are too small to be detected with micrometer within 10 years.

Measured **corrosion rates** are usually very low. On average, from -0.0015 to 0.0074 mm/a of corrosion can be expected. If we exclude corrosion rates caused by iron oxide, corrosion rates influenced also by corrasion and biocorrosion, average corrosion rates are much lower (~ -0.001 mm/a). In present-day situation, such low rates point out that speleogenesis is a slow and long-term process, which needs several 100,000s of years for development of passable passage. Despite this fact, some caves develop at much higher rates (up to -0.1664 mm/a – Lekinka) and even formation of micro-features requires just several 100s of years.
At some places, **flowstone/tufa deposition rates** were recorded. This shows that water can be also oversaturated with respect to calcite in epiphreatic (or shallow phreatic) zone. Nevertheless, flowstone/tufa deposition rates are as small as corrosion rates (about

0.0001 mm/a) – except in Križna jama, where flowstone deposition rate is significantly higher (0.1012 mm/a).

Spatial variability of corrosion or flowstone/tufa deposition rates can be quite high due to spatially changeable factors that influence corrosion rates. The highest variability was observed between Lekinka and Postojnska jama, where the ratio of corrosion rates amounts to 36:1 although the caves are less than 1 km apart. An even higher rate was found at the foot of Brkini hills, where the ratio of corrosion rates between Ponikve v Odolini and Račiške ponikve amounts to 70:1.
Nevertheless, some areas and caves show similar rates of processes in the epiphreatic zone. Such areas can be found along Postojnska jama-Planinska jama cave system, between Cerknica polje and Planina polje, at springs at the edges of Lož polje and Cerknica polje and at right tributaries of Krka river. All these areas are characterized by similar factors that influence corrosion or flowstone deposition rates.

The most obvious **factors** that influence corrosion rates are illumination, which influences biocorrosion rates on the surface, and total water hardness. The first one is not characteristic for caves but it is very strong in some karst springs. Even if the water is only slightly aggressive, illumination can cause significant increase of total corrosion rates (up to -0.16 mm/a at right tributaries of Krka river). This factor is equally important as low total hardness of water, which can lead to corrosion rates up to -0.16 mm/a – in Lekinka cave.
At springs which drain at least partly autogenically recharged water, higher CO_2 concentration in the water supports relatively high total hardness without flowstone/tufa deposition but also absence of corrosion, especially if in such water CO_2 is outgassed from the water. Significant outgassing of CO_2 from the water can lead to oversaturation, where high flowstone deposition rate is a logical consequence.
Low corrosion rates are usually a result of saturated water, where saturation can take place along superficial or underground water courses. Slightly higher CO_2 concentration under the surface usually does not raise aggressiveness of concentrated autogenic water courses. Lower corrosion rates can depend also on micro-location if the measurement point is rarely exposed to water – even the water is highly aggressive.

Allogenic water courses are not always aggressive – if they derive from superficial drainage rich in carbonates, they can be non-aggressive. Quite similar are concentrated autogenic waters that sink at the edge of poljes or partly karstic basins. Since they usually derive from diffuse autogenic recharge with high concentration of carbonates and CO_2, the outgassing of the latter from the water leads to (over)saturation.

At measurement points with especially high rates, rates are measurable with limestone tablets with accuracy ±0.0004 mm within several weeks or even days. **Daily rates** are measurable in Lekinka and in Križna jama, while some other locations (Velika Lebinca, Ponikve v Odolini, Veliki Obrh and maybe Jelovička jama and Predjama) requires monthly period of measurement. Nevertheless, due to variability of rates during a year, we can expect that some rates would be very close to the maximum or average error of measurement.

4 Case studies

Results obtained during 8-month-long measurement showed that additional more intense and detailed measurement can be done at several places with methodology of limestone tablets where the corrosion or flowstone deposition rates are sufficiently high. More intense 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 rates at several measurement points can lead toward better understanding of spatial and temporal factors that control present-day genesis of selected caves. Nevertheless, we took into consideration also some caves which are important due to their (inter)national recognizability or their special geomorphic or hydrologic function. From these points of view the following caves (cave systems) were chosen for more intense research:

4.1 **Križna jama-Križna jama 2 cave system** (well ventilated subhorizontal cave system in epiphreatic zone with high flowstone deposition rates most probably due to autogenic recharge and outgassing of CO_2; conditions in Križna jama 2 have not been studied yet),

4.2 **Lekinka** (a subhorizontal cave in epiphreatic zone with high corrosion rates as a result of allochtonous recharge from Pleistocene accumulation terrace of Nanoščica/Pivka),

4.3 **Škocjanske jame** (an excellent example of underground gorge of Reka river, which is characterized by extreme power of allogenic water at middle-high water levels and extensive backflooding at very high water levels),

4.4 **Postojnska jama-Planinska jama cave system** (a long underground network of dry and hydrologically active subhorizontal passages – an underground flow of Pivka river from Pivška kotlina (=Pivka basin) to Planinsko polje (=Planina polje) and one of the world's largest underground confluences),

4.5 **Tkalca jama** (a downstream part of hydrological connection of Cerkniško polje (=Cerknica polje) and Planinsko polje characterized by underground Rak river in weakly ventilated and usually hydrologically active subhorizontal passages),

4.6 **Malni springs** (springs at the SW part of Planinsko polje that drain mostly allogenically recharged Cerkniško polje and autogenically recharged Javorniki mountains) and

4.7 **Jelovička jama** (a short portion or underground water course on the left bank of Kolpa river, where water course carries a lot of siliceous bed and suspension load and huge differences in flow velocities occur between two sumps).

4.1 Križna jama – Križna jama 2 cave system

Križna jama (=cave of the Holy Cross; Reg. No. 65) is a scientifically well known cave due to high biodiversity (45 defined troglobionts – 4th place in the world; CULVER & SKET, 2000) and numerous findings of *Ursus spelaeus* bones. At the end of 19th century F. von Hochstetter excavated more than 2.000 *Ursus spelaeus* bones but a still unknown quantity lies untouched in the cave. Although Križna jama was visited by chemist and geologist Humphry Davy and his companion John James Tobin (SHAW, 2008) before Hochstetter, the latter was actually the first one who started with scientific work in the cave. At that time Križna jama got the first detailed map of Glavni rov (=Main passage) to the 1st lake done by geodesist Szombathy (dated to 1879). Continuation was known and interesting only for few people. Hochstetter investigated cave primarily from the paleontological point of view but he described the cave in detail and also described some geomorphological features: flowstone coating in water channel near Ponor, "erosional" cross-section of the same channel etc. The first one who related passages of Križna jama with corrosion was F. Kraus (1894). Between world wars in 20th century, investigations of the cave were primarily dedicated to the survey of passages upstream of 1st lake. Therefore, speleogenetical observations were done basically by cavers of Društvo za raziskovanje jam Ljubljana (=Caving Society Ljubljana; PLANINA, 1965; PUC, 1986). In the 1960s, Novak (1966, 1969, 1990) traced the stream in Križna jama twice and confirmed water connection with Šteberščica spring. Later, Gospodarič (1974, FORD & GOSPODARIČ, 1989) was interested in allochtonous sediment in Jezerski rov (=Lake passage; a part of Glavni rov) and Pisani rov (=Coloured passage) and from that time we have some data about sedimentology and U/Th datings. The last datings of allochtonous sediments in Križna jama were done by Zupan Hajna et al. (2008) and Pohar et al. (2001). Morphology of passages was within framework of speleology firstly studied by Gospodarič (1974) and later by Slabe (1989, 1989, 1992). We have to stress that none of those people ever measured any process and that all studies were strictly occupied with morphology or cave fills - sediments. The first one who started to measure the flowstone deposition rate with micrometer was Mihevc (1997); at three places between the 1st lake and Ponor.

Križna jama 2 (Reg. No. 6286) has much shorter history of research since the entrance was widened enough in 1991. Before 1991, entrance was blocked with boulders at the edge of collapse doline Grdi dol which separates Križna jama and Križna jama 2. The only brief description has been given by Drole (1997), who led the cave survey. Due to fragile flowstone dams, Križna jama 2 is on the list of 6 highly protected caves in Slovenia and accessible only with special permission by Ministry of the Environment and Spatial Planning.

Geological and gemorphological characteristics

Križna jama and Križna jama 2 are located in the centre of a triangle between Bloška planota (=Bloke plateau; ~720 m a.s.l.), Cerkniško polje (=Cerknica polje; ~550 m a.s.l.) and Loško polje (=Lož Polje; ~570 m a.s.l.). The majority of nearly horizontal water passages are developed between 577 m a.s.l. (the lowest siphon in Križna jama 2) and 630 m a.s.l. (spring under the ending breakdown in Blata passage). Main trunk passages (Glavni rov, Pisani rov and Blata passage) are usually more than 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, collapse chambers in Blata passage, chamber Kobe in Križna jama 2). Where the flowing water is absent, the rocky cave floor is covered by breakdown material or speleothems. At flooding places several meters thick layers of fine sand, silt and clay appear. Water passages are characterized by stagnant water bodies (lakes) and areas of flowing water between them. Lakes are usually formed behind rimstone dams.

The surface above Križna jama is typical high karst plateau – elongated conical hills and closed depressions without superficial streams. Relative elevation amplitude between hills and depressions can be quite high – up to 200 m. Thickness of vadose zone below karst plateau ranges from 10 to 270 m.

The highest peaks at Bloška planota are nearly in the same elevation as the hills above Križna jama, but the surface around peaks at Bloška planota is leveled along superficial streams. Since the lowest levelled surface of southern Bloška planota is occasionally flooded, Bloška planota can be treated also as a border polje (GAMS, 2003, 330). It seems that the surface at Bloška planota was similar to the area above Križna jama in the past until the depression reached the piezometric level. At that time, corrosional lowering stopped at piezometric level. Due to continued denudation of hills, the area of even surface progressively enlarged and formed also some residual hills (hums). Southern part of Bloška planota was also influenced by allocthtonous material, which was carried from the northern Bloška planota with Bloščica stream.

Cerkniško polje can be determined as well-developed over flow polje. It has almost flat bottom with partly developed hums. Its genesis is related to Idrija fault zone, which crosses polje in the NW-SE direction. Since the polje's bottom lies slightly below usual piezometric water level, it is flooded almost all through the year.

Landscape morphology can be related to local geology to a limited extent. Northern Bloška planota is made up of Lower, Middle and Upper Triassic rocks. The latter prevail in the southern part of Bloška planota. Lower Triassic dolomites are due to thicker layers of impurities usually impermeable for water. Permeability of dolomite rises toward Upper Triassic (Norian and Rhaetian) rocks, but in the latter tectonic deformation plays an important role for permeability. If it is strongly tectonized, it behaves similar to Lower Triassic dolomites. Slight tectonic deformation enables underground water flow through Upper Triassic dolomites and probably this is the reason that ponors of major superficial streams at Bloška planota (Bloščica, Farovščica and Studenec pri Ravnah) are already in Upper Triassic dolomite before the streams reach even better permeable rocks (limestones; see Fig. 4.1.3). Caves are very rare even in Upper Triassic dolomite since its low resistance to physical weathering produces usually parallelepipedic gravel (PLENIČAR, 1953). Such weathered material completely covers compact base layers of dolomite and produces thicker soils in comparison with limestones. On steeper slopes dolomitic soils creep to the hill's foot and produces well-expressed colluvial slopes. Such colluvial slopes, where colluvium material was already dissolved in the past, can be easily noticed at Bloška planota and below Slivnica mountain. 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-gained sand, which is incorporated in the soil matrix. Such residual dolomitic "sand" may inhibit further karstification (BOGLI, 1980 after GUNN, 1986). Upper part of Blata passage in Križna jama already lies in Lower Jurassic limestone.

The host rock for majority of Križna jama's passages and area above it is Lower-Middle Jurassic limestone. Karstification of this type of limestone is extremely high, which is proved with lack of any superficial streams and springs. According to Folk's classification this limestone is classified as micrite and oomicrite. Due to partial secondary dolomitization, dolomite layers, lenses and nests can be found within Lower-Middle Jurassic limestone. In the Middle Jurassic rocks, dolomites can completely prevail.

Cerkniško polje is developed on the tectonic contact between Upper Triassic dolomites, Jurassic dolomites and limestones and Cretaceous limestones. Although geological structure is quite complicated, levelled surface cuts all boundaries without morphological differences. Due to long geomorphological evolution, several metres of sediment accumulated at Cerkniško polje. Drilling in the bottom of Cerkniško polje indicated up to 15 m deep sequence of gravel, sand and clay from the surrounding area (PLENIČAR, 1953).

The most important tectonic feature in the area of Križna jama-Križna jama 2 cave system is the syncline between Bloška planota and Notranjsko podolje (=Notranjska lowland) and Idrija fault zone (Fig. 4.1.1). 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 syncline of Racna gora (GOSPODARIČ, 1974).

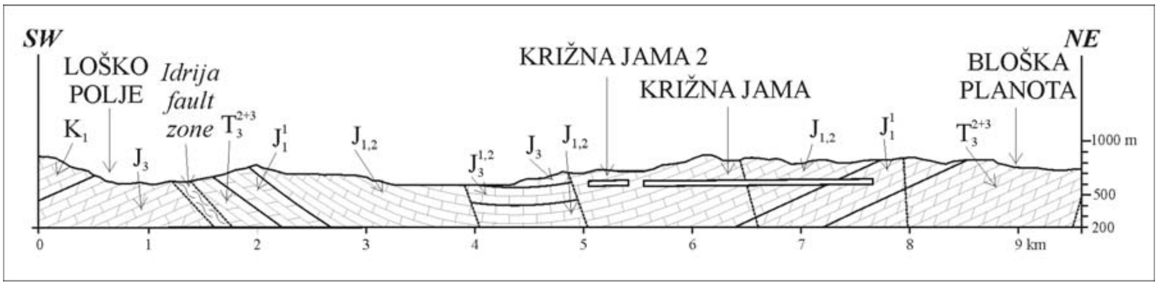


Figure 4.1.1: *Schematic geological cross-section perpendicular to the syncline's axis (from Bloška planota to the middle point between Cerkniško polje and Loško polje) with position of Križna jama and Križna jama 2 (modified after GOSPODARIČ, 1974).*

Although Križna jama and Križna jama 2 lie several kilometres from the Idrija fault zone carbonate massive between Bloška planota, Cerkniško polje and Loško polje did not suffer any important tectonic movement. Therefore the syncline is very well preserved in the studied area. Major movement occurred 4 km southwest from Križna jama, where the syncline is cut and we have a tectonic junction of Upper Triassic dolomite and Upper Jurassic limestone with very different dipping (Fig. 4.1.1). Although, there are some minor tectonic movement near Križna jama, for example fault-junction of Upper Jurassic dolomites which border Middle Jurassic limestones in the axis of syncline (Fig. 4.1.1; GOSPODARIČ, 1974). Relatively slight tectonic movements are observed also in Križna jama.

Hydrological characteristics

From a hydrological point of view, cave system Križna jama-Križna jama 2 lies between three differently elevated poljes with upstream karst springs and downstream ponors. Between them, the well kastified area spreads without superficial streams of water. Therefore the aquifer between poljes is fed by alogenic and autogenic recharge.

Because of its high elevation, Bloška planota was determined by Gams (2003) as a roof of Notranjska karst. The water is flowing toward Cerkniščica, Ribniško polje (=Ribnica polje), Loško polje, directly to Cerkniško polje and toward Ljubljansko barje (=Ljubljana marsh). Superficial streams on Bloška planota get water from many small springs. Since they are collecting water in well-fractured dolomite, average hardness of water is therefore high (13.9 ºN after Gams (1966a; 2003, 73). The minor portion of water is derived from surface runoff which has, due to thin carbonate soils, also quite high hardness. The majority of water is collected in Bloščica stream, whose catchment area covers an area of 19.5 km^2. Much smaller catchment area (about 4 km^2) is characteristic for Farovščica stream. According to Gospodarič & Habič (1976, 49) measurements, minimal discharge of Bloščica between 1972 and 1975 amounted 0.02 m^3/s, average discharge 0.42 m^3/s and maximal discharge 15.9 m^3/s. Due to similar characteristics but much smaller catchment area, average discharge of Farovščica can be about 0.09 m^3/s. At low-middle water level ponors of Bloščica lie near Velike Bloke. At high water level Bloščica continues superficial stream toward Nova vas, where it joins Farovščica stream and they sink together near Fara settlement.

On the basis of past tracer tests (Fig. 4.1.3; Šerko, 1946, 126; Novak, 1966, 1969, 1990; Kogovšek et al., 2007; Kogovšek et al., 2008), Bloščica and Farovščica appear on the surface again at the eastern edge of Cerkniško polje (in Štebrščica and Žerovniščica spring). A minority of water flows also toward two springs at Podlož but not toward the spring in Lož at Loško polje (Kogovšek et al., 2007). Mean Štebrščica (1.30 m^3/s) and Žerovniščica discharges (0.21 m^3/s; Gospodarič & Habič, 1976, 49) are much higher than Bloščica and Farovščica. This suggests the important contribution of primary infiltration. Comparison of mean discharges of superficial input to the aquifer between Bloška planota, Cerkniško polje and Loško polje (Bloščica and Farovščica) on one side and outflows from the aquifer (Štebrščica and Žerovniščica) on another side shows that about 66 % of water derives from primary infiltration above the aquifer. Therefore the Bloščica and Farovščica contribution to the aquifer was assessed to about 34 %.

Underground water flow downward from Križna jama was never questionable – tracing test done by Novak (1966, 1969) in Križna jama confirmed 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 access to Križna jama 2 (1991), connection between Križna jama and Križna jama 2 was never confirmed by tracing test. Similar physical characteristics of water, short distance (242 m; Fig. 4.1.2), charcoal findings, *Ursus spelaeus* bones found in Križna jama 2 and similar quantity of water suggest continuation of water flow from Križna jama through Križna jama 2. Since we know that the water temperature in Križna jama 2 slightly deviates from the water temperature in Križna jama (for about +0.2 ºC in summer and -0.2 ºC in winter) we should expect a minor tributary between the two caves. This tributary was confirmed with a tracer test in 2007 (KOGOVŠEK ET AL., 2007) and is probably related with underground flow of Farovščica combined with autogenically recharged water.

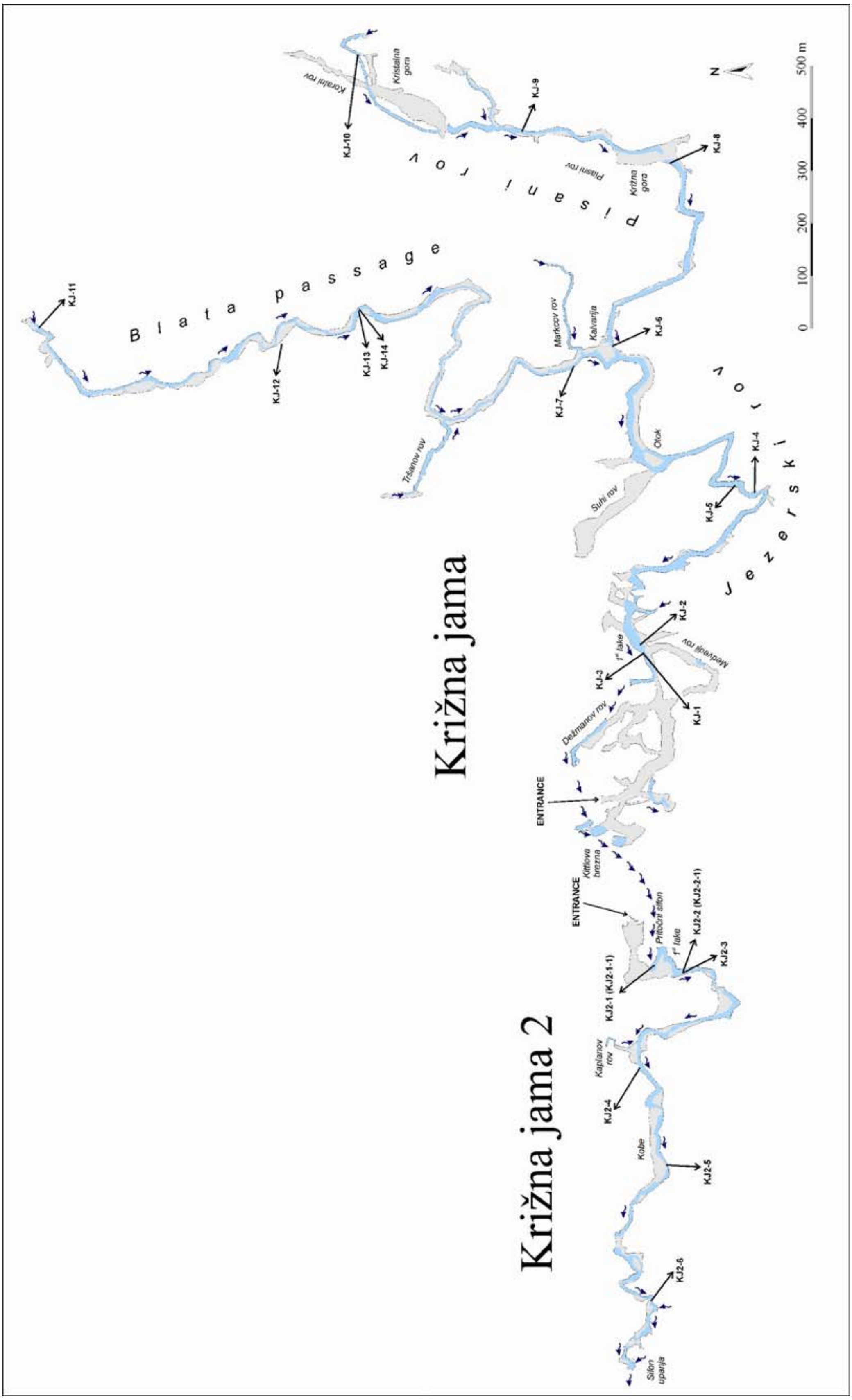


Figure 4.1.2: *Ground plan of the Križna jama – Križna jama 2 cave system with measurement points.*

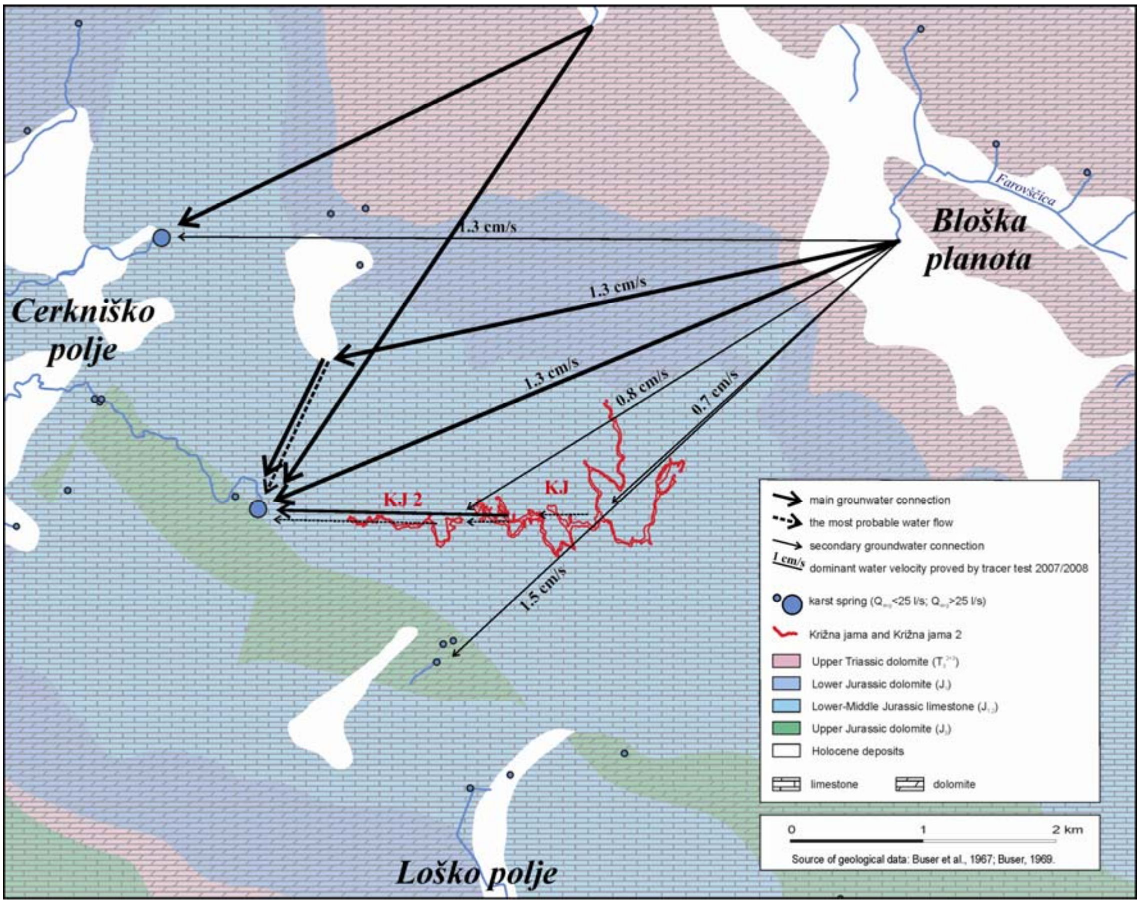


Figure 4.1.3: *Hydrogeological map of the area between Bloška planota, Cerkniško polje and Loško polje with tracing tests (ŠERKO, 1946; NOVAK, 1966; NOVAK, 1969; NOVAK, 1990; KOGOVŠEK ET AL., 2008).*

Despite several tracing tests in the aquifer, the origin of water in Križna jama – Križna jama 2 system was unclear for a long time due to lack of sampling in Križna jama during the only tracing test in the hinterland of the caves in 1939 (ŠERKO, 1949, 128). Springs which feed main water courses at Bloška planota have 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 higher Ca^{2+}/Mg^{2+} ratio (1.59-2.34 at 1st lake), which indicates important portion of inflow through limestone. Such an inflow is possible only through primary infiltration in the neighborhood of the cave system. If we take into account also primary infiltration through Lower Jurassic dolomite in the upstream part of the cave system, portion of allogenic water should be very low in Križna jama – Križna jama 2 cave system. This was confirmed also with a tracer test in 2007 at middle water levels from Farovščica ponor – recovery of tracer was very low in Križna jama (1.3 % - 3 g of 226 g injected uranin) and probably slightly higher in Križna jama 2 (KOGOVŠEK ET AL., 2007). Very small annual temperature variation in Križna jama (about 1 °C) and much higher in Mrzla jama pri Bločicah (more than 5 ºC) also shows that at least at low-middle water level allogenic water flows north and not through the cave system Križna jama – Križna jama 2. Such water course was already proposed in the past by Novak (1966).

Spine of hydrological system in Križna jama – Križna jama 2 are two streams from Pisani rov and 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. 4.1.4). In Pisani rov and Blata passage, water appears under the ending breakdowns. Along Blata passage, at least 6 tributaries were detected during SEC, T and pH measurements. They contribute various quantities of water depending on water level; for instance tributary from Tršanov rov (=Tršan passage) contribute 92 % of all water in Blata passage at middle water levels and less than 43 % at low water levels. At high water level, their contribution cannot be evaluated since the access to passages is not possible. Nearly all tributaries end as sumps or the water flows from narrow very poorly ventilated passages.

In the upper end of Pisani rov, water appears under the breakdown at 3 places. At low-middle water levels physicochemical characteristics of all three spring are very similar. Between Križna gora and Kalvarija left tributary joins the main water course through the sump. It has significantly higher SEC, lower temperature and lower pH. At middle water level it contributes 16 % of all water in Pisani rov.

Streams from Pisani rov and Blata passage join at Kalvarija. Regarding to 6 measurements of SEC and temperature at different water level (from $H_{1st\ lake}$ = -4 cm to $H_{1st\ lake}$ = +8 cm), discharge from Pisani rov and Blata is in the ratio from 1:4.3 to 1:0.69. Although we are dealing with relatively small amount of measurements, quite high Pearson product moment correlation coefficient (0.68) suggests that with higher water level contribution from Blata passage increases. Downstream from Kalvarija a few l/s of water is lost in at least 3 places. At high water levels (above $H_{1st\ lake}$ = 50 cm), an important quantity of water flows from V-rov to the 1st lake. The portion from V-rov

in such hydrological conditions is estimated to be about 80 % of the water that flows downstream of 1st lake. At middle-low water level discharge from V-rov is negligible.
In Križna jama, water disappears in the sump at Ponor, reappears again and ponors in Dežmanov rov and finally reappears and disappears in the 70 m deep sump Kittlova brezna. This connection was proved with tracing test (NOVAK, 1966). In Križna jama 2, water appears from over 50 m deep sump and flows mainly as free surface flow toward ending sump Sifon upanja (=Sump of hope). Along this water course, the stream gets 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 (less than 5 %). Few tens of metres upstream from 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, 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 underground Farovščica stream (KOGOVŠEK, 2007). A portion of this tributary is unknown but, since discharge and physicochemical properties of water are not significantly increased between Križna jama and Križna jama 2, it seems to be quite small.

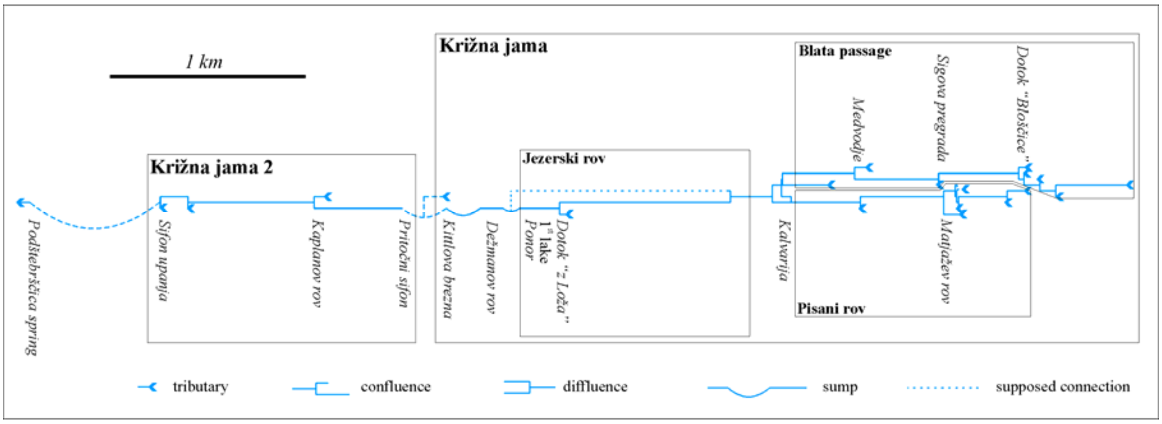


***Figure 4.1.4:** Hydrological network of the cave system Križna jama – Križna jama 2 regarding to visual observations and SEC, temperature and pH measurements at low and middle water level.*

Relation between water level (Fig. 4.1.5) and discharges were measured at the 1st lake by means of NaCl-solution injection and integration of the specific electrical conductivity as a function of time (salt dilution method). Water level 0 cm was set to upper limit of flowstone-covered wall in 2nd lake. At such water level discharge is about 0.1 m^3/s. The highest measured discharge at water level ($H_{1st\ lake}$ = +59 cm) was 2.08 m^3/s. At $H_{1st\ lake}$ = -7 cm outflow from the 1st lake ceases. According to extrapolation of stage-discharge curve (Fig. 4.1.6), the highest observed discharge between 2004 and 2008 amounted about 7 m^3/s and the lowest 0 l/s.

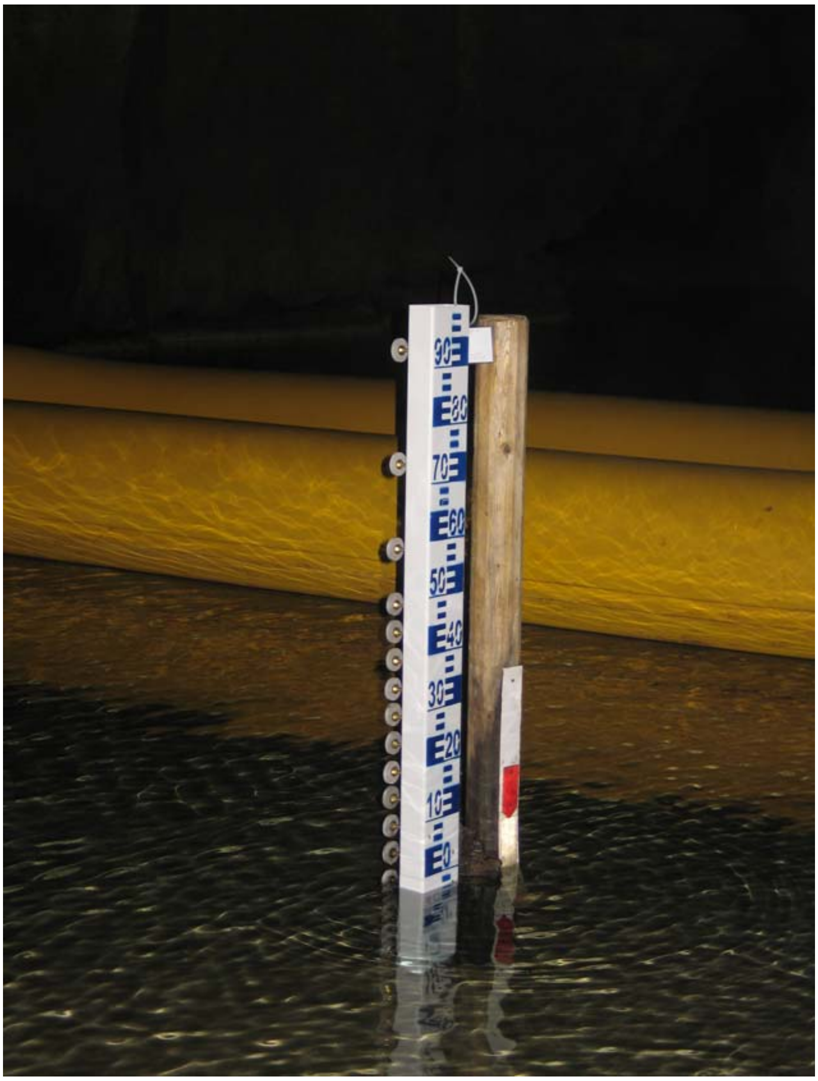


Figure 4.1.5: *Gauging station with 21 limestone tablets at measurement point KJ-2 in the 1st lake. According to our observations and the cave guide's comments average monthly fluctuation of water amounts ±5 cm around 0 cm, yearly ±50 cm and usually every second year for more than ±100 cm.*

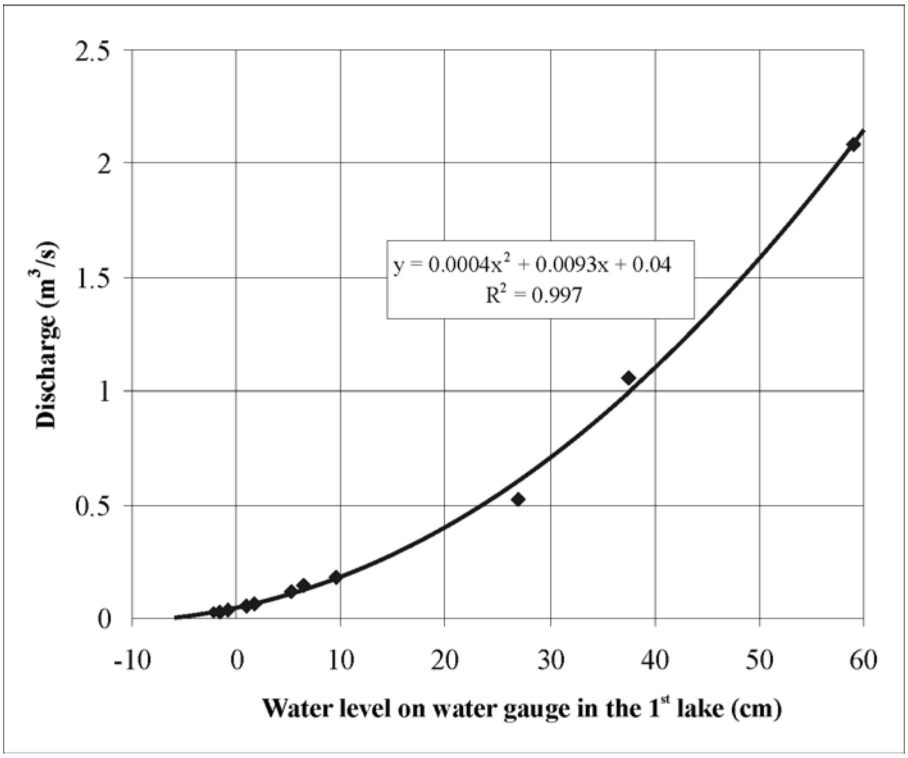


Figure 4.1.6: *Stage-discharge curve for gauging station in the 1st lake in Križna jama.*

Meteorological characteristics

Meteorological conditions in Križna jama – Križna jama 2 cave system are influenced by outside temperature, temperature in cave, number and position of entrances (currents of air) and temperature of flowing water. The last seems to be equilibrated with temperature of carbonate massive and amounts to 8.5 °C (see Fig. 4.1.5.1 in Chapter 4.1.5). Average annual temperature at Bloška planota is, according to meteorological station Nova vas na Blokah, 6.9 ºC (KLIMATSKI PODATKI..., 2008). Lower average temperature at meteorological station is caused by common temperature inversion at Bloška planota. Positive or negative difference between outside and cave temperature defines direction and strength of ventilation if the cave has at least 2 entrances.

Entrance to Križna jama is in the shape of an equilateral triangle with side length of 4 meters (Fig. 4.1.7). Before the 1940s, entrance to Križna jama was probably for some m^2 smaller. This entrance is the lowest and the only one which is accessible to man. But observation of karst surface above Križna jama shows the existence of at least 3 higher entrances, partly blocked with collapse material but passable for air. Therefore, we observe air current from the main entrance toward Kalvarija in winter time and the opposite in summer time. The weakest restriction to air flow exists at the upstream part of Pisani rov and Matjažev rov but much stronger at the end of Blata passage. Consequently the strongest air currents are observed in Pisani rov and much weaker in Blata passage. Wind velocity increases with higher deviation from about 8 °C.

Križna jama 2 has only hydrological connection with Križna jama. After 1991 it has only one known entrance which is accessible to men. It is about 0.5 m wide and 0.5 m high (Fig. 4.1.7). Before man-made widening of entrance, Križna jama 2 was less under the influence of air currents but accessible for bats. In winter time the air is coming from the cave and vice versa in summer time. If temperature differences are small, ventilation can be reversed in less than one minute. Other entrances are probably so narrow that they are functioning as strong obstacles for ventilation. Cross-sections of passages in Križna jama 2 are bigger as in Križna jama. This is the reason why air current seems to be lost along main water passages.

Figure 4.1.7: *Entrance to Križna jama (left) and Križna jama 2 (right).*

Corrosion and flowstone deposition rate measurements and their relation to key factors and features

4.1.1 Measurement place KJ-1 – temporal variability of processes at Brzice

A widely accepted belief in karst is that intensity of corrosion strongly corresponds to discharge. During higher discharge the corrosion rates should be more and at lower discharge less intensive (PALMER, 2007). This is related with kinetics of limestone/dolomite dissolution, which is at the first contact with soluble rock very fast (exhibit high corrosion rates) and later slow down while reaching equilibrium (DREYBRODT, 1988; GABROVŠEK, 2005). Therefore, during high discharge, flow is faster and corrosive water can deeply affect karstified carbonate massif. Non-linear reaction of water with carbonates, while the water approaches equilibrium, keep the water aggressive all the way from the first contact with carbonate rock to the spring (PALMER, 2000, 78). This also enables widening of long karst conduits and formation of long hydrological connections between ponor and spring sites. If we relate this phenomenon with velocity of water which is going through an aquifer, we can conclude that faster the waters is, higher corrosion rates can be observed at one point downstream from the first contact with soluble rock. Nevertheless, equilibrium is strongly influenced by CO_2 concentration, which varies in the aquifer and can lead to oversaturation, especially during low discharges. In some cases, differences in water pathways and differences in partial pressure of CO_2 within an aquifer can turn slightly aggressive water at middle water level to even oversaturated water at low water level. This phenomenon was observed by Palmer (2002, 2007) in the McFaill's Cave (New York, USA), where calcite saturation index (SI_{Ca}) falls below 0 at high water level and grow above 0 at low water level. At such water level flowstone deposition occurs.

At 1st lake in Križna jama, discharge fluctuates annually from some l/s to more than 7 m^3/s. Low discharge is characteristic for winter and summer time, when we observe retention because of snow accumulation in first case and high evapotranspiration in the other one. High discharges appear in autumn and spring. They are related to submediterranean precipitation regime, lower evapotranspiration and partly to snow melting. According to general theoretical knowledge, rain-snow flow regime, flowstone deposition rate measurements done by Mihevc (1997) and Prelovšek (Chapter 3) and abundance of scallops on the cave walls, we would expect the highest deposition rates in summer/winter time (during the lowest discharge) and the highest corrosion rates in autumn/spring time (the highest discharge). Regarding to Gams (1966b, 33), flowstone deposition below Kalvarija is possible because of junction of two streams with high dolomitic hardness.

Measurements of temporal variation in flowstone deposition started on 14th February 2006 and finished on 5th April 2009 (1146 days). Measurement point named KJ-1 was located at Brzice (=Rapids) 10 m below 1st lake; this is about 340 m from the entrance to Križna jama. Water flow here is considered as fully developed turbulent flow with mean water velocities more than 0.5 m/s. Water flow at measurement point was absent when water level in 1st lake fell below -7 cm. We used 2 limestone tablets – one was exposed at the measurement point and the second one was at the same time dried in chemical laboratory at Karst research Institute ZRC SAZU. We exchanged tablets after 15 days of drying/exposure. Such period was thought to be long enough to get some reliable values considering precision of methodology and previously measured values (Chapter 3; MIHEVC, 1997). Limestone tablets were fixed on iron screws with iron nuts and 2 felted stainless steel washers 2 cm above the channel bed. Although we noticed some iron oxide on the limestone tablets we estimated its influence as negligible (less than -0.0001 mm/15 days).

Results from measurement point KJ-1 are represented in Fig. 4.1.1.1. By far the highest flowstone deposition rates occur in winter time, when the water level is usually lower. But lower water level occurs also in summer time, when higher flowstone deposition rates are absent. Even more, in some summer months weak corrosion was detected. Corrosion rates are extremely weak and are not lower than -0.0003 mm/15 days. Corrosion occurs usually in the late summer or in the early autumn months and is usually absent in spring months. Even at exceptionally high water level on 30th May 2006 ($H_{1st\ lake}$ = +120 cm) corrosion rate was relatively low, only -0.0001 mm/15 days. Weak correlation between height of water and corrosion or flowstone deposition can be seen also in Fig. 4.1.1.2, where flowstone deposition and corrosion rates are plotted together with height of water and specific electrical conductivity measured at 1st lake. If we consider specific electrical conductivity as rough approximation of Ca^{2+} and Mg^{2+} concentration, we see practically no correlation between height of water and flowstone deposition or corrosion rates. Even quite high water level in March 2007 ($H_{1st\ lake}$ = +52 cm) did not cause any corrosion. Even more, slight flowstone deposition was recorded at that time.

Discharge should be an important factor controlling flowstone deposition and corrosion rates. But acquired data are far from expected and need an additional factor which could influence corrosion/flowstone deposition rate. Since the highest flowstone deposition rates seems to correspond to strong ventilation of at least the entrance part of Križna jama in winter months, high flowstone deposition rates can be related to this phenomenon. Connection between flowstone deposition rate and aeration can be found in outside air, which is reducing CO_2 concentration in the cave and maybe enhance flowstone deposition.

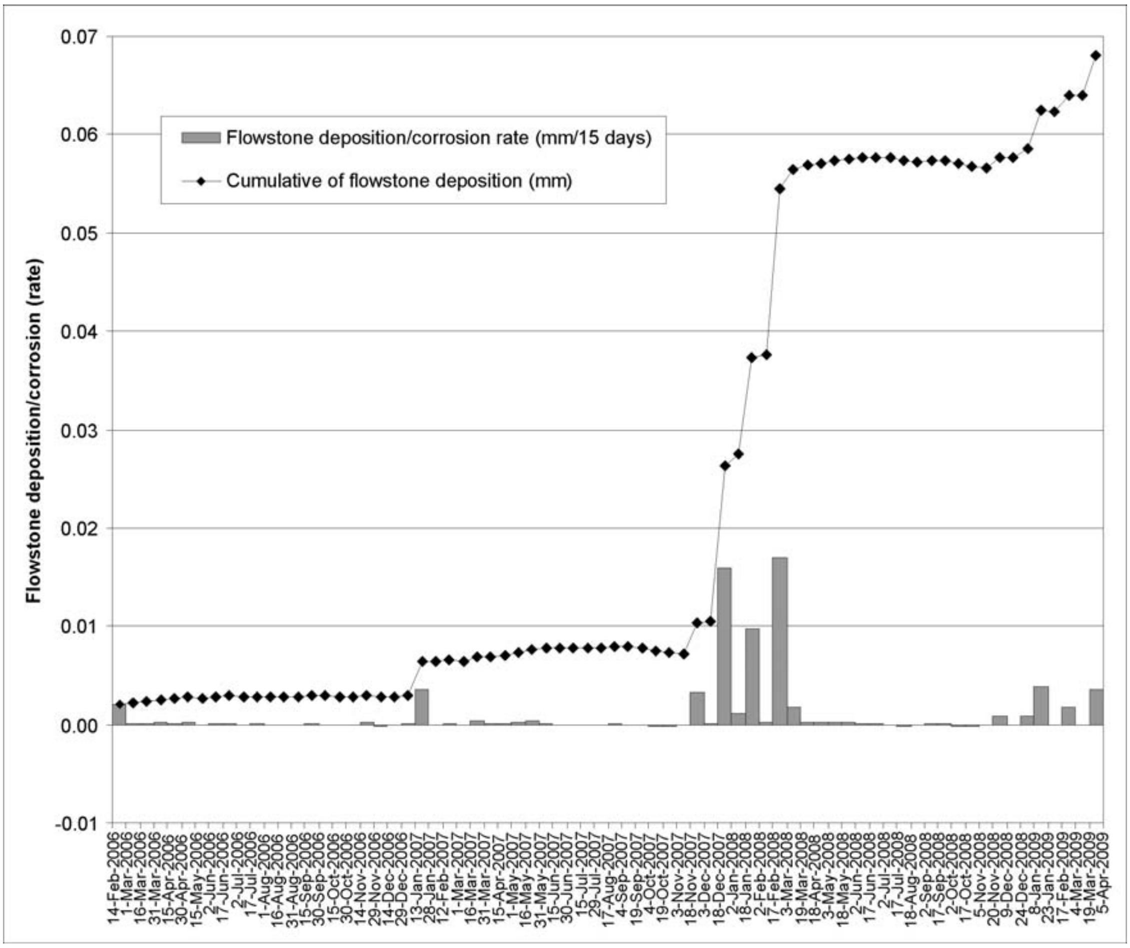


Figure 4.1.1.1: *Corrosion or flowstone deposition rates between 14th February 2006 and 5th April 2009 at measurement point KJ-1 in Križna jama.*

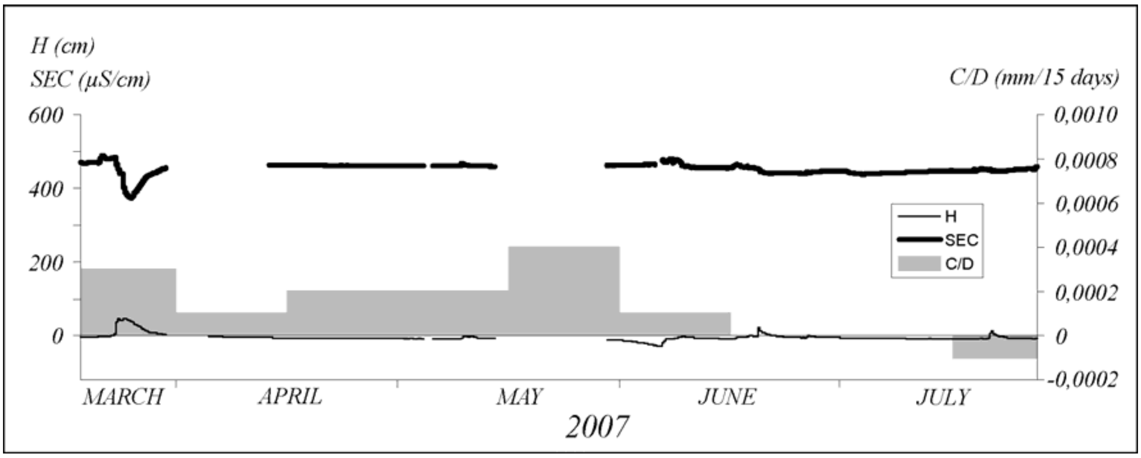


Figure 4.1.1.2: *Corrosion/flowstone deposition rates (C/D) between 21st March 2007 and 25th July 2007 at measurement point KJ-1, height of water (H) and specific electrical conductivity (SEC) measured at 1st lake.*

Precipitation of calcium from water solution is a final result of several chemical reactions (Fig. 4.1.1.3). First reaction is outgassing of CO_2 from the water and the final one chemical deposition of $CaCO_3$ (DREYBRODT, 1988). Cause for flux of CO_2 from the water is lower CO_2 concentration in air. This flux reduces CO_2 concentration in the water and production of fresh CO_2 begins. The latter CO_2 is formed from H_2CO_3 and therefore production of new H_2CO_3 has to occur. For new formation of H_2CO_3 ions of H^+ and HCO_3^- are consumed. Finally, lowering of H^+ concentration leads to increase of calcite saturation index and if the latter is higher than 0, calcite starts to precipitate from the water. This stage is usually determined by Ca^{2+} concentration in the water, CO_2 concentration difference between air and water and some foreign ions which have influence to reactions. If the water and air concentration of CO_2 are equal, flux of CO_2 and calcite precipitation does not appear.

Therefore, 4 reasons have to be fulfilled for flowstone deposition:

a) water has to contain high amount of Ca^{2+} or has to be close to equilibrium concentration of Ca^{2+},
b) interface between water body and air has to be high enough for satisfactory flux of CO_2 from the water,
c) some nuclei (calcite crystals) have to be available for deposition, especially at low oversaturation (ROQUES, 1969, 155) and

d) concentration of CO_2 in the air has to be sufficiently low to support degassing of CO_2 from the water.

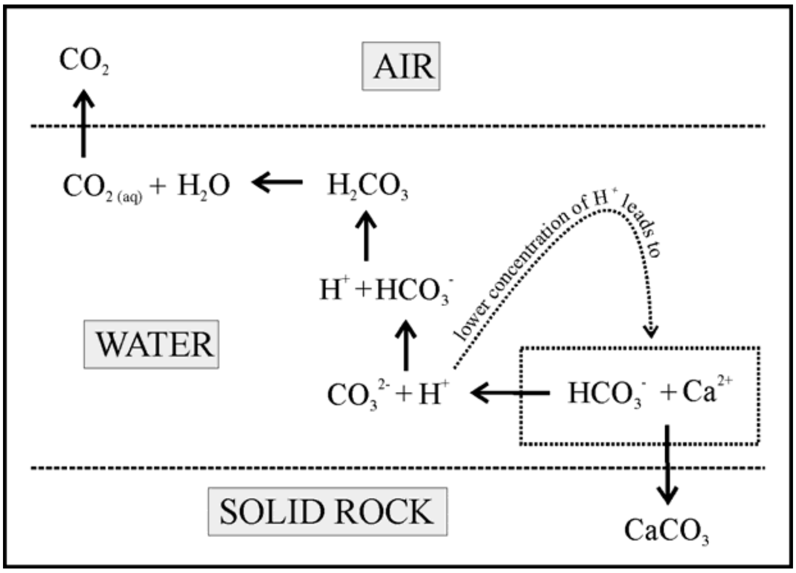


Figure 4.1.1.3: *Schematic presentation of reaction sequence due to differences in CO_2 concentration between water and air.*

Periodic measurements of specific electrical conductivity and several chemical analyses of water show that the water which flow over measurement point KJ-1 contains relatively high amount of Ca^{2+}, Mg^{2+} and low concentration of other cations. Typical specific electrical conductivity at 1st lake during middle water level is usually between 445 and 490 µS/cm. The lowest recorded was 366 µS/cm (27th March 2007; $H_{1st\ lake}$ = +52 cm). Regarding to chemical analyses of water, concentration of Ca^{2+} is 4.0-4.5 meqv/l at middle water level. Such concentration gives saturation indexes with respect to calcite between 0.3 and 0.7. When the water level is very high (for example on 30th May 2006; $H_{1st\ lake}$ = +120 cm), concentration of Ca^{2+} falls to 2.85 meqv/l and the water should become slightly aggressive (SI_{Ca} = -0.1). These data show that water in near 1st lake in Križna jama contains high amount of Ca^{2+} and that it is almost all the time slightly oversaturated with respect to calcite. Therefore, condition a) is not problematic for flowstone deposition at measurement point KJ-1. Just at higher and very high water levels ($H_{1st\ lake}$ ≈> +10 cm) concentration of Ca^{2+} seems to be too low for detectable flowstone deposition.

Condition b) seems to be not problematic at KJ-1 since the measurement point 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. 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.

Nucleation can be a problem in the 1st 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 flowstone deposition in winter time (Fig. 4.1.1.1) and occasional measurement of air CO_2 concentration, the strongest control seems to be difference in CO_2 concentration between water and cave air. Such differences are very common at karst springs, where karst waters with relatively high CO_2 concentration face the atmospheric values (≈380 ppm; WHITE, 1988; according to our measurements 330-390 ppm). Consequently, vast travertine deposits can be observed at many karst springs. Cave concentrations of CO_2 are much more complex since the atmospheric background is disturbed from the side of biological activity in soil. Cave air CO_2 concentration vary in time and space regarding to (ATKINSON, 1977 after GUNN; BALDINI ET AL., 2006; DELECOUR ET AL., 1968; EK & GEWELT, 1985 after BALDINI ET AL., 2006; JAMES, 1977 after BALDINI ET AL., 2006):

- inputs:
    - outgassing from percolating water,
    - decay of organic matter,
    - influx of air from vadose and epikarstic zone,
    - deep-seated CO_2 seepage from porous reservoirs, usually ingneous in origin,
- output:
    - influx of atmospheric air.

At measurement point KJ-1, measurements of CO_2 concentration (Fig. 4.1.1.4) show that short-term variations of CO_2 concentration are strongly influenced by direction of air flow in the cave and long-term variations of CO_2 by season. CO_2 concentration generally rises from the spring (less than 500 ppm) to the middle of autumn (up to

3.880 ppm), this is the end of vegetation season. In the middle of autumn and during winter time, CO_2 concentration gradually reduces to spring values. This trend corresponds to the prevailing air flow in the cave; lower concentrations are characteristic for air flow directed from the main entrance toward Kalvarija and *vice versa*. During cold winter days, CO_2 concentration can be equal to outside concentration (~330-390 ppm).

General winter inflow and summer outflow of air from the cave can be turned into opposite direction due to several temperatures, which are unusually high/low for the winter/summer. Such an event happened in the middle of June 2008 for two days, when the outside temperature fell several degrees below 8 ºC and resulted in a steep decrease of CO_2 concentration at measurement point KJ-1. Inversely, steep increase was observed in the beginning of December 2008 and in February 2009. The response to inverted ventilation is fast – CO_2 concentration can be reduced for 1,500 ppm within one day and restored to previous values in the same time (see middle of November 2008 and beginning of December 2008 on Fig. 4.1.1.4).

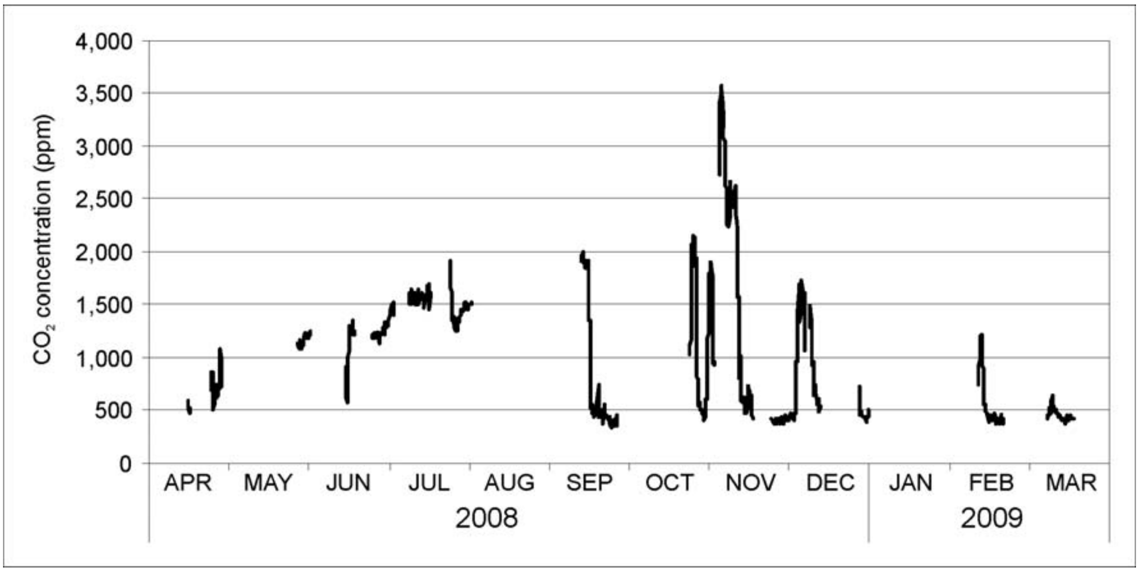


Figure 4.1.1.4: *Cave air CO_2 concentration at KJ-1 during the year.*

It is interesting that sometimes even atmospheric concentration of CO_2 near measurement point KJ-1 is not sufficiently low for high flowstone deposition rates. Even more, when the water level is low and concentration of CO_2 is almost constant at 380 ppm between entrance and Kalvarija, we did not observe substantial flowstone deposition rates (see second part of September 2008 and second part of October 2008 in Fig. 4.1.1.1 and Fig. 4.1.1.4). In Fig. 4.1.1.5 we can see that high flowstone deposition rates are better related to strong and long winter ventilation of cave and that minor autumn and spring ventilation is not sufficient for high flowstone deposition rates. Therefore, substantial flowstone deposition rates at KJ-1 can be observed only if ventilation is strong and long enough to ventilate all Glavni rov, big collapse chambers Križna gora and Kristalna gora, known and unknown passages behind them and maybe also poorly ventilated Blata passage. In such meteorological conditions outgassing of CO_2 takes place all along water course and can reach substantial high SI_{Ca} at KJ-1 for high flowstone deposition rates. Substantially high calcite saturation indexes and consequently high flowstone deposition rates occur only on days when the maximum daily temperature remains below -2 °C and the water level does not exceed $H_{1st\ lake} \approx +10$ cm. The latter limitation can be seen in relatively low flowstone deposition rates in December 2007, January, February and March 2008 when meteorological conditions seem to be suitable for flowstone deposition but the water level in 1st lake ranged between $H_{1st\ lake} \approx +10$ cm and $H_{1st\ lake} \approx +30$ cm. Therefore, both factors should be fulfilled for high calcite saturation index and calcite precipitation. After Palmer (2007), calcite can precipitate at approximately $SI_{Ca} > +0.2$ but Usdowski (after DREYBRODT, 1988, 269) states much higher values (even $SI_{Ca} \approx +1$). Some other authors (JACOBSON & UDOWSKI, 1975 after DREYBRODT, 1988, 256) did not recognize calcite precipitation even at $SI_{Ca} = +1$, which is probably related with presence of other ions. In Križna jama we did not analyse any water sample at high flowstone deposition rates but we are sure that high flowstone deposition rates definitely occur above $SI_{Ca} > +0.7$. The latter saturation index was measured out of winter months and is therefore not sufficient to detect flowstone deposition rates that are higher than 0.0005 mm/15 days.

Fig. 4.1.1.5 also demonstrates how important long-lasting low temperatures are in winter time for total amount of flowstone deposited at measurement point KJ-1. Although minimal average daily temperatures were similar in winters 2006/2007 and 2007/2008, intrusions of atmospheric air into the entrance part of Križna jama were much longer in winter 2007/2008. Such long-lasting events strongly ventilated passages in Križna jama and caused many high flowstone deposition rates in winter 2007/2008. In relatively warm winter 2006/2007 only 7.3 % of flowstone was deposited in comparison with much colder and longer winter 2007/2008. Direction, duration and intensity of air flow in winter time therefore strongly influence the amount of flowstone deposited at KJ-1.

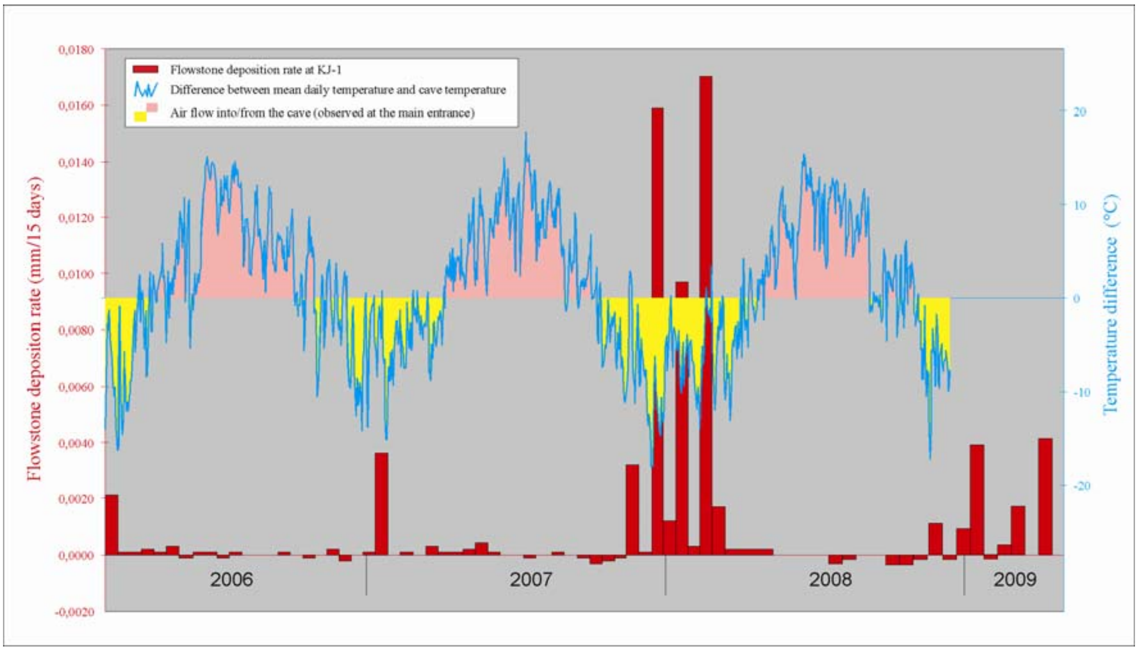


Figure 4.1.1.5: *Difference between average daily outside temperature measured at meteorological station Nova vas na Blokah*[1] *and cave temperature (~8 °C), wind direction and corrosion or flowstone deposition rates between 14*th *February 2006 and 5*th *April 2009.*

Observations at several springs (PITTY, 1968 after WHITE, 2006; SHUSTER & WHITE, 1971 after WHITE, 2006, 145) showed two types of fluctuations regarding to hardness, SI_{Ca} and CO_2 concentration in water:

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

Similar variations in flowstone deposition/corrosion rates were observed in Križna jama (Fig. 4.1.1.1), but the reason here seems to depend on ventilation rather than discharge. Flowstone deposition rates higher than 0.0005 mm/15 days are related to exceptionally

[1] Meteorological station Nova vas na Blokah lies at Bloška planota, only 4.5 km northeastern from Križna jama. With its similar environment it reflects very similar climatic conditions as the entrance to Križna jama. Temperatures above passages of Križna jama can have slightly higher average daily temperatures due to absence of temperature inversion.

intensive ventilation of the cave, which occurs several days per winter. If we exclude such events from analysis, seasonal pattern can be seen especially in the years 2007 and 2008 (Fig. 4.1.1.6). Seasonally, flowstone deposition is more or less related to winter and spring months with peak in early spring, while lower flowstone deposition or even corrosion rates are related to summer and autumn months. Seasonal fluctuation can be related to general seasonal fluctuation of CO_2 in the cave air (or in the karst massif; Fig. 4.1.1.4), while the unseasonal variation can be ascribed to exceptionally low cave air CO_2 concentration, long-lasting very high discharges or error of measurement.

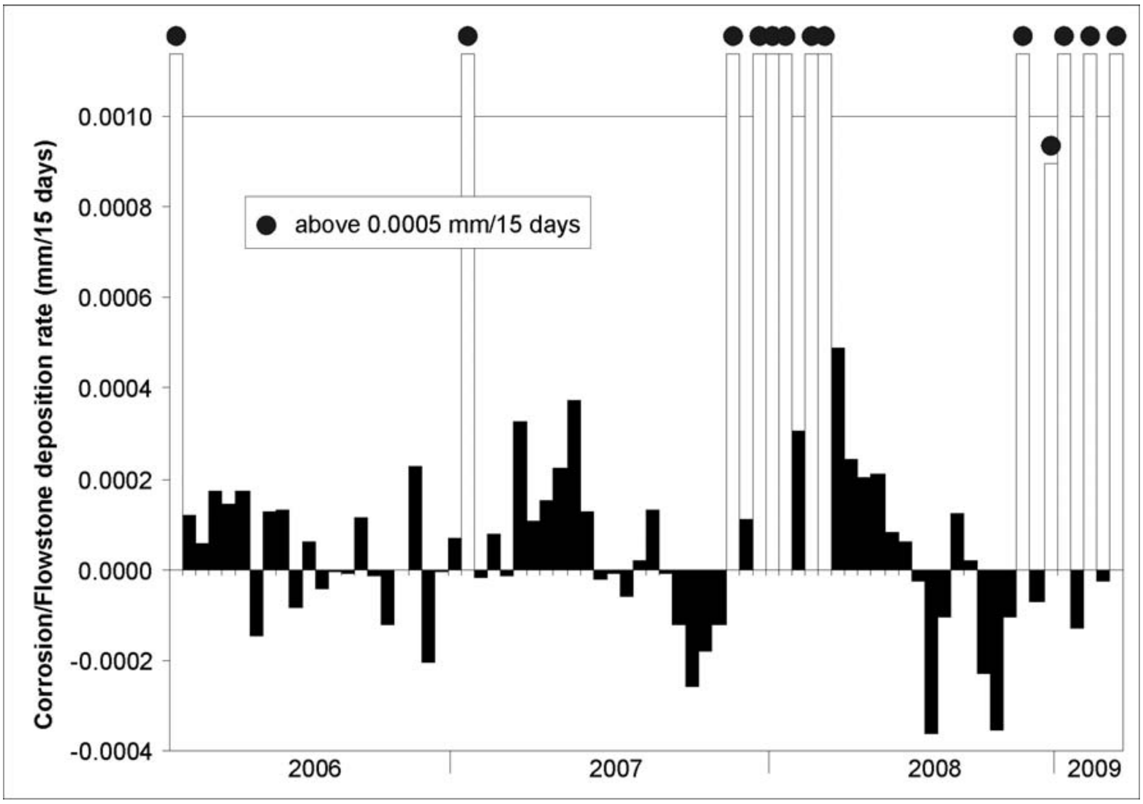


Figure 4.1.1.6: *Seasonally dependent flowstone deposition and corrosion rates at KJ-1.*

Gospodarič (1974, 332), Gospodarič & Habič (1979, 59) and Slabe (1989, 91; 1992, 217) state that corrosion takes place in Križna jama at high water levels, when scallops are formed. At high water level also erosion should take place (GOSPODARIČ, 1974, 332), since some potholes are developed the in present-day water channel. Such statements are based exclusively on study of morphology of the active part 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 point KJ-1 although the limestone tablet was placed in the middle of the water flow and high water definitely transports up to 2 mm diameter particles. Corrosion rates are also surprisingly low. The highest corrosion rate (-0.0004 mm/15 days; 4th–19th October 2007 and 17th October 2008-5th November 2008) was detected out of very high water levels. We should also stress that the highest corrosion rates were detected in autumn time. Even when water level was very high (30th May 2006; $H_{1st\ lake}$ = +120 cm) corrosion rate was very small, which corresponds to slightly negative calcite saturation index (SI_{Ca} = -0.1). When big and long-lasting floods occurred at Bloška planota (between 2nd and 15th April 2008) and water level in Križna jama did not fall below $H_{1st\ lake}$ = +20 cm for 13 days, we detected flowstone deposition (+0.0008 mm in 30 days) instead of corrosion. All these data show that corrosion rates are extremely low in Križna jama and always very close to the average error of methodology (±0.0002 mm).

Since the corrosion rates are so low in Križna jama, even the smallest 3 mm deep scallops could be hardly formed even in 12,000 years. Since scalloped walls of 1st lake do not correspond to present-day slow-flowing water (even at high water level, water flow is too slow for formation of 3 cm long scallops), such corrosional features seem to be relict forms inherited from the past. Decantation flutings, which can be observed under the water level several tens of meters upstream of Brzice, are nowadays always under the water level and covered with flowstone coating. Location (under the water level) and flowstone coating on them are proofs that they are not developing with present-day processes and that they have to be relict. Factors, which would cause higher corrosion rates, are connected with ventilation (reduced winter ventilation) or with hydrology (lower total hardness). Closure or opening of entrances occurs probably quite often (BRODAR, 1949; BRODAR, 1966; BRODAR, 1970; SPÖTL ET AL., 2005, 2467) and would lead to weaker ventilation, higher CO_2 concentration in the massif and higher corrosion rates – most probably in autumn time. 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 was replaced by grassland with clumps of trees (ŠERCELJ, 1974) due to lower temperatures. Corrosion rates could be higher also with more intense precipitation, which result in flood flush events.

Nowadays the prevailing process at Brzice is flowstone deposition. According to Mihevc (1997), flowstone deposition rate amount 0.1 mm/a. Our value is 4.6 times lower (0.0217 mm/a), which can be result of difference between methodologies (see Fig. 2.1.3.13 in Chapter 2.1.3) of a result of warmer winters 2006/2007 (and 2008/2009). In 12,000 years, flowstone deposition rate observed by Mihevc (1997) would be result in 1.2 m high rimstone dam. Such height roughly corresponds to actual estimated height of rimstone dam. According to our values, which are less reliable in this case, a 0.26 m high rimstone dam would develop. If we take into account that rimstone dam is 1.2 m high, our results show higher flowstone deposition rates in the past or longer period of development.

4.1.2 Measurement place KJ-2 – temporal and spatial variability of processes in the 1st lake

In truth we could hardly detect corrosion at measurement point KJ-1 if a period of high water level is followed by low water level or vice versa within 15 days. If corrosion rates are very small, even low flowstone deposition rates would nullify corrosion because limestone tablet at KJ-1 was exposed to low and high water level. Therefore we started to measure in the 1st lake with a vertical set of limestone tablets. Such type of measurement also gives us corrosion or flowstone deposition rates according to depth and makes possible comparison between measurement points KJ-1 and KJ-2 (Chapter 4.1.3).

Measurements at KJ-2 (at the water gauge in the 1st lake; Fig. 4.1.5) started on 17th June 2006 and finished on 5th April 2009. Vertical set of 21 limestone tablets was installed 360 m from the entrance on water gauge. Limestone tablets were interspaced for 5 cm between -37.5 and +47.5 cm. Between 47.5 and 92.5 cm vertical distance between limestone tablets was longer. Water flow was much slower in comparison with KJ-1 since the discharge is equal but cross-sectional area is much bigger. Under $H_{1st\ lake}$ = +20 cm water flow can be defined as low turbulent and subcritical. During higher discharges water flow was more turbulent but not supercritical. We used 2 groups of 21 limestone tablets – one was exposed at measurement point and the second one was at the same time dried in chemical laboratory at Karst Research Institute ZRC SAZU. Limestone tablets were fixed on plastic water gauge with brass screws, nuts and washers and exchanged after 15 days of drying/exposure. We observed no corrosional damage under brass screws and washers.

According to the morphology of the passage we should expect flowstone deposition below $H_{1st\ lake} = 0$ cm and slight corrosion above this limit. Below $H_{1st\ lake} = 0$ cm we should expect two contrary processes (corrosion and flowstone deposition) with prevailing flowstone deposition. Such net deposition was already supposed by Slabe (1992, 91). Above $H_{1st\ lake} = 0$ cm we should expect only corrosion. Results represented on Fig. 4.1.2.1 partly confirm this presumption.

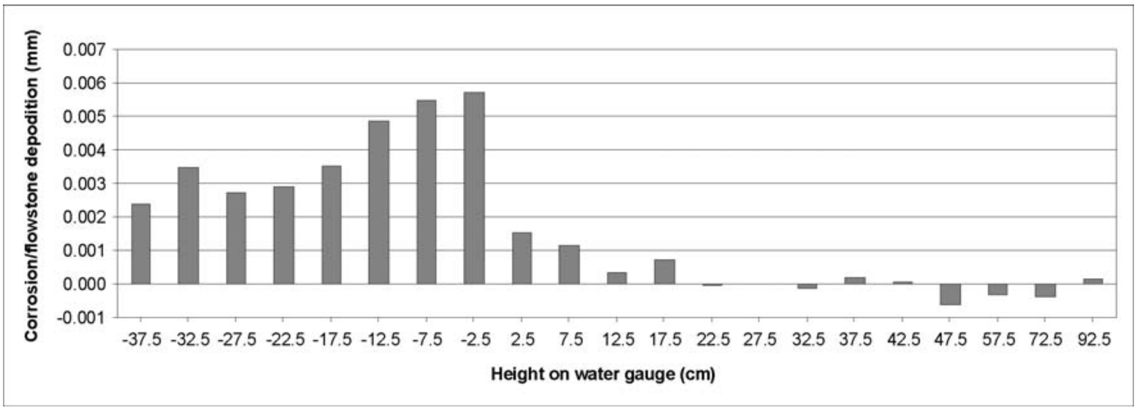


Figure 4.1.2.1: *Corrosion and flowstone deposition at KJ-2 between 17th June 2006 and 5th April 2009. Results represent sum of 15-days values.*

Results can be summarized in 3 vertical zones: 1 – zone of gradual lowering of flowstone deposition rates downward (below $H_{1st\ lake} = 0$ cm), 2 – zone of gradual lowering of flowstone deposition rates upward (between $H_{1st\ lake} = 0$ cm and $H_{1st\ lake} = +20$ cm) and 3 – zone without changes or with slight corrosion (above $H_{1st\ lake} = +20$ cm).

Flowstone deposition in zone 1 takes place at the same time as at measurement point KJ-1, this is within few days in winter when the passage is well ventilated (Fig. 4.1.3.1). Since the outgassing of CO_2 occurs at the water level, we observe the highest flowstone deposition rates at height, where the water level was during the days of high flowstone deposition rates. Below water level, concentration of CO_2 gradually increases and this results in lower flowstone deposition rates. At $H_{1st\ lake} = -37.5$ cm flowstone deposition rate drops to only half of that one at $H_{1st\ lake} = -2.5$ cm. This type of flowstone deposition is reflected on cave walls as up to 3 cm thick subaqueous deposited flowstone coating.

Surprisingly, flowstone deposition was observed also in zone 2. Flowstone deposition 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 KJ-1 and limestone tablets at $H_{1st\ lake} = +2.5$ cm amounts 0.19 and decreases with height). In zone 2 flowstone deposition takes place exclusively in late autumn, winter and spring months (November-April) in periods of higher water levels (up to $H_{1st\ lake} = +20$ cm). Quite low flowstone deposition rates result in thin layer of flowstone coating, which can be visible on cave walls just in the lowest section. Higher, thickness is too small for observation with the naked eye.

Zone 3 indicates almost equal values before and after exposure and therefore no or very weak corrosion. Average of all results in zone 3 from 17th June 2006 to 5th April 2009 is -0.0002 mm. Since the values are very small, results are quite uncertain. Nevertheless, absence of any chemical process between $H_{1st\ lake} = +20$ cm and $H_{1st\ lake} = +45$ cm with increase of corrosion to $H_{1st\ lake} = +55$ cm and decrease of corrosion above $H_{1st\ lake} = +55$ cm can be logical. Increase of corrosion rates in the lower portion of zone 3 is expected, due to smaller and smaller flowstone deposition rates. Upward, corrosion rates have to be smaller due to lower time of exposure. Although, vertically quite dispersed values of corrosion rates can be random. Very weak corrosion rates in the zone 3 (on average -0.0002 mm/a) points out that scalloped wall of 1st lake could correspond to present-day processes but it would need more than 12,000 years of measured corrosion rates. Nevertheless, about 3 cm long scallops on the wall indicate faster water flow that is characteristic for present-day situation; therefore, length of scallops is unbalanced with present-day hydrodynamic conditions and corresponds to higher discharges or smaller cross-sections of passages. The latter explanation is possible since we know that Križna jama was intensively filled with allochtonous material, which was later washed away (GOSPODARIČ, 1974).

4.1.3 Comparison of measurement points KJ-1 and KJ-2 – micro-local changes in flowstone deposition rates

Comparison between measurement points KJ-1 and KJ-2 shows some differences in flowstone deposition rates which are result of almost the same physicochemical properties of water but different velocity of water flow and closely linked degassing of CO_2 from the water. Such difference in calcite deposition rates produces 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 due to changes in flowstone deposition rates between measurement points KJ-1 and KJ-2 represented in Fig. 4.1.3.1.

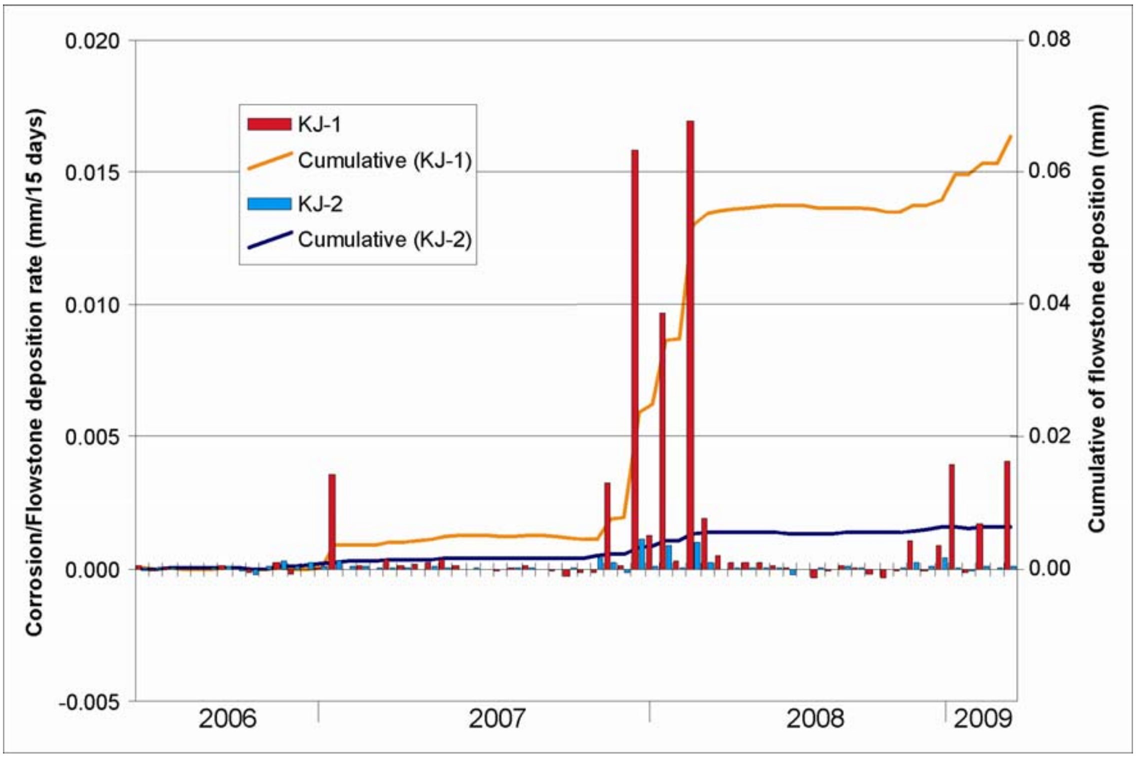


Figure 4.1.3.1: *Corrosion/Flowstone deposition rates and cumulative of deposition at measurement points KJ-1 and KJ-2 between 17th June 2006 and 5th April 2009.*

If we take into account just very low flowstone deposition rates (below 0.0002 mm/15 days) we notice that flowstone deposition rates at KJ-1 and KJ-2 are equal or even KJ-2 slightly prevails. Differences appear only at higher flowstone deposition rates. At that time flowstone deposition rate is most probably controlled by flux of CO_2 from water, thickness of diffusion layer at the contact rock-water (LIU, 1996; DREYBRODT, 2004, 187) and also degree of water circulation between contacts air-water and rock-water (ROQUES, 1969, 158). Differences are the bigger the higher flowstone deposition rates are observed at KJ-1 which is the best seen in Fig. 4.1.3.2. 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.

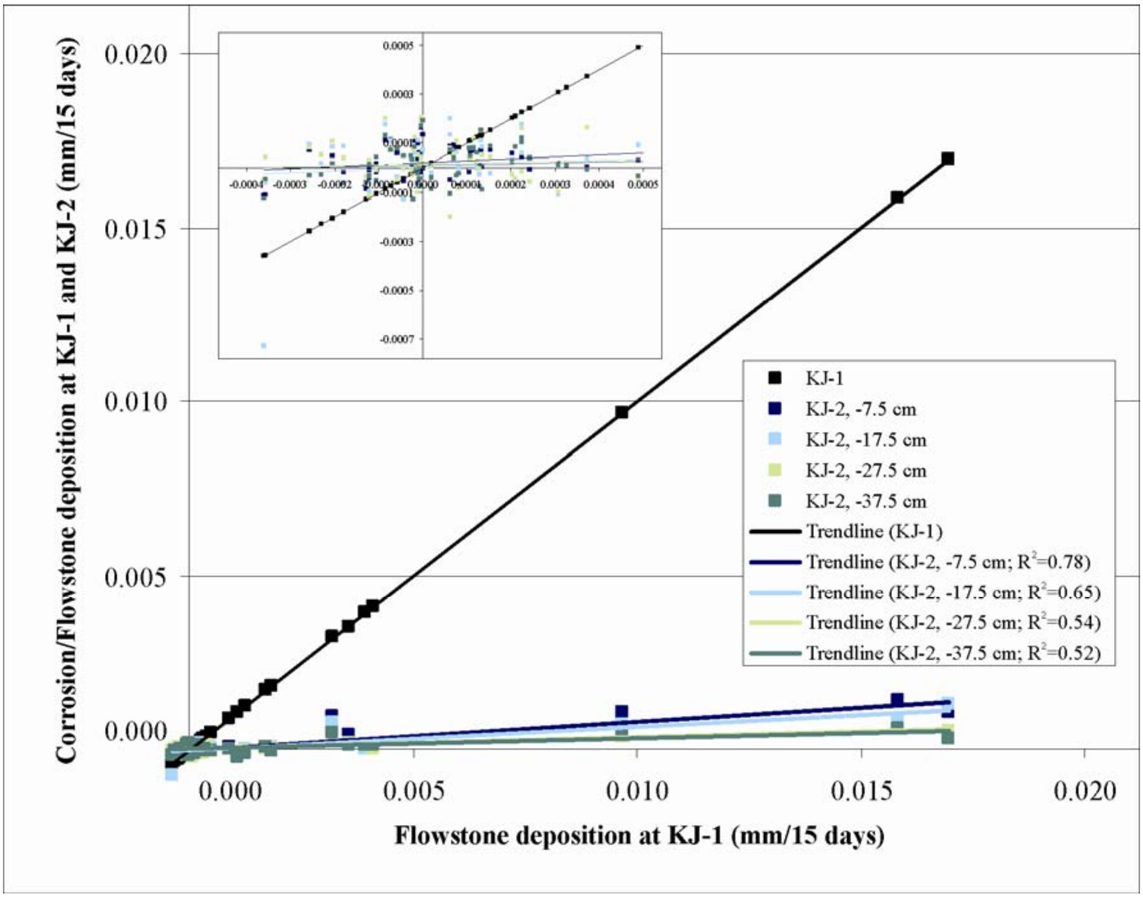


Figure 4.1.3.2: *Relation between flowstone deposition rates at KJ-1 and flowstone deposition rates at four depths at KJ-2 for period from 17th June 2006 to 5th April 2009. Small plot represents corrosion and flowstone deposition rates below 0.0002 mm/15 days.*

Table 4.1.3.1: *Portion of deposited flowstone at different depths at KJ-2 in comparison with KJ-1 based on data between 17th June 2006 and 3rd May 2008.*

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

Tab. 4.1.3.1 shows portions of flowstone deposited at different depths at KJ-2 in comparison with KJ-1. Difference in flowstone deposition rate between KJ-1 and KJ-2

at depth $H_{1st\ lake}$ = -7.5 cm is evident – only 10.0 % of flowstone is deposited at the latter depth in comparison with KJ-1. Downward, the flowstone deposition rates are even smaller – at depth $H_{1st\ lake}$ = -37.5 cm only 4.3 % of flowstone is deposited). For all data high Pearson product moment correlation coefficient is characteristic but it falls with depth. The latter phenomenon is a result of higher measurement errors, which increase with smaller values.
Regarding to values presented in Tab. 4.1.3.1, we can describe decreasing flowstone deposition rates with Eq. 4.1.3.1.

$$\Delta d_{(-37.5--2.5cm)} = \Delta D \times 0.1168 \times e^{0.0283 \times H}$$ ***(Equation 4.1.3.1)***,

where $\Delta d_{(-37.5—2.5\ cm)}$ is the amount of flowstone deposited in depth between $H_{1st\ lake}$ = -37.5 cm and $H_{1st\ lake}$ = -2.5 cm at measurement point KJ-2, ΔD is amount of flowstone deposited at KJ-1 and H is depth at measurement point KJ-2.

Between $H_{1st\ lake}$ = -2.5 cm and $H_{1st\ lake}$ = +20 cm flowstone deposition rates decreases with Eq. 4.1.3.2. Pearson product moment correlation coefficient for these data is relatively high (-0.79).

$$\Delta d_{(-2.5-20cm)} = \Delta D \times (-0.0013 \times H + 0.0277)$$ **(Equation 4.1.3.2)**,

where $\Delta d_{(-2.5—20\ cm)}$ is the amount of flowstone deposited in depth between $H_{1st\ lake}$ = -2.5 cm and $H_{1st\ lake}$ = +20 cm at measurement point KJ-2, ΔD is amount of flowstone deposited at KJ-1 and H is depth at measurement point KJ-2.

Regarding to Eq. 4.1.3.1, Eq. 4.1.3.2 and average deposition rate 0.1 mm/a near KJ-1 (MIHEVC, 1997), we can extrapolate flowstone deposition with some cautiousness to the last 12,000 years. If flowstone deposition rates were similar in this period to present-day values, rimstone dams would be 120 cm high and the thickest flowstone coating at the wall of 1st lake would be about 3.2 cm thick (Fig. 4.1.3.3). Comparison with real values is difficult due to absence of cuts in rimstone dams and very heterogeneous thickness of flowstone coating even at the same depth. Thickness of coating is also under the influence of loam, which is deposited at some places and therefore incorporated into the flowstone matrix (especially at walls with lower inclination). In spite of these reasons results show that flowstone coating with small amount of loam very rarely exceeds 3.5 cm, which is in very good correlation with predicted values. Since the actual thickness of flowstone coating is in so good agreement with calculated value for 12,000 years we can suppose that present-day flowstone deposition rates roughly correspond to Holocene epoch, at least in 1st lake. Nevertheless, thickness of flowstone cover above $H_{1st\ lake}$ = 0 cm does not correspond to present-day morphology (flowstone coating is several millimeters thick and not ~1 cm), which can be a result of lower flowstone deposition rates at KJ-1 or higher flowstone deposition rates above $H_{1st\ lake}$ = 0 cm in the last thousands years. At least during the last (Würmian) glaciation, the flowstone deposition rates at KJ-1 and KJ-2 has to be much smaller or even turned to corrosion otherwise flowstone coating would be much thicker and rimstone dams higher.

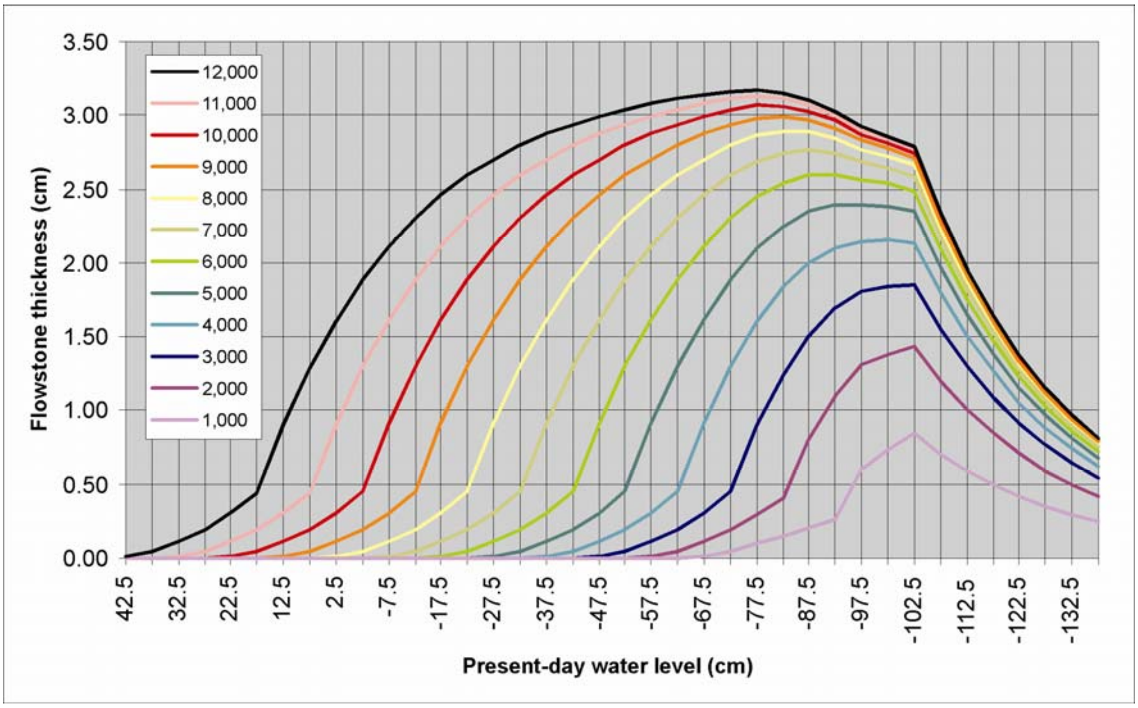


Figure 4.1.3.3: *Extrapolated flowstone coating growth regarding to Eq. 4.1.3.1, Eq. 4.1.3.2 and flowstone deposition rate 0.1 mm/a near measurement point KJ-1 (MIHEVC, 1997) for the last 12,000 years.*

4.1.4 Measurement points KJ-3, KJ-4 and KJ-5 – spatial variability of processes between Kalvarija and Ponor

Water course between Kalvarija and Ponor is characterized by 13 lakes, which have been formed behind rimstone dams. Position of rimstone dams indicates that they started to grow at places with highly turbulent water flow, such as inclined passage floors and breakdowns. Such places act partially as barriers where the water flow is thinned and higher flowstone deposition rates are characteristic. Observations show that the number of rimstone dams was higher in the past and that some of them were later flooded with higher growth of lower rimstone dams (Fig. 4.1.4.6). With measurements at different places between Ponor and Kalvarija we observed spatial dynamics of flowstone deposition rates and try to recognize basic processes and factors which led to present-day morphology.

Length of water passage between Kalvarija and Ponor is 1,150 m. At Kalvarija two streams from Pisani rov and Blata passage join and flow uniformly toward Ponor. Along the water courses measurements of SEC, T and pH show no important tributary at low and middle water levels. At high water level tributary from V-rov (=V-passage) becomes important and could influence processes below 1st lake. Leakage of water between Kalvarija and Ponor is low and can be observed at least at low and middle water levels in 13th lake (few l/s) and at very low water levels from 1st lake. Therefore water quantity remains almost the same.

Geomorphic processes between Kalvarija and Ponor were measured with micrometer, limestone tablets and measurements of physicochemical properties of water.

Micrometer measurements were taken at 3 places below 1st lake already set by Mihevc on 30th November 1994. At each place we can get 3 values. On 20th November 2006 we extended measurements to 3 upstream places, where we can get 6 values per measurement place. All places are lying on rimstone dams with similar water flow. Nonetheless, hydraulic conditions are slightly different – at measurement place between 7th and 8th lake, rimstone dam is partly flooded. Therefore we can expect much lower flowstone deposition rates due to slow and low turbulent water flow.

Measurements with limestone tablets started on 16th August 2006 at KJ-4 and KJ-5. Later, on 13th January 2007, they were extended also to KJ-3, which lies 4 m beside KJ-1. Due to difficulties with fixing and environmental limitations they were fixed in much more heterogeneous hydraulic conditions as places for micrometer measurements. Nonetheless, all were fixed in similar water depth. Due to development of iron oxide on iron screw at KJ-4 and KJ-5 which caused corrosion (Chapter 2.1.3), we started with contemporary measurements with limestone tablets fixed on stainless steel parts several centimetres

beside older measurement points on 18th December 2007. At measurement point KJ-3 we used stainless steal screw, washers and nut from beginning of measurements. Limestone tablets were changed after 30 days of exposure like the limestone tablets at KJ-1 or KJ-2.
Spatial measurements of physicochemical properties of water (SEC, T and pH) were done with WTW Multiline P4 at different hydrological and climatic conditions between 15th October 2006 and 8th January 2009 (Appendix II).

Rates and spatial distribution of processes are best seen in Fig. 4.1.4.1 and in Fig. 4.1.4.2, which represents results of measurements taken with micrometer. It is clear that flowstone deposition rates decrease from Ponor toward Kalvarija despite slightly different hydraulic conditions. Only at measurement point between 7th and 8th lake, flowstone deposition rate is significantly lower. Decrease in flowstone deposition rates is characteristic for winters 2006/2007 and 2007/2008. Pearson product moment correlation coefficient between flowstone deposition rate and distance from the entrance is significantly high even if we take into account measurement between 7th and 8th lake, 0.92. Without measurement between 7th and 8th lake, Pearson product moment correlation coefficient is very close to perfect correlation (-0.96). In general, flowstone deposition rate decreases after equation B represented in Fig. 4.1.4.2. This means that between 9th and 10th lake only 54 % of flowstone is deposited in comparison with measurement points at Brzice.

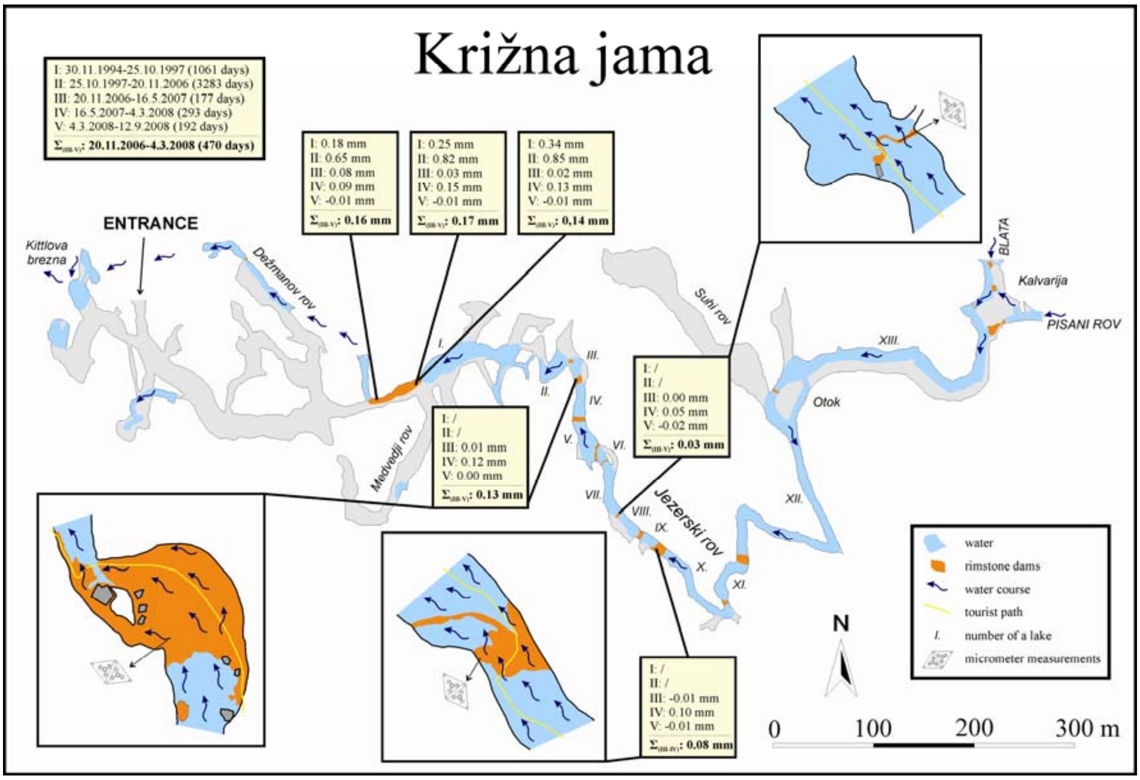


Figure 4.1.4.1: *Locations and results of micrometer measurements between Kalvarija and Ponor from 30th November 1994 to 12th September 2008 (data from 1994-1997 were measured by* M*IHEVC, 1997).*

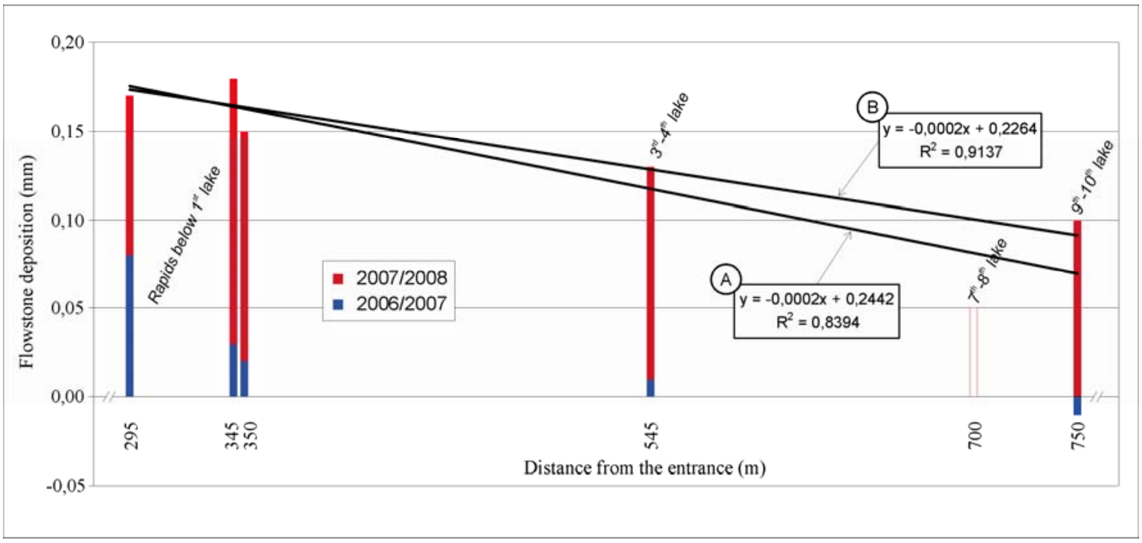


Figure 4.1.4.2: *Decrease in flowstone deposition rates from Ponor toward Kalvarija. In equation A, we take into account also flowstone deposition at rimstone dam between 7th and 8th lake, in equation B these values are excluded.*

Another very obvious phenomenon is connection between flowstone deposition rates and winter ventilation already known from measurement point KJ-1 at Brzice (Chapter 4.1.1). Since the winter 2006/2007 was significantly warmer than winter 2007/2008, a much thicker flowstone layer was deposited in winter 2007/2008 at the majority of measurement places. In Fig. 4.1.4.2 we can see that differences are the largest the higher is a distance from the entrance. In winter 2006/2007 Križna jama was so poorly ventilated that flowstone deposition between 3rd and 4th lake was slightly above 0.00 mm but at rimstone dam between 9th and 10th lake we detected even slight corrosion (-0.01 mm). Such slightly negative values are the most characteristic for summer and autumn months.

Measurements with limestone tablets should be taken cautiously because of much more heterogeneous hydraulic conditions between measurement points than between places for micrometer measurements. Furthermore, from 16th August 2006 to 18th December 2007 rusting of iron parts at KJ-4 and KJ-5 usually turned low flowstone deposition rates to misleading corrosion rates. In spite of these problems, results acquired at KJ-3, KJ-4 and KJ-5 show similar temporal variations in flowstone deposition (and corrosion) rates (Fig. 4.1.4.3). Peaks of flowstone deposition rates occur in winter time during strong ventilation of the cave at all places. If we take into account limestone tablets fixed on stainless steel screws, Pearson product moment correlation coefficients are higher than 0.96 between KJ-3 and KJ-4 or KJ-3 and KJ-5. At low flowstone deposition rates, differences between measurement points are minimal - we can observe even enlargement of flowstone deposition rates from Ponor toward Kalvarija. The biggest differences occur at high flowstone deposition rates, when by far the highest flowstone deposition rates are observed at KJ-3. Toward Kalvarija, flowstone deposition rate strongly decreases. At KJ-4 it falls to 12.6 % and at KJ-5 it falls to 7.1 % of that one deposited at KJ-3. This decrease is much higher than that one observed with micrometer measurements due to much faster water flow at KJ-3 in comparison with KJ-4 and KJ-5.

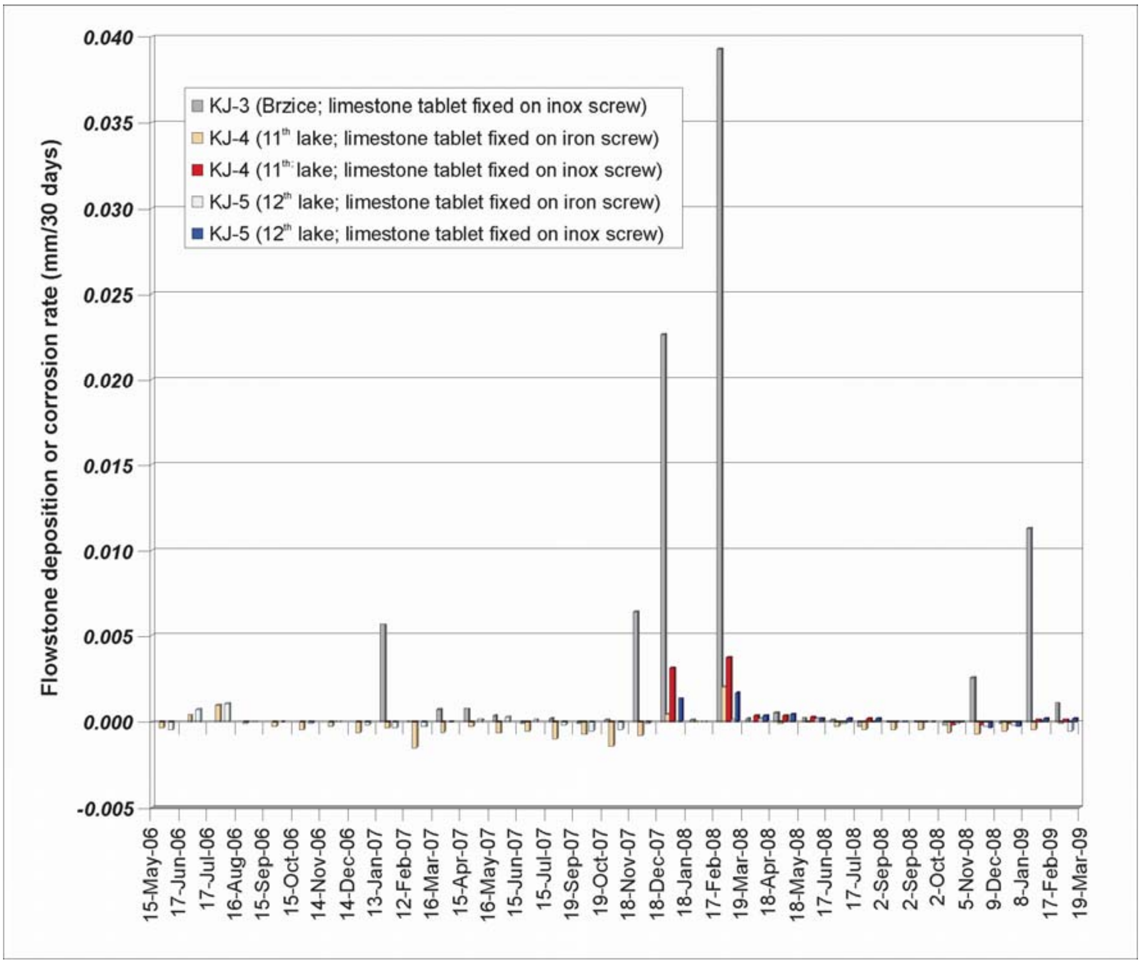


Figure 4.1.4.3: *Comparison of flowstone deposition and corrosion rates between KJ-3, KJ-4 and KJ-5 from 13th January 2007 to 19th March 2009. After 18th December 2007 we plotted also values measured with limestone tablets fixed on stainless steel (inox) screws.*

Physicochemical processes in water between Ponor and Kalvarija can be studied also with spatial measurements of SEC and pH. Such measurements are reliable especially in this case where we have no tributaries which could change water chemistry and complicate interpretation. Therefore we are sure that any change in water body is caused by physicochemical processes along water course. Fig. 4.1.4.4 shows such changes in pH value. It is evident that pH is growing from Kalvarija toward Ponor. The highest change (+0.31 pH value) was observed on 18th July 2008 when the water level was low ($H_{1st\ lake}$ = -5 cm). Growth of pH indicates reduction of H^+ concentration along water course which can be, regarding to theoretical knowledge (DREYBRODT, 1988), caused by dissolution of limestone or outgassing of CO_2 from the water. Dissolution is less probable since it was rarely detected with limestone tablets and never with spatial measurements of SEC (SEC usually falls from Kalvarija toward Ponor (Tab. 4.1.4.1 and Appendix II), which points out on flowstone deposition and related decrease of pH). Therefore growth of pH value can be related only to outgassing of CO_2. It is somehow surprising that growth of pH occurs in summer and winter months or at low and middle discharge. This means that CO_2 concentration in water always surpasses the one in the air and that water at low and middle discharges never absorbs CO_2 from the cave air. Downstream growth of pH along water course and relatively low changes of SEC (see Appendix II) lead to higher SI_{Ca} and therefore to higher flowstone deposition rates in downstream direction. This explains why we detected higher flowstone deposition rates at Ponor and lower near Kalvarija. It also shows that SI_{Ca} at KJ-1 does not depend just on outgassing of CO_2 near measurement point but throughout the water course from Kalvarija to Ponor or even higher upstream – in Pisani rov and Blata passage.

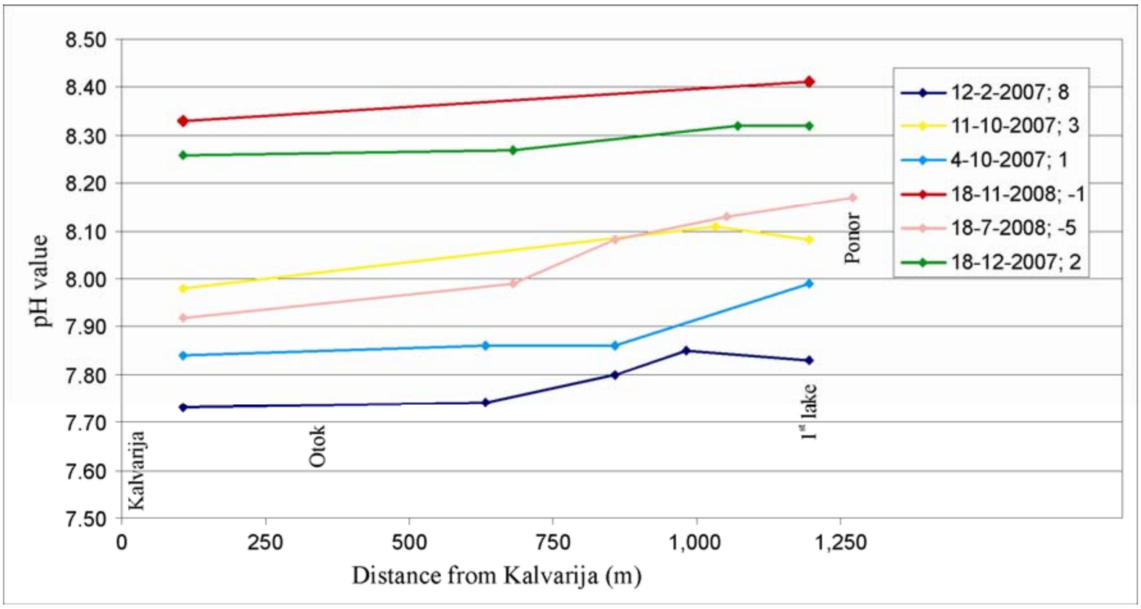


Figure 4.1.4.4: *Growth of pH between Kalvarija and Ponor at different water levels (marked after date in centimetres).*

Rate of outgassing depends on difference in CO_2 concentration between air and water, surface of contact air-water and mixing of water. Lower CO_2 concentration near the cave's entrances and higher CO_2 concentration in the karst massifs were confirmed also with measurements (BALDINI ET AL., 2006; EK & GEWELT, 1985 po BALDINI ET AL., 2006; PALMER, 2007). In the cave air, CO_2 concentration can be up to 10 times higher in comparison with that one in atmospheric air (PALMER, 2007). This would also mean that the rate of outgassing of CO_2 decreases from an entrance to inner parts of a cave. Since we observe decreasing flowstone deposition rates from Ponor toward Kalvarija (which is connected with more outgassed water with respect to CO_2 near the Ponor) we should suppose that different flowstone deposition rates are also a result of different rate of outgassing.

CO_2 concentration was measured periodically with Vasiala Hand-Held Carbon Dioxide Meter GM70 at several places between Ponor and Kalvarija from 24th April 2008 to 8th January 2009. We found out that spatial CO_2 concentration trend corresponds to ventilation of Križna jama. In summer we detected slightly increasing concentration of CO_2 from Kalvarija toward Ponor due to arrival of atmospheric air at the upstream end of Pisani rov (and, in smaller quantity, through Blata passage). This air exits Križna jama at the entrance and is enriched with CO_2 through the cave. Nevertheless, summer changes of CO_2 concentrations are quite small – from 1,470 ppm at Kalvarija to 1,520 ppm at Ponor. Change of longitudinal trend of CO_2 concentration is relatively fast in the autumn and occurs within a few days. At the beginning CO_2 concentration falls to atmospheric value near the entrance. Since the concentration at Kalvarija remains for a while equal to concentration in summer time, changes of CO_2 concentration from 380 ppm near the entrance to about 1,500 ppm near Kalvarija are common. Later, CO_2 concentration starts to fall also at Kalvarija and almost fall to atmospheric concentration (~440 ppm). So low concentration is not typical just for winter time but can happen also at the beginning of autumn and can last several days (such situation occurred from 26th to 28th September 2008). Such spatially equal CO_2 concentrations should result in very similar outgassing from Kalvarija toward Ponor. Surprisingly, even at so low concentration we did not detect any flowstone deposition at KJ-3, KJ-4 or KJ-5 and therefore no differences in flowstone deposition rates. Flowstone deposition was recorded at even stronger ventilation in winter time, presumably due to decrease of CO_2 concentration upstream of ending breakdown in Pisani rov. At that time, we can observe formation of floating rafts in Jezerski rov, which are composed manly of calcite (Fig. 4.1.4.5). Consequently, we can conclude that spatial changes in CO_2 concentration between Ponor and Kalvarija probably have influence to rate of outgassing but have no significant influence in decreasing flowstone deposition rates from Ponor toward

Kalvarija. Changes in flowstone deposition rates occur because of length (time of outgassing), which grows from Kalvarija toward Ponor.

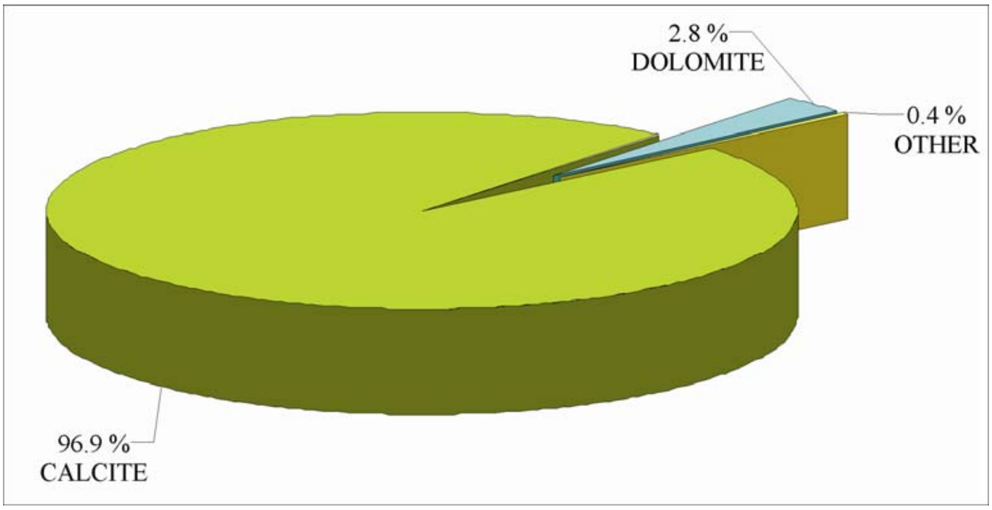


Figure 4.1.4.5: *Chemical composition of rafts formed in the 2nd lake in Križna jama.*

Measurements of SEC make possible also some calculation of flowstone, which is deposited along water course. Total hardness of water at Kalvarija and at Ponor can be calculated with Eq. 4.1.4.1, which relatively well relates SEC and total hardness in mg/L (KRAWCZYK & FORD, 2006 after FORD & WILLIAMS, 2007, 63).

$$TH = \frac{SEC - 31.5}{1.86} \qquad \textbf{(\textit{Equation 4.1.4.1})},$$

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

The amount of water flowing between Kalvarija and Ponor was calculated using a stage-discharge curve presented in Fig. 4.1.6. Cross-sectional area of water flow was calculated using estimated width of passage (~7 m) and average depth of water measured at 127 locations between 1st lake and Otok (PLANINA, 1985) with Eq. 4.1.4.2.

$$A = \frac{\pi \times W \times D}{2} \qquad \textbf{(\textit{Equation 4.1.4.2})},$$

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

If we take into account also length of passage between Kalvarija and Ponor, thickness of the flowstone layer can be calculated with Eq. 4.1.4.3.

$$\Delta d = \frac{\left(\frac{SEC_{Kalvarija} - 31{,}5}{1{,}86} - \frac{SEC_{Ponor} - 31{,}5}{1{,}86}\right) \times 1{,}000 \times Q \times t}{A}$$ **(Equation 4.1.4.3)**,

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

Results represented in Tab. 4.1.4.1 are calculations for 30 days, the time used for measurements with limestone tablets. It is clear that the most extensive flowstone deposition take place at high discharges. Lower values are observed at low discharges or at higher SEC at Kalvarija. Although quantity of deposited flowstone at discharge of 140 l/s amounts 1,951 kg, the surface of the passage is so big (29,080 m^2) that average thickness of flowstone amounts to only 2.5×10^{-5} mm. So thin a layer cannot be measured with limestone tablets. Even if we take into consideration about ten times higher flowstone deposition rates at rimstone dams, thickness of the flowstone layer is usually within error of measurement. Very thin flowstone deposition rates are proved also with measurements with limestone tablets – for all periods calculated in Tab. 4.1.4.1 we observed flowstone deposition rates less than 0.0001 mm/15 days.

Table 4.1.4.1: *Amount of deposited calcite (Δm), average thickness of deposited flowstone layer (Δd) and average weight change of average limestone tablet (Δm) regarding to discharge and spatial SEC measurements between Kalvarija and Ponor.*

	Discharge (l/s)	**$SEC_{Kalvarija}$**	**SEC_{Ponor}**	**ΔSEC (µS/cm)**	**Δm (kg)**	**Δ d (mm)**	**Δm (g; 3.000 mm^2)**
12th February 2007	140	456	446	10	1951	0.000025	0.00020
15th October 2006	9	461	452	9	113	0.000001	0.00001
11th October 2007	72	476	459	17	1706	0.000022	0.00018
18th July 2008	4	462	457	5	28	0.000000	0.00000

Increase of flowstone deposition rates from Kalvarija toward Ponor has clear morphological evidence in this part of Križna jama. Change is best seen in thickness of flowstone coatings in lakes – it increases from less than 1 mm at Kalvarija to about 3 cm in the 1st lake. Similar changes downstream of confluences were noticed also in Pisani rov and Blata passage.

The second consequence is decreasing length of lakes from Kalvarija toward Ponor due to increased growth rate of rimstone dams from Kalvarija toward Ponor. Initiation of rimstone dam growth is definitely related to micro-location factors (for example inclined parts of passages with open surface flow, position of breakdowns which partly block the water passage; Chapter 4.1.3) but further growth is controlled with distance from Kalvarija. Since the growth of rimstone dams near Ponor is the most favoured, lower lakes progressively flood upper rimstone dams. At such places flowstone deposition rate progressively turns from the one at the rimstone dam (Chapter 4.1.1) toward the one in the lakes (Chapter 4.1.2). This phenomenon can be observed at many places above the 3rd lake and was measured with micrometer also at rimstone dam between 7th and 8th lake. Even more widespread are places with flooded flowstone-covered floors, which indicate past rimstone dams and are now due to their softness partly eroded by corrasion (Fig. 4.1.4.6). As a consequence, at least 12 rimstone dams and lakes behind them already disappeared in the past between Kalvarija and Ponor.

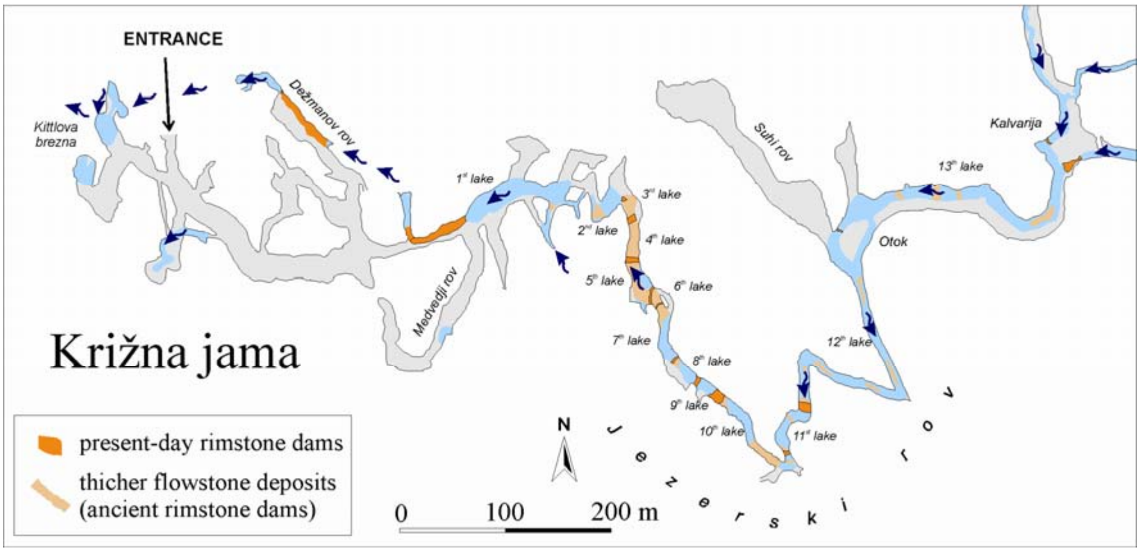


Figure 4.1.4.6: *Active and ancient rimstone dams between Kalvarija and Ponor.*

Growth of rimstone dams decreases ventilation of Križna jama because of reduction of cross-sectional profile above lakes. This phenomenon forms a negative feedback loop. It is especially the case above the 2nd 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. We can expect that flowstone deposition rates will decrease and will be rarer in future even without climatic changes (i.e. warmer winters). Growth rate of water level due to growth of rimstone dams will decrease exponentially. As a result, middle water level will never reach the cave ceiling.

4.1.5 Measurement points KJ-5, KJ-6 and KJ-7 – confluence of stream from Pisani rov and stream from Blata passage at Kalvarija

Kalvarija is a place of confluence of two underground streams. One comes from Blata passage and is characterized by water flow in a muddy channel formed in 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 months in comparison with Blata passage.

Discharge ratio between two streams varies in time and amounts from 1:4.3 to 1:0.69. Portion of discharge from Blata passage is usually higher at higher water level. Physicochemical properties of water differ slightly with respect to measured T, SEC, pH and Ca^{2+}/Mg^{2+} ratio. Temperature in Pisani rov is quite stable at 8.4 ± 0.1 °C at low-middle water level through all the year (Fig. 4.1.5.1). At very high water level, overflow of waters from Bloška planota (combined Bloščica and Farovščica streams) can be identified (in winter with substantially lower temperature). In Blata passage, 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.

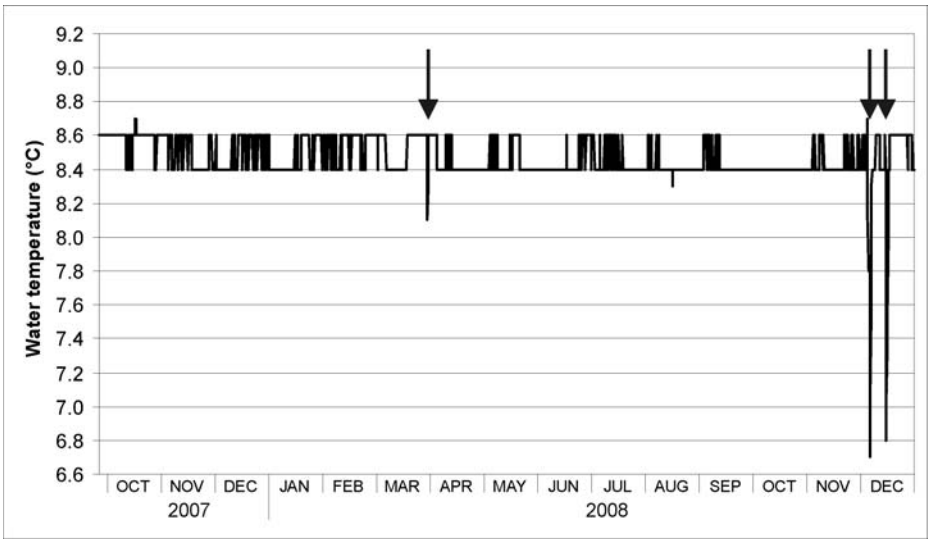


Figure 4.1.5.1: *Water temperature in Pisani rov near Kristalna gora (data courtesy of Anton Brancelj, NIB). Overflows of water from Bloška planota are marked with arrows. Resolution of data is 6 hours.*

Specific electrical conductivity (SEC) of water from both passages ranges from 432 to 504 µS/cm at low-middle water level. Average SEC is nearly the same: 461 µS/cm for Blata passage and 463 µS/cm for Pisani rov. Correlation between SEC and water level is weak. Much better correlation was found between SEC and season. The highest SEC was found in early summer months and in early winter months (Fig. 4.1.5.2). Between these peaks two periods with low values appear.

Similar oscillation of SEC in Blata and Pisani rov indicates similar interaction between rock and percolating water. Despite many similarities, higher Ca/Mg ratio (3.52) in Blata passage indicates higher portion of limestone aquifer than in Pisani rov (1.91). In Blata passage, we should take into account also minor contribution of the underground Farovščica watercourse, which was proved with tracing test (KOGOVŠEK ET AL., 2008). In both cases, always positive SI_{Ca} (from +0.29 to +0.76) at low-middle water level indicates slightly oversaturated waters. Nevertheless, SI_{Ca} is usually higher in Pisani rov than in Blata passage, which is a result of lower pH in Blata passage (Fig. 4.1.5.3).

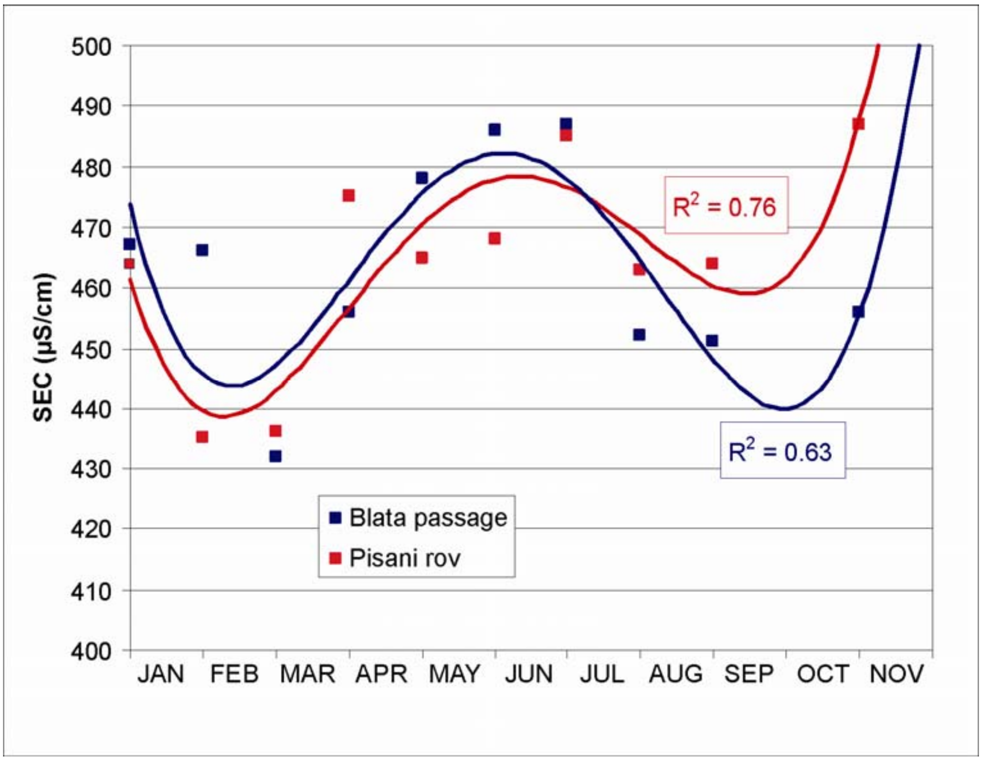


Figure 4.1.5.2: *Oscillation of SEC (~total hardness of water) in Pisani rov and in Blata passage near Kalvarija during a year.*

The biggest difference between streams was found in pH value, which is on average for 0.27 higher in Pisani rov. Such differences appear in all water levels and in all seasons (Fig. 4.1.5.3). Almost perfect correlation was found between season and pH value: high pH values correspond to early summer and winter months and low to late winter and early spring months. Higher pH corresponds to higher SEC due to chemical equilibrium – water with higher hardness has higher pH values at equilibrium. Correlation between pH value and water level is very low for both streams.

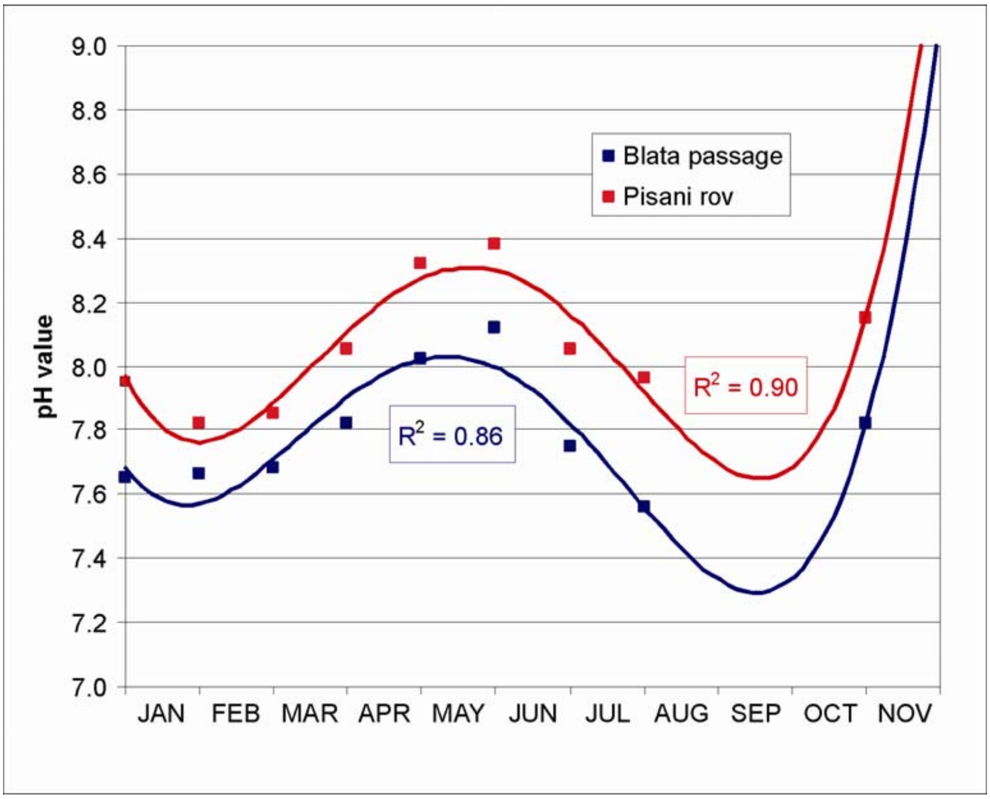


Figure 4.1.5.3: *Oscillation of pH value of water from Pisani rov and from Blata passage near Kalvarija during a year.*

Measurements of physicochemical properties of water indicate very similar water from Blata passage and Pisani rov. The biggest differences appear in Ca/Mg ratio (which is connected with different portion of limestone/dolomite in aquifer) and in pH value. Therefore we should expect similar geomorphic behaviour of streams if the ventilation does not play a significant role at geomorphic processes.

Geomorphic processes of stream from Pisani rov, stream from Blata passage and the combined stream (all at Kalvarija) were studied with limestone tablets at measurement points KJ-5, KJ-6 and KJ-7. Measurements at KJ-5 (combined water flow downstream of Kalvarija) and KJ-6 (Pisani rov) started on 16th August 2006. Limestone tablets were fixed on iron screw which caused misleading corrosion especially at KJ-5 and much less at KJ-6. On 18th December 2007, iron parts were replaced with stainless steel. Measurements at KJ-7 (Blata passage) started on 15th July 2007. Limestone tablets at KJ-7 were fixed on stainless steel from the beginning of measurements. We used a pair of limestone tablets for each measurement point. Tablets were replaced every thirtieth day of exposure.

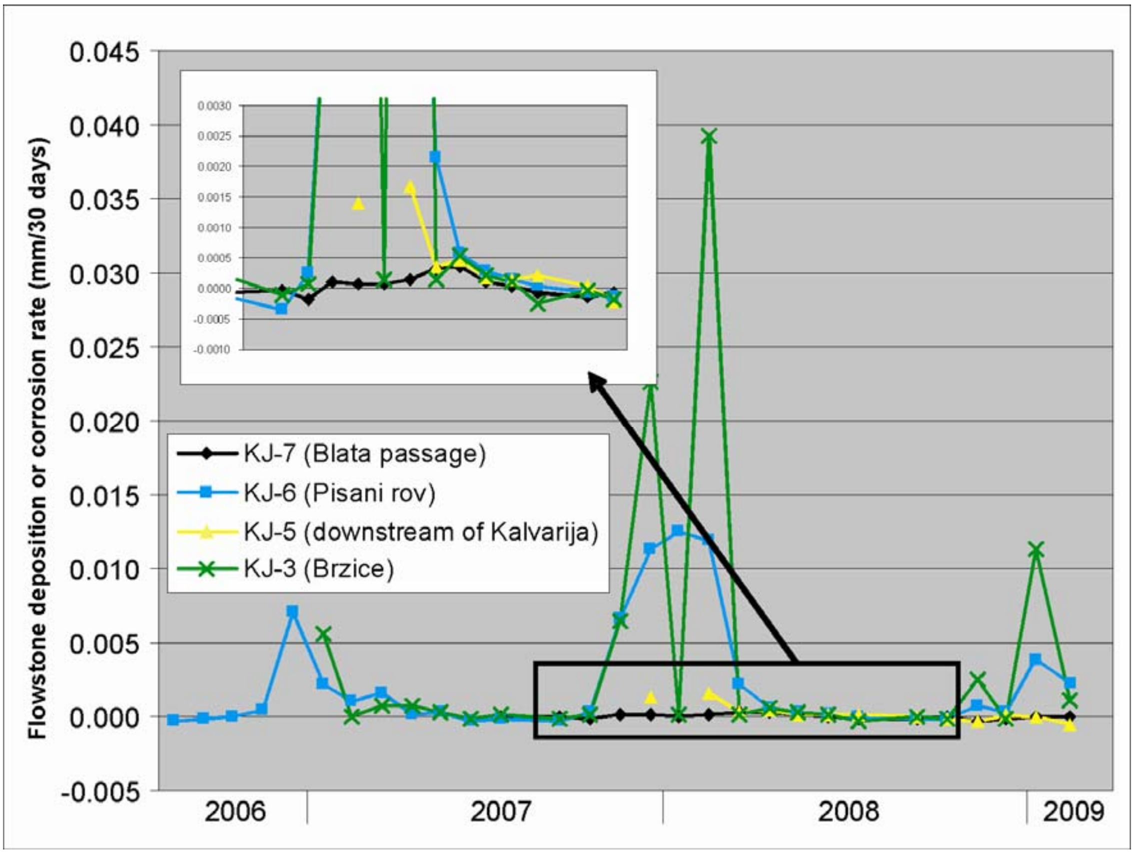


Figure 4.1.5.4: *Results of measurements at KJ-5, KJ-6, KJ-7 and at KJ-3 for comparison from 13th January 2007 to 27th February 2009[1]. Presented are just results of measurements which were not seriously influenced by corrosion at the contact with rusted iron screw.*

Fig. 4.1.5.4 shows results of measurements at KJ-5, KJ-6, KJ-7 and at KJ-3 for comparison. We can see that flowstone deposition and corrosion rates at KJ-6 correspond to flowstone deposition rates at KJ-7 only in summer and autumn. At this times, flowstone deposition or corrosion rates are nearly the same, which shows similar characteristics (origin) of water. It is interesting how closely fits KJ-6 with KJ-7 between 18th April 2008 and 5th November 2008 – rates are just for 0.0001-0.0002 mm higher at KJ-6 (Pisani rov) in comparison with KJ-7 (Blata passage). Decrease of flowstone deposition rates at both measurement points from the beginning of spring to the late autumn is evident – during late autumn, flowstone deposition rates even turn into low corrosion rates. The biggest differences between measurement points appear in

[1] Instead of column chart, line chart is chosen for better illustration.

winter months, when we do not find high flowstone deposition rates in Blata passage (KJ-7). In Pisani rov (KJ-6), response to winter ventilation is similar to KJ-3, although flowstone deposition rates at KJ-3 are more closely related to extreme winter ventilation. Similar response of KJ-3 and KJ-6 corresponds to intensive winter ventilation of Jezerski rov and Pisani rov, which strongly decrease CO_2 concentration. Blata passage is much worse ventilated and has therefore higher CO_2 concentration even during winter months.

Although differences in CO_2 concentration between upstream end of Blata passage and Pisani rov exist, they are not so high (~150 ppm) that the differences in CO_2 concentration would produce much different rate of outgassing of CO_2 from the water. The main reason for different flowstone deposition rates in winter months has to be in differential ventilation of the whole karst massif upstream of both passages, which are up to now inaccessible due to upstream breakdowns. However, ventilation through the breakdowns indicates that the passages continue further into the karst massif.

Peaks in flowstone deposition rates at KJ-6 and KJ-7 show gradual transition from low corrosion rates at the end of autumn toward flowstone deposition during winter and spring months. At the end of spring, gradual transition from flowstone deposition rates toward corrosion rates can be observed. Although, peak in flowstone deposition rate at KJ-6 corresponds to the strongest winter ventilation of Križna jama, while the peak at KJ-7 corresponds to the end of winter ventilation, when CO_2 concentration behind the end of Blata passage has to be the most depleted. If we look very carefully, the same pattern can be observed also at KJ-6 and KJ-3 at the end of high flowstone deposition rates in winter months. Therefore, response to long-term winter ventilation is expressed at KJ-6, KJ-7 (and KJ-3), while very high flowstone deposition rates appear just at KJ-6 (and KJ-3) since Pisani rov (and Jezerski rov) is intensively ventilated.

Different catchment areas of streams from Pisani rov and Blata passage is evident from different variation of annual temperature of water, Ca/Mg ratio and tracing test (KOGOVŠEK ET AL., 2008). But in spite of different catchment areas, both are synchronous in flowstone deposition or corrosion rates in late spring, summer and autumn. This indicates similar way of primary infiltration, homogeneity of dissolution in vadose zone and therefore similar geomorphic behavior of water in epiphreatic zone. The biggest differences in flowstone deposition rate occur during winter and during early spring days, when flowstone deposition rates are strongly influenced by exceptionally strong ventilation. Without intensive ventilation of Pisani rov, flowstone deposition rates would be similar or even equal to flowstone deposition rates in Blata passage or to flowstone deposition rates several hundreds of metres downstream of Kalvarija.

Flowstone deposition rates below confluence (KJ-5) are under the influence of mixed physicochemical properties of water from Pisani rov and from Blata passage. In such occasion, we could expect also some mixture corrosion (BÖGLI, 1964 after GUNN, 1986) although chemical composition of water (at least with regard to Ca^{2+} concentration) seems to be very similar. If we take into account that water from Pisani rov and from Blata passage is oversaturated with respect to Ca^{2+} (at least during low-middle water level), we can expect flowstone deposition rate between KJ-6 and KJ-7 or slightly smaller. If the water would be much different with respect to dissolved CO_2 or concentration of Ca^{2+}, we should expect even some corrosion. Measurements during the winter time 2007/2008, when results are the most reliable, show that flowstone deposition rates at KJ-5 are usually between KJ-6 and KJ-7. Only when the rates are very low and therefore close to measurement error or in the case of very strong ventilation, rates downstream of Kalvarija are not between Pisani rov and Blata passage. If we suppose equal discharges from Pisani rov and Blata passage, flowstone deposition rates should be slightly lower than the average rates from Pisani rov and Blata passage due to mixing corrosion. Such a difference was observed but is relatively low (0.0005 mm/a, which is 6 % of annual flowstone deposition rate at KJ-5). Mixing of streams at Kalvarija certainly does not lead to corrosion at KJ-5.
Mixture corrosion could much more easily result in the water which is not so far from equilibrium. This happens in Križna jama during summer and autumn months. In spite of expectations, mixture corrosion was not detected even at that time, since the rates at KJ-5 very often correspond to average between KJ-6 and KJ-7. Once detected negative corrosion rate at KJ-5 (-0.0002 mm/30 days in autumn) show corrosion rates slightly higher in comparison with KJ-6 and KJ-7 (-0.0001 mm/30 days), but the difference is within error of measurement and therefore cannot be simply ascribed to mixing.
Consequently, mixture corrosion seems to be absent or at least negligible due to similar and/or slightly oversaturated waters from Pisani rov and Blata passage. In any case, tributary from Blata passage significantly reduces flowstone deposition rates along

Pisani rov-Jezerski rov water course downstream of Kalvarija but does not lead to corrosion. Limited potential of mixing corrosion was already warned by Gunn (1986, 378), who states that mixing corrosion can be responsible up to 20 % additional dissolution, but 1-2 % is more usual in normal waters. Therefore we could hardly ascribe to it any important geomorphic effect in Holocene, at least from the measurement at Kalvarija.

4.1.6 Measurement points KJ-8, KJ-9 and KJ-10 – geomorphic processes in Pisani rov

The known water course in Pisani rov begins under the breakdown at the end of trunk passage. Along its underground course toward Kalvarija, the main stream is fed by at least 5 springs/tributaries. Since the uppermost 4 tributaries are very similar in SEC and temperature we suppose that Kristalna gora (=Chrystal mountain) acts as a barrier for a combined stream in an unknown passage behind collapse chamber, which diffluences uniform water course with big breakdown.

Along the water course in Pisani rov, we observe similar geomorphic phenomena as in Jezerski rov between Kalvarija and Brzice – scalloped wall above middle water level, rimstone dams with lakes behind them and flowstone coating on the wall under the middle water level. The latter 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. Due to lack of ventilation during free surface flow and probably also behind the sump, spring water has up to 21 µS/cm higher SEC and up to 0.60 lower pH in comparison with the main water course. This tributary is characterized also with generally 0.5-0.7 °C lower temperature. Influence of this tributary on the main stream is supposed to be relatively small since it contributes only about 16 % of water to main stream.

Present-day processes in Pisani rov were studied at three measurement points: KJ-8, KJ-9 and KJ-10 from 15th July 2007 to 27th December 2008. At each measurement point we used 3 limestone tablets at the same time for higher precision. Limestone tablets were fixed on stainless steel parts from the beginning of measurement. Limestone tablets were always under the water level. Due to remoteness of the end part of Pisani rov, limestone tablets were replaced after several months of exposure. Consequently, we have insight into the 3 measurement periods (15th July 2007-11th October 2007 (88 days), 11th October 2007-24th April 2008 (196 days) and 24th April 2008-27th December 2008 (247 days).

Results of measurements in Pisani rov are represented in Fig. 4.1.6.1 and Table 4.1.6.1. Two phenomena can be identified: (1) flowstone deposition rates are significantly higher in the colder part of the year (Table 4.1.6.1) and (2) flowstone deposition rates increase from upstream part of Pisani rov toward Kalvarija (Fig. 4.1.6.1). High flowstone deposition rates in winter time and low flowstone deposition rates in summer time are similar to phenomenon already known from Jezerski rov (Chapter 4.1.4). They are related to winter ventilation of Križna jama, which significantly lowers CO_2 concentration in the karst massif. But it is somehow surprising that summer ventilation does not reduce CO_2 concentration in upstream part of Pisani rov so much that high or even medium flowstone deposition rates would be recognized. One explanation for low flowstone deposition rates in summer time is the long unknown continuation of Pisani rov, where the atmospheric concentration of CO_2 is enhanced by CO_2 from the epikarst and vadose zone, which is rich in CO_2 concentration especially during vegetation season – during spring, summer and autumn time. The second explanation is related to an inaccessible entrance to Pisani rov, which was found on the surface exactly above collapses in the upstream part of Pisani rov – it is possible that enhancement of atmospheric concentration of CO_2 is so high in summer time along collapsed 175 m long way toward ending part of Pisani rov, that CO_2 concentration in Pisani rov already reaches almost that one present in the karst massif. Nevertheless, CO_2 concentration in the warmer part of the year seems to be too high for high flowstone deposition rates. Very interesting is a decrease in flowstone deposition rates downstream of the end of the breakdown, which was recorded in summer-autumn time during 1st measurement period. Downstream decrease of flowstone deposition rates can be related to downstream increase of CO_2 concentration along 710 m long underground water course but the values are quite low and often close to the average error of measurements. Nonetheless, winter 2007/2008 strongly inverted this trend toward increasing flowstone deposition rates downstream of the breakdown end.

Table 4.1.6.1: *Flowstone deposition rates in Pisani rov (at KJ-8, KJ-9 and KJ-10) during 3 measurement periods from 15th July 2007 to 27th December 2008.*

	KJ-8			KJ-9			KJ-10		
15th July 2007-11th October 2007 (mm)	0,0002	0,0004	0,0002	0,0003	0,0003	0,0002	0,0000	0,0001	0,0000
15th July 2007-11th October 2007 (mm/a)	0,0010	0,0017	0,0007	0,0013	0,0012	0,0007	-0,0001	0,0002	-0,0001
AVG (mm/a)		**0,0011**			**0,0010**			**0,0000**	
11th October 2007-24th April 2008 (mm)	0,0084	0,0085	0,0077	0,0498	0,0477	0,0477	0,1135	0,1114	0,1115
11th October 2007-24th April 2008 (mm/a)	0,0142	0,0144	0,0130	0,0842	0,0806	0,0806	0,1918	0,1883	0,1883
AVG (mm/a)		**0,0139**			**0,0818**			**0,1895**	
24th April 2008-27th December 2008 (mm)	0,0005	0,0004	0,0004	0,0005	0,0004	0,0003	0,0019	0,0018	0,0022
24th April 2008-27th December 2008 (mm/a)	0,0008	0,0007	0,0006	0,0008	0,0007	0,0005	0,0031	0,0029	0,0035
AVG (mm/a)		**0,0007**			**0,0007**			**0,0032**	

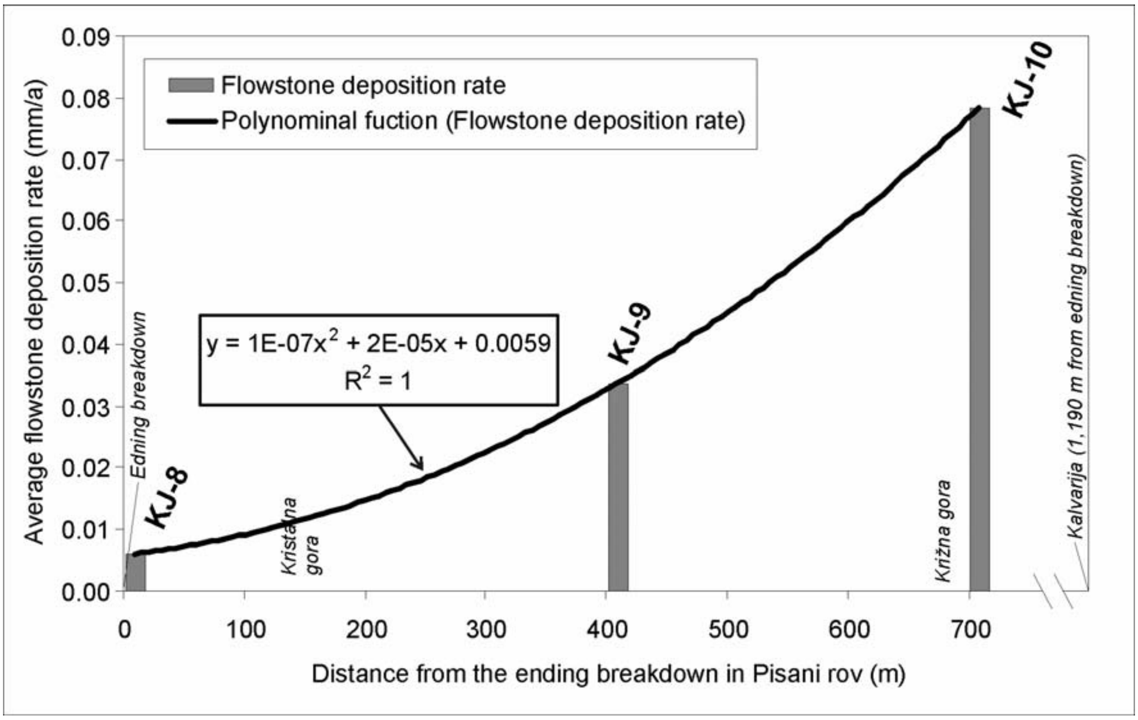


Figure 4.1.6.1: *Flowstone deposition rates in Pisani rov (at KJ-8, KJ-9 and KJ-10) from 15th July 2007 to 27th December 2008.*

Downstream increase of flowstone deposition rate in Pisani rov (0.0102 mm/100 m) is similar to Jezerski rov (0.0085 mm/100 m; Chapter 4.1.4) – as a result, between KJ-8 and KJ-10 flowstone deposition rate increases by 12.8 times. Nevertheless increase is not linear but rather curved, with smaller increase in flowstone deposition rate in the upstream part and higher in the downstream part.

During 2nd measurement period, average thickness of flowstone at KJ-10 (0.1121 mm) is by 39.2 % higher in comparison with KJ-6 (0.0446 mm). Although we can be careful since some differences can appear due to measurement interval, difference between

KJ-10 and KJ-6 is higher than the maximum observed difference due to measurement interval (29 %; Chapter 2.1.3). This means that flowstone deposition rate downstream of measurement point KJ-10 is definitely lower in comparison with KJ-10, most probably because of the left tributary located about 20 m downstream of KJ-10.

Influence of the lowest tributary in Pisani rov toward Kalvarija can be seen also from spatial measurements of SEC, pH and T (Appendix III). From springs under Kristalna gora toward Križna gora, SEC constantly falls down due to flowstone deposition. The only significant rise in SEC is observed below confluence with the left tributary downstream of Križna gora. pH value usually rises because of outgassing of CO_2 from the water. The only significant fall of pH is observed below confluence with the left tributary downstream of Križna gora. Downstream toward Kalvarija, pH is rising again. SEC and pH shows that CO_2 and concentration in water is not in equilibrium with CO_2 concentration in water passage and therefore outgassing of CO_2 from the water occurs when the water enters Pisani rov. Since the water is close to equilibrium at springs below Kristalna gora, outgassing of CO_2 causes rising of SI_{Ca}, which leads to flowstone deposition. Due to higher SI_{Ca} downstream, the highest flowstone deposition rates are characteristic for downstream part of Pisani rov before confluence with left tributary.

Flowstone deposition below middle water level is in agreement with morphological observation. All along water course, features as a result of net flowstone deposition can be observed – rimstone dams and flowstone coatings. Thickness of flowstone coating is the smallest near the ending breakdown and increases downstream – as observed with limestone tablets. Net flowstone deposition rates are most probably absent above middle water level since scallops without flowstone coating are developed there (Fig. 1.1.6.2).

Figure 4.1.6.2: *Stripes of flowstone above and under the water level, located about 20 m downstream of KJ-8 (photo: Alojz Troha, DLKJ).*

Very interesting features in the upstream part of Pisani rov are horizontal stripes, which are composed of more than 1 mm thick flowstone coating (Fig. 4.1.6.2). They are developed about 10 cm above and below middle water level. It seems that they were formed at the water level at the time of the strongest winter ventilation through Križna jama and later partly corroded since the flowstone coating is absent between them.

The wall is covered by scallops but since the measurements were done below medium water level and all measurement points show net flowstone deposition, nothing can be said about corrosion rates in this part of Križna jama. The only season and location where the corrosion is possible seems to be near the KJ-10 in late summer or autumn months since we detected non-prevailing process at this point during 1st measurement period. This is in agreement with observation at KJ-6 (Fig. 4.1.5.4 in Chapter 4.1.5).

4.1.7 Measurement points KJ-11, KJ-12, KJ-13 and KJ-14 – geomorphic processes in Blata passage

Blata passage is more complicated from a hydrological point of view since the main water course is fed by several significant left and right tributaries. Therefore related geomorphic processes, forms and factors are much more complicated than in Pisani rov. Scallops are found all along the main passage, except in the upstream part, where the passage is developed in Lower Jurassic dolomite. They are not absent due to lack of corrosion process but because of sandy dolomite, which weathers partly chemically (cement) and partly mechanically (grains). It is well known that grain size and heterogeneity of rock have profound effects on surface karren and similar bedrock sculpture underground (FORNOS & GINES, 1996, 36 after FORD, 2002; SLABE, 1995, 14). Contact between walls and flowing water is often interrupted with high amount of loamy alloctonous sediment. Within these sediments, the water channel is incised for up to 2 m. Walls are often but not always covered with flowstone coating. Walls of passages, from where tributaries are coming through sumps, do not have any flowstone coating. Along main water course several rimstone dams form underground lakes, similar as in Jezerski rov and Pisani rov.

Blata passage is significantly less ventilated than Jezerski rov and Pisani rov. Air movements can be perceived only at narrows while in typical passage with diameter more than 5 m ventilation can not be felt. Therefore, CO_2 concentration is higher in comparison with Jezerski rov and Pisani rov, especially during winter months but most probably also during summer months. 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 complex morphology and (most probably) also complex rates of present-day processes and relevant factors, corrosion and flowstone deposition rates were measured only at 4 places. Results do not give us full insight into the geomorphological activity in Blata passage but, nonetheless, they give us some information about the intensity and temporal variation of geomorphic processes. Measurements were taken at KJ-11 (spring of the longest known water course under the ending breakdown), at KJ-12 (periodic tributary which is thought to be underground Bloščica course according to first explorers), at KJ-13 (above siphonal tributary at rimstone dam) and at KJ-14 (below siphonal tributary). Measurements started on 15th July 2007 and ended on 27th December 2008. Due to remoteness of the end part of Blata passage, limestone tablets were replaced once or twice per year, at the same time as in Pisani rov. Therefore, results for 3 measurement periods are available for this timespan. At all measurement points we placed 3 limestone tablets, which were fixed on stainless steel screws.

As in all measurement places in Križna jama, the highest flowstone deposition rate at KJ-11 was recorded during winter months (Tab. 4.1.7.1). This proves that although Blata passage is much less ventilated in comparison with Jezerski rov and Pisani rov ventilation has influence also in other less ventilated passages. Nevertheless, due to weaker ventilation, flowstone deposition rate at KJ-11 is about 3.2-times smaller than flowstone deposition at the end breakdown in Pisani rov (KJ-8; Chapter 4.1.6). In summer time, slight flowstone deposition rate close to the error of measurement was recorded. Detected flowstone deposition corresponds to actual morphology, since all end breakdown material under the medium water level is covered with flowstone coating. Where the water is intensively outgassed with respect to CO_2, rimstone dams have been formed. Thickness of flowstone deposits is hard to estimate but for sure it exceeds several cm.

At KJ-12, where the measurements were done in the side passage of a tributary, the clear dolomite wall without flowstone coating suggests that we can expect corrosion. Micro-corrosional features are absent since the Lower Jurassic dolomite is heavily fractured and grained. In agreement with expectation, corrosion rates out of maximum error of measurement (0.0004 mm) were recorded in the last measurement period, which was characterized by several strong flood events. Nonetheless, recorded corrosion rates are so small that slight flowstone deposition rates recorded in winter time during 2nd measurement period turn the net chemical process toward inactivity. Since the 1st measurement period was the shortest, slight corrosion rates within average error of measurement do not significantly change the situation. Final conclusion for this tributary can be that higher flowstone deposition rates are absent, while the corrosion can occur at the highest water level. Nevertheless, real corrosion rate in the passage can be up to 10 times smaller since the Lower Jurassic dolomites is much slowly corroded (Fig. 2.1.3.11 in Chapter 2.1.3). Detection of corrosion at high water levels, which is exceptional in the case of Križna jama, suggests that the water can be different in origin and could be at least part of underground Farovščica or Bloščica flow, since a portion of Farovščica underground water flow was confirmed during tracing test with sampling at measurement point KJ-7 (Blata passage at Kalvarija; KOGOVŠEK ET AL., 2008). Since this tributary contributes significant amount of water only at very high water level, when flowstone deposition rates are low and corrosion rates are absent (or at least very low), it has no important influence on net flowstone deposition rates downstream.

Table 4.1.7.1: *Flowstone deposition and corrosion rates in Blata passage measured between 15th July 2007 and 27th December 2008 during 3 measurement periods.*

	KJ-11			KJ-12			KJ-13			KJ-14		
15th July 2007-11th October 2007 (mm)	0,0001	0,0001	0,0002	-0,0001	-0,0001	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
15th July 2007-11th October 2007 (mm/a)	0,0003	0,0005	0,0007	-0,0005	-0,0004	0,0001	-0,0002	0,0002	-0,0002	-0,0001	-0,0001	0,0000
AVG (mm/a)	**0,0005**			**-0,0003**			**-0,0001**			**-0,0001**		
11th October 2007-24th April 2008 (mm)	0,0023	0,0022	0,0026	0,0005	0,0006	0,0006	0,0117	0,0115	0,0110	0,0003	0,0012	0,0004
11th October 2007-24th April 2008 (mm/a)	0,0043	0,0041	0,0048	0,0010	0,0012	0,0012	0,0217	0,0214	0,0205	0,0006	0,0022	0,0008
AVG (mm/a)	**0,0044**			**0,0011**			**0,0212**			**0,0012**		
24th April 2008-27th December 2008 (mm)	0,0005	0,0003	0,0002	-0,0007	-0,0006	-0,0004	0,0009	0,0008	0,0002	0,0000	0,0000	-0,0001
24th April 2008-27th December 2008 (mm/a)	0,0008	0,0004	0,0003	-0,0010	-0,0009	-0,0006	0,0013	0,0012	0,0003	0,0000	0,0001	-0,0001
AVG (mm/a)	**0,0005**			**-0,0008**			**0,0009**			**0,0000**		

Measurement points KJ-13 and KJ-14 are separated by only about 7 meters (Fig. 4.1.2 and Fig. 4.1.7.2). Their location is interesting since an underwater tributary, detected with SEC, T and pH measurements, seems to have strong influence on the micro-morphology of present-day water channel. The upstream part of water course, characterized by several cm thick flowstone coating, ends with about 1 m high rimstone dam, where measurement point KJ-13 was located. Beneath the rimstone dam, a pool with invisible tributary channel is located. Measurement place KJ-14 was located about 5 m downstream of the confluence. Several hundreds of metres downstream, the water course is characterized by absence of flowstone coating but close to the confluence with Tršanov rov (see Fig. 4.1.2), flowstone coating and rimstone dams appear again due to outgassing of CO_2 from the water and consequential increase of SI_{Ca}. Where the water flow has a contact with a limestone wall, the wall is scalloped. At other places, scallops can not be observed (but necessary absent) since they are coved with loamy sediment.

Once again, flowstone deposition was detected only during winter or early spring time (2nd measurement period), while during summer and autumn time (1st and 3rd measurement period) water is inactive (Fig. 4.1.7.1). During summer and autumn months, inactivity of water is characteristic for KJ-13 and KJ-14. Important difference occurs only during winter and early spring months, when big difference appears between KJ-13 and KJ-14. At that time, flowstone deposition is for 20.5 times smaller at KJ-14 in comparison with upstream measurement point KJ-13 (but is not turned to corrosion due to mixing!). This difference is without any doubt caused by the tributary,

which has due to relatively low pH and high SEC lower SI_{Ca}. Different characteristics of the catchment area in comparison with the longer water course in Blata passage are reflected also in the lower temperature of water. Because of relatively high SEC, low pH and increase of pH due to outgassing of CO_2 from the water downstream of confluence, the passage system of the tributary has to be very poorly or not ventilated with high CO_2 concentration. Although we were not able to sample tributary water, relatively high SEC and low pH also indicates water that is close to equilibrium or even slightly aggressive. Therefore, junction with the main water course between KJ-13 and KJ-14 results in lowered ability of the main water course to deposit flowstone. This is proved with much lower flowstone deposition rates and in present-day morphology.
From a morphological point of view, rimstone dam between KJ-13 and KJ-14 has very interesting, probably two-stage shape (Fig. 4.1.7.1). The lower part of a dam is formed as a convex massive deposit of flowstone. On the top of this massive rimstone dam, about 15 cm high almost vertical rimstone dam has been developed (Figure 4.1.7.2). Its height more or less corresponds to amount of flowstone, which could be deposited during Holocene with a slightly higher than measured rate 0.0114 mm/a (which is logical since the thickness of water film at the top of flowstone dam is smaller and flowstone deposition rates, consequently, slightly higher).
Rimstone dams are formed due to longitudinal differences in flowstone deposition rates. Their shape is also influenced by longitudinal changes in flowstone deposition rates – the highest rates are observed at the upstream part and the lower at the downstream end of rimstone dams– otherwise they will be not able to form vertical distance. At KJ-13, outgassing of CO_2 takes place several hundreds of metres upstream, but since it occurs in a lake, there is lack of nucleation sites. Therefore, the best place for flowstone deposition is the first place where the water flow is thinned. This corresponds to the highest point of massive rimstone dam, where much thinner rimstone dam was formed. This is an answer to the question, why thinner rimstone dam was formed exactly on the top of massive rimstone dam.
Length of a rimstone dam can be related to discharge, whose influence was studied at stalagmite formation. Stalagmites are formed due to oversaturated water, which drips on the ground. The higher the drip rate, the thicker the stalagmite is due to increased thickness of water film, which enhances higher water flow and more widespread flowstone deposition. This phenomenon was confirmed also with modelling

(DREYBRODT, 1988, 260) and application of this phenomenon to rimstone dam formation suggests that discharge was suddenly significantly reduced at the end of Pleistocene. Reasons for changed discharge are numerous and poorly understood.

Figure 4.1.7.1: *Rimstone dam between measurement point KJ-13 and KJ-14 (photo: Alojz Troha, DLKJ).*

Another reason for thin rimstone dam formation can be found in changed physicochemical properties of water. Implication of phenomena observed and modelled at stalagmite shape formation suggests that wider stalagmites (or longer rimstone dams) require weaker outgassing of CO_2 from the water and not so highly oversaturated water. Weaker outgassing of CO_2 from the water relates to higher cave air CO_2 concentration or lower CO_2 concentration in the water. The latter corresponds to the lower CO_2 productivity in soil, which is characteristic for colder than present-day climate (Ice Age). If this is true, flowstone deposition at KJ-13 already existed during Ice Ages but it was much weaker.

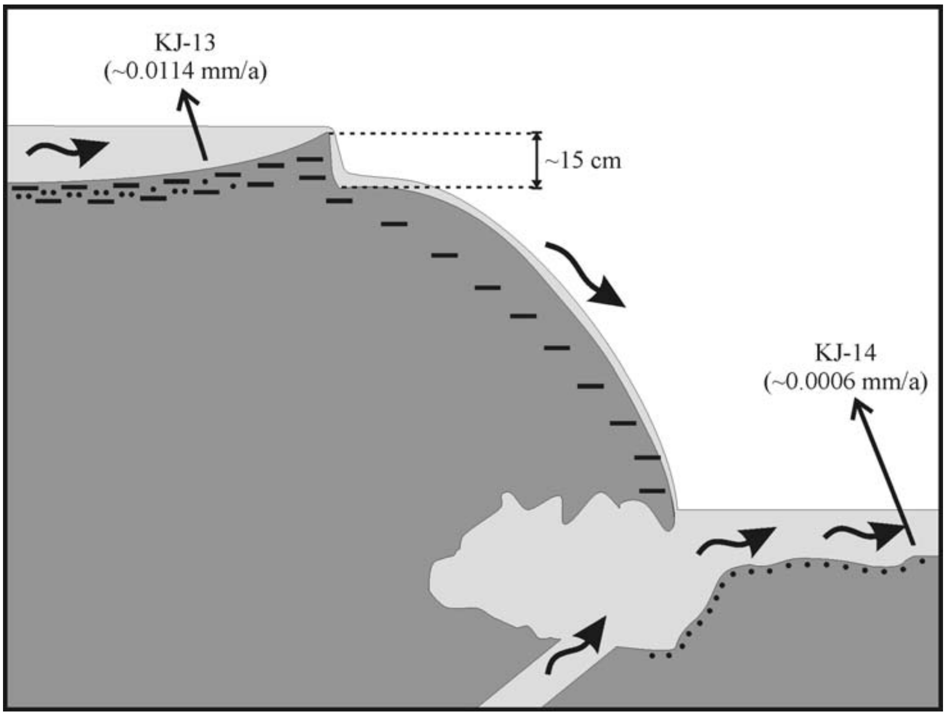


Figure 4.1.7.2: *Measurement points KJ-13 and KJ-14 in the framework of present-day morphology differences.*

According to morphological observation, downstream of KJ-14 flowstone deposition increases and reaches its peak before the confluence with right tributary from Tršanov rov. During this watercourse, increase of pH due to outgassing of CO_2 was observed together with decrease of SEC, which indicates flowstone deposition (Appendix IV). This phenomenon reappears downstream of confluence with Tršanov rov and downstream of some confluences upstream of KJ-13.

4.1.8 Measurement points KJ-3 and KJ2-2 (KJ-2-1) – temporal variation of corrosion or flowstone deposition rates in entrance part of Križna jama 2

Križna jama 2 (Fig. 4.1.2) is supposed to be a hydrological and geomorphic continuation of Križna jama. This presumption is supported by very similar physicochemical characteristics of water (see Appendix II) and similar morphology of trunk passages. Although the caves are separated for 242 m with over 50 m deep sump because of collapse doline Grdi dol, 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 tracing test done in 2007/2008, we know for at least one tributary between caves, which influences physicochemical properties of water and probably also geomorphic activity of water.

Geomorphic processes in Križna jama 2 were studied with pairs of limestone tablets at KJ2-2 (one was exposed in the water flow and another one dried in laboratory at Karst Research Institute ZRC SAZU. Measurements, which make possible comparison, started on 13th January 2007. Results at measurement point KJ2-2 were substantially improved on 18th November 2007 when synchronous measurements with a pair of limestone tablets fixed on stainless steel parts started (KJ2-2-1). The same procedure was done at measurement point KJ2-1 (KJ2-1-1), which was located 100 m upstream of measurement point KJ2-2.
Limestone tablet KJ-3 was located about 4 m upstream of KJ-1 (Chapter 4.1.4). Pairs of limestone tablets were fixed on stainless steel screws, felted washers and nuts and replaced every 30 days. Measurements, which make comparison possible, started on 13th January 2007.
A pair of limestone tablets at KJ2-2 was placed at the downstream end of 1st lake in Križna jama 2. Hydraulic conditions here are quite different to KJ-3 since the bigger cross-sectional area caused slower and therefore less turbulent subcritical water flow at middle water level. At the beginning (16th August 2006), limestone tablets were fixed on iron screws which caused substantial misleading corrosion. On 18th November 2007 we started with synchronous measurements with two limestone tablets fixed on stainless steel (measurement point KJ2-2-1), which were placed just 3 cm away from KJ2-2. Tablets at KJ2-2, KJ-3 and KJ2-2-1 were replaced every 30 days.

Results of measurements at points KJ-3 and KJ2-2 (KJ2-2-1) are represented in Fig. 4.1.8.1. During the spring, summer and autumn months, the course of flowstone deposition/corrosion rates is similar at all measurement points and is characteristic for the main water courses in Križna jama (Fig. 4.1.5.4 in Chapter 4.1.5) and Križna jama 2. Measurements taken at KJ2-2 are for only about 0.0005 mm/30 days smaller in comparison with KJ2-2-1, but misleading corrosion turns slight net flowstone deposition rates toward slight net corrosion rates. However, the annual course is almost the same – during spring we detected slight flowstone deposition rates (up to 0.0005 mm/30 days), which turns to very low corrosion rates during autumn months. We have to stress that the latter are within average measurement error but reliable due to several results that indicate slight corrosion. Influence of discharge can be neglected, since we lack peaks of flowstone deposition at the lowest discharges (during summer and winter months).

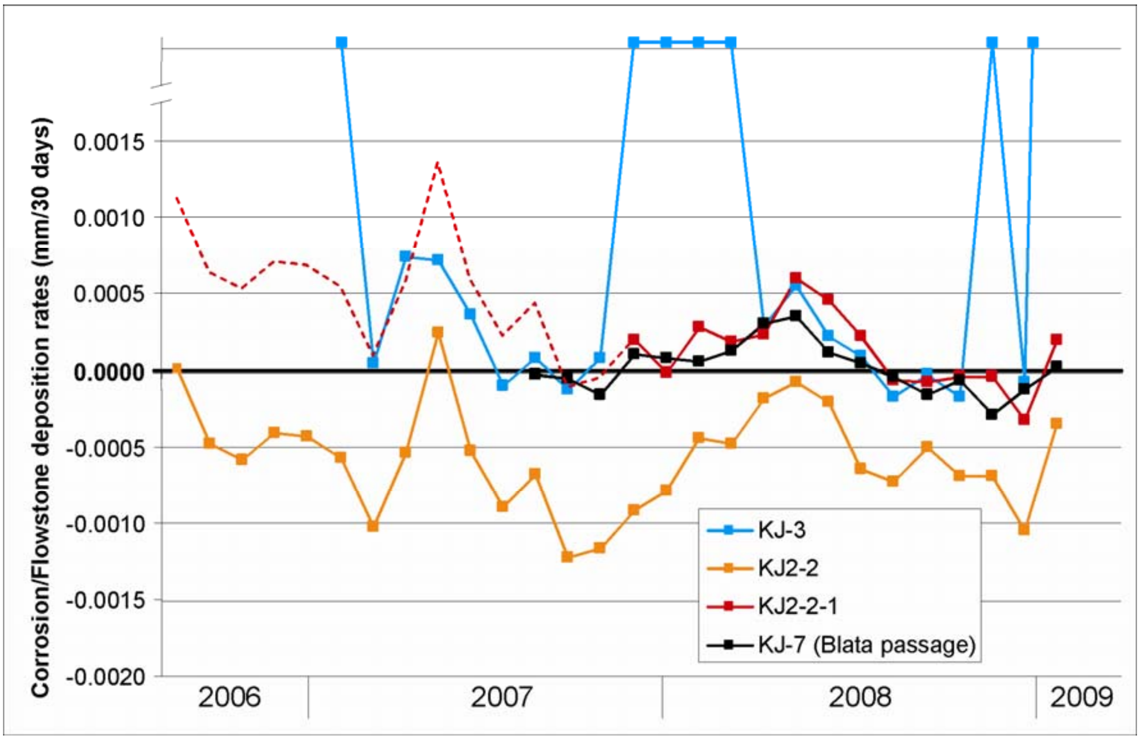


Figure 4.1.8.1: *Corrosion and flowstone deposition rates at measurement points KJ-3 in Križna jama and KJ2-2[1] (KJ2-2-1) in Križna jama 2 from 13th January 2007 to 17th February 2009[2]. Data from KJ-7 (Blata passage) are for comparison.*

During winter 2007/2008, a tracing test indicated partial junction with underground Farovščica between Križna jama and Križna jama 2 (KOGOVŠEK ET AL., 2008). A tributary was detected also with comparison of physicochemical characteristics of water in Križna jama and in Križna jama 2. Although the watercourse from Križna jama and water course of tributary has at least partly different origin of water and therefore different physicochemical characteristics, junction has no geomorphic influence since the processes remain unchanged downstream of confluence. If we take into account data from 19th March 2008 to 9th December 2008, flowstone deposition at KJ2-2-1 is even slightly higher (for 0.00005 mm) in comparison with KJ-3 – although we would expect higher flowstone deposition rates at KJ-3, where measurements were done in much faster and much more turbulent water flow.

[1] *Limestone tablet at KJ2-2-1 was fixed on iron screw – therefore the values are for about 0.0010 mm/30 days lower due to misleading corrosion (Chapter 2.1.3).*
[2] *Instead of column plot, line plot was chosen for better illustration.*

The most evident difference between Križna jama downstream of 1st lake (KJ-3) and Križna jama 2 at the downstream end of 1st lake (KJ2-2 and KJ2-2-1) is lack of high winter flowstone deposition rates in Križna jama 2. During all observed winters, flowstone deposition rate at KJ-3 at least once exceeds 0.002 mm/30 days, while the highest recorded flowstone deposition rate at KJ-2-1 amounts slightly above 0.0005 mm/30 days, but this peak is characteristic for seasonal peak in flowstone deposition and not to intensive ventilation of passages. This results in total amount of deposited flowstone – from the beginning of measurements at KJ2-2-1 (18th November 2007) to 17th February 2009, difference in flowstone deposition rates between KJ-3 and KJ-2-1 amounts 0.0772 mm. Therefore, winter months are responsible for the greatest difference in flowstone deposition rates between KJ-3 and KJ2-2-1.

Due to the most evident differences in flowstone deposition rates between KJ-3 and KJ2-2-1, which appear in winter months, and differences in rates of ventilation between Križna jama and Križna jama 2, intensive winter ventilation is recognized to be the most important factor that produces high differences in flowstone deposition rates between caves. In winter time, ventilation of passages in Križna jama reduces CO_2 concentration at KJ-3 to almost atmospheric concentration (below 400 ppm). The majority of upstream passages (Jezerski rov, Pisani rov and partly Blata) are also well ventilated and outgassing of CO_2 from the water can take place all along water course. A very different situation can be found in Križna jama 2, where we were able to observe annual fluctuations of CO_2, but they are much smaller in comparison with Križna jama. First of all, Križna jama 2 has inverse air circulation – outside air that is poor with CO_2 enters the entrance part of a cave during summer months while the cave air is exiting the cave during winter months. Therefore the highest CO_2 concentrations at KJ2-2-1 (~3,700 ppm) can be observed during winter months and the lowest (~900 ppm) during summer months. Secondly, since the entrance to Križna jama 2 and related wind velocity is relatively small in comparison with Križna jama, exchange of cave air with outside atmosphere is considerably lower. Therefore, high CO_2 concentration during winter months seems to be the most important factor that detains high deposition rates during winter months.

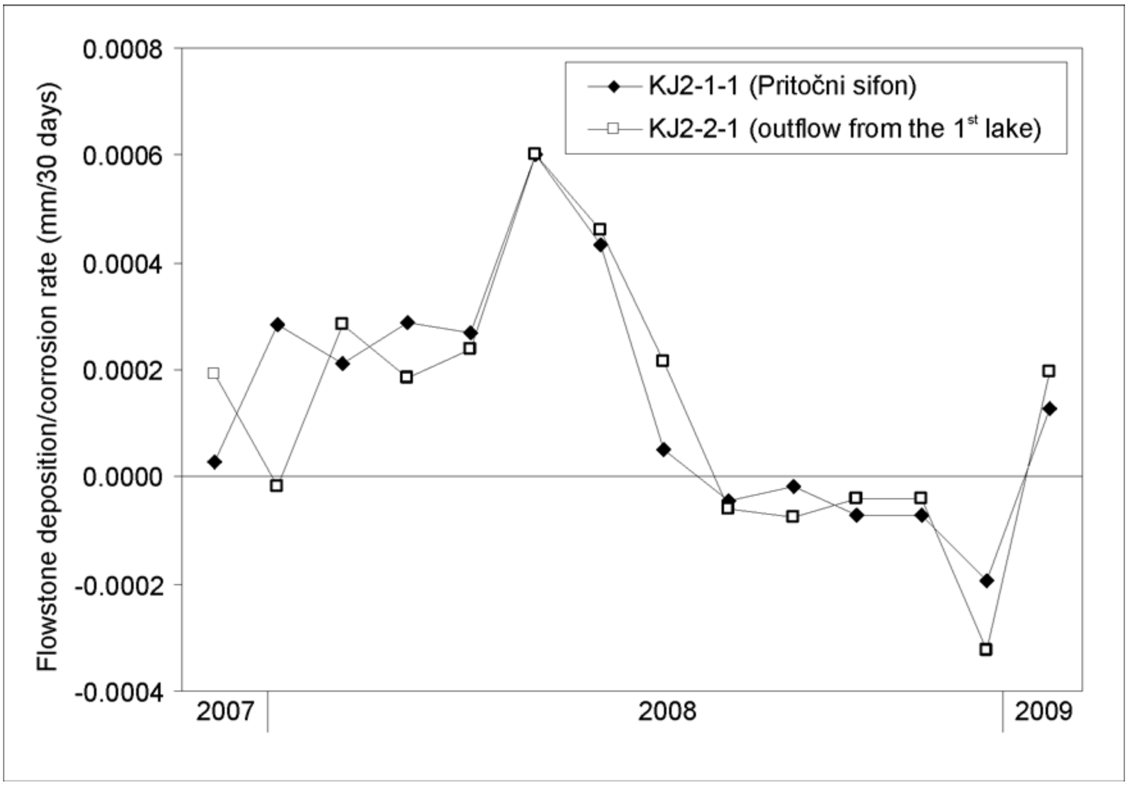


Figure 4.1.8.2: *Comparison of corrosion/flowstone deposition rates between KJ2-1-3 and KJ-2-1.*

Another important factor that controls flowstone deposition is duration of open water between confluence and measurement point. Upstream of KJ-3, almost all water passages in Križna jama are located and water has enough time to outgas CO_2. Although both main watercourses get several tributaries, which can hold up flowstone deposition, outgassing of CO_2 below the confluence leads to flowstone deposition. In Križna jama 2, a tributary in the sump between Križna jama and Križna jama 2 most probably holds up flowstone deposition for a while, but the latter is not increased either between measurement point KJ2-1-1, which is located 3 m downstream of Pritočni sifon (=Inflow sump), and KJ2-2-1, which is located about 100 m downstream of KJ2-1-1 (Fig. 4.1.8.2) or downstream of KJ2-2-1 (see Chapter 4.1.9). Therefore, rate of outgassing of CO_2 (and not duration of outgassing) seems to be the limiting factor for higher flowstone deposition rates in Križna jama 2. From this point of view it is interesting that much lower CO_2 concentration in summer months does not result in higher flowstone deposition rates, either on KJ2-2-1 or downstream (see Fig. 4.1.9.1 in Chapter 4.1.9). From this point of view, the situation seems to be equal to low flowstone deposition rates at the beginning of winter between Ponor and Kalvarija, when flowstone deposition is absent despite low cave air CO_2 concentration (~360 ppm all along the Jezerski rov (see Chapter 4.1.4).

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 we did not measure any important corrosion rates below middle water level (Fig. 4.1.8.1), where scallops are developed, the situation seems to be similar to trunk passages in Križna jama, where scallops are most probably related to Pleistocene epochs. Therefore they cannot be a result of low present-day corrosion rates.

The total amount of annually deposited flowstone at KJ2-2-1 is relatively low (~0.0016 mm/a) in comparison with KJ-3 (0.0641 mm/a). Even if we take into account that measurements with limestone tablets indicate on average 3 times lower values in comparison with micrometer (Fig. 2.1.3.13 in Chapter 2.1.3), and the latter are more relevant, expected thickness of flowstone layer in 12.000 years could not be thicker than 6 cm. Contrary to this finding, flowstone coating is completely absent in the 1st lake in Križna jama 2. The latter discrepancy between morphology and measured processes is similar to upstream part of Jezerski rov in Križna jama (0.0043 mm/a at KJ-5; Chapter 4.1.4), where discrepancy between rates and morphology seems to be similar although very thin flowstone coating can be observed near KJ-5 (but still far from at least 5.1 cm in 12.000 years). The reasons can be as follows:

- corrasion,
- corrosion under the film of sedimented loam or by biofilm,
- different physicochemical properties of water in Holocene and/or
- widening of entrance passage.

Corrasion definitely takes place in Križna jama 2 since the underground stream transports sediments from Križna jama. However, the most relevant question, how high is the corrasion rate, is very difficult to answer due to very small rates. Regarding measurement point KJ2-2-1 it is very low since it can not be recognized after high discharge, but it can be much higher at fragile flowstone coating. Therefore thin flowstone coating can be removed persistently by corrasional force of water flow.

The second possibility seems to be attractive since we lack flowstone coating at many loamy banks. Enhanced corrosion under the sediment was suggested also by Gams

(1967, 51) and is certainly responsible for some superficial and speleogenetic features (dissolution pan=kamenitze, below-sediment bevels=decantation flutings, below-sediment floor pits; SLABE, 1995, 71; FORD & WILLIAMS, 2007, 329). Since some of these features are found also in Križna jama and Križna jama 2, corrosion under the sediment seems to be important. After 30 days of exposure, limestone tablets were gently cleaned and dried (see Chapter 2.1.3). With this procedure, we avoided weighing sediment deposited on a limestone tablets but we might also break or slow down slight corrosion, which can be caused by biofilm or by decay under sediment. Action of heterotrophic and chemolithotrophic organisms can be observed as the manganese coating on a dolomitic cave wall (FORD & WILLIAMS, 2007, 62), while the corrosion under the sediments can result in decantation flutings. Again, we do not know how high is the corrosion rate under the sediments. Although the limestone tablet at KJ2-2-1 was often covered with sediments, a significant corrosion rate was never observed (Fig. 4.1.8.1). Nevertheless, allochtonous sediments at limestone tablets were carefully washed away, which can significantly reduce corrosion rate under the sediment.

The same uncertainty arises if we are dealing with changeable physicochemical properties of water in Holocene. Lower winter outside temperature would increase flowstone deposition rate at KJ-3 in Križna jama, but just in winter and spring time. Total flowstone deposition and corrosion rates at KJ2-2-1 in Križna jama 2 depend mostly on durability of the winter ventilation of Križna jama. Shorter and less intensive winter ventilation of Križna jama will lead to lower flowstone deposition rates also in Križna jama 2 and could increase corrosion rates during summer/autumn months. But higher winter temperatures in the near past are less probable, especially during Little Ice Age when at least average annual temperatures were lower. Lower annual temperatures would also cause lower production of CO_2 in the soil, lower total hardness of water and consequently lower flowstone deposition rates, but it is less probable that the Little Ice Age can influence physicochemical properties of water so much that the net flowstone deposition would be absent.

Another reason which would raise flowstone deposition rate is widening of the entrance passage. Before Križna jama 2 was explored, ventilation was observed but it was weaker than in the present-day situation. But since we observe no relation of ventilation and flowstone deposition rates in the entrance part of Križna jama 2, increased ventilation does not seem to be an appropriate reason for (potentially) higher flowstone deposition rates. A more probable reason is widening of the entrance to Križna jama in the 1940s, which increases flowstone deposition rates in Križna jama and Križna jama 2.

Nonetheless, the rate of flowstone deposition or corrosion is relatively low at measurement point KJ2-2-1. Morphological observation at KJ2-2-1 shows that denudation and flowstone deposition are at the equilibrium or slightly turned toward denudation, while the results of process measurements show slight predominance of flowstone deposition.

4.1.9 Measurement points KJ2-3, KJ2-4, KJ2-5 and KJ2-6 – spatial variation of corrosion or flowstone deposition rates along the main water course in Križna jama 2

Downstream of the 1st lake in Križna jama 2, on average 10 m wide and 20 m high water passage continues toward the terminal sump named Sifon upanja (=Sump of hope). This terminal sump is located 1,300 m downstream of Pritočni sifon (=Inflow sump). This trunk passage is characterized by many rimstone dames that developed on more resistant dolomite layers or on breakdowns. Since we were measuring flowstone deposition at KJ2-1 (KJ2-1-1) and KJ2-2 (KJ2-2-1), the main question arises upon flowstone deposition rates below 1st lake. Between KJ2-3 and KJ2-6, only one tributary from Kaplanov rov was detected. Since it is relatively small in comparison with 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 geomorphic process along water course.

Flowstone deposition and corrosion rates were measured at 4 measurement points (KJ2-3, KJ2-4, KJ2-5 and KJ2-6). Measurement point KJ2-3 was located 10 cm beside KJ2-2 (KJ2-2-1). At all 4 locations, 3 limestone tablets on each location were fixed with stainless steel screws, nuts and felted washers. All measurement points lie in nearly equal hydraulic conditions – in fast, turbulent and supercritical water flow. Even at low water level, all limestone tablets were located below water level. Measurements started on 11th April 2007 and finished on 18th February 2009. Due to remoteness of measurement points and fragile flowstone dams along the main water course, limestone tablets were replaced only 3 times. Therefore, we have measurements for 3 periods, which lasted 181, 202 and 295 days.

Physicochemical properties of water were measured with WTW Multiline P4 with pH, T and SEC probe. CO_2 concentrations were measured with hand-held Vaisala GM70 meter.

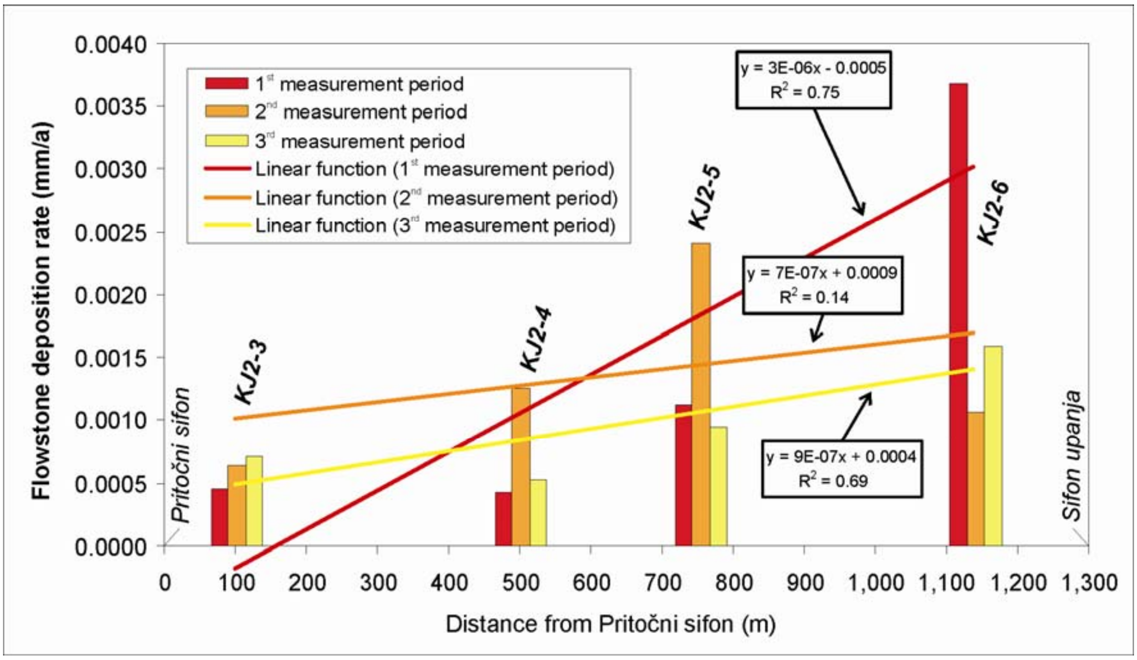


Figure 4.1.9.1: *Flowstone deposition rates in Križna jama 2 from Pritočni sifon to Sifon upanja during 3 measurement periods (1st: 11th April 2007-10th October 2007; 2nd: 10th October 2007-29th April 2008; 3rd: 29th April 2008-18th February 2009).*

At all measurement points, measurements show flowstone deposition and no corrosion (Fig. 4.1.9.1). Moreover, all linear functions show the same trend – increase of flowstone deposition from Pritočni sifon toward Sifon upanja. The best fit to the trend line was achieved during 1st and 3rd measurement periods since the majority of measurement points show downstream increase of flowstone deposition (differences between KJ2-3 and KJ2-4 are in the range of measurement error). Results from the 2nd measurement period are interesting since we detected increase of flowstone deposition from KJ2-3 to KJ2-5, which was followed by steep decrease of flowstone deposition at KJ2-6 (this also strongly reduces R^2 value). The only logical difference between 1st or 3rd measurement period and 2nd measurement period is the season of the measurements – 2nd measurement period took place only during late autumn, winter and early spring months, while the other measurement periods took place during spring, summer and autumn months. Nevertheless, the main reason for the decrease of flowstone deposition rates downstream of KJ2-5 during 2nd measurement period remains unknown.

Deviation at each measurement point between measurement periods grow from Pritočni sifon toward Sifon upanja; therefore the lowest can be observed at KJ2-3 and the highest at KJ2-6. This shows that deviation is a result of water flow within Križna jama 2 and a result of temporary changeable conditions along the main water course. Since the 1st measurement period is the shortest and the 3rd one the longest, we would expect lower flowstone deposition during the 1st measurement period and higher flowstone deposition during the 3rd measurement period. This is the case only at KJ2-3, while at other measurement points important differences appear. Again, the reason can be found in temporary changeable conditions along the watercourse, which are poorly understood due to limited access and sparse data on physicochemical properties of water and cave air CO_2 concentration.

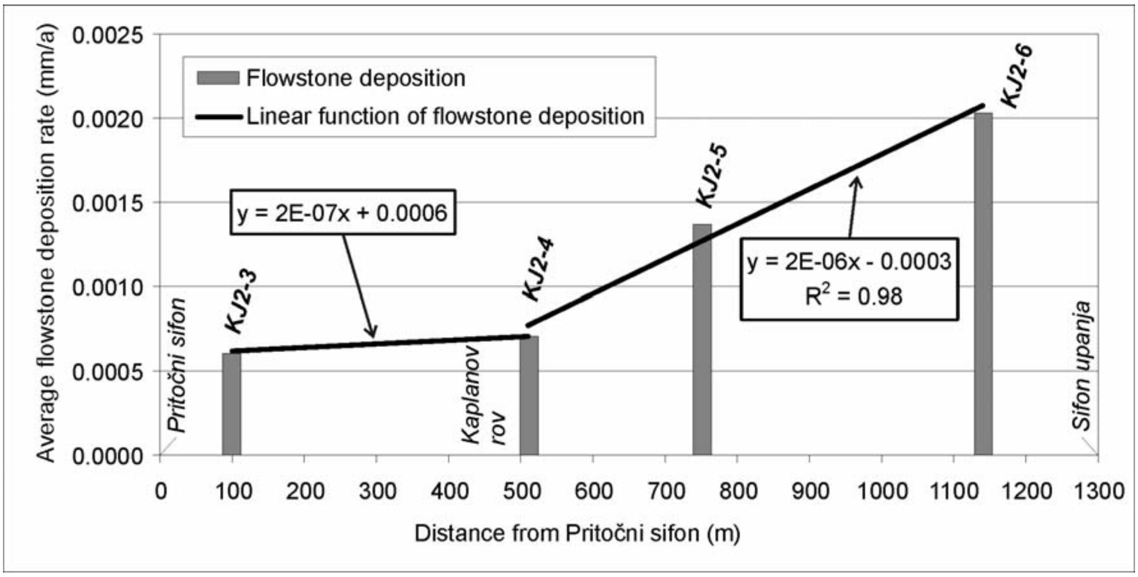


Figure 4.1.9.2: *Average flowstone deposition rate in Križna jama 2 from Pritočni sifon to Sifon upanja between 11th April 2007 and 18th February 2009.*

Average annual deposition rates at KJ2-3, KJ2-4, KJ2-5 and KJ2-6 are represented in Fig. 4.1.9.2. In the upstream part of the water flow, flowstone deposition rates remain almost constant at about 0.0006 mm/a. This value corresponds to annual flowstone deposition rate downstream of 1st lake in Križna jama if we exclude high flowstone deposition rates caused by intensive ventilation in winter months. Therefore deposition rate 0.0006 mm/a seems to be background value of flowstone deposition without very intensive winter ventilation.

Downstream of measurement point KJ2-4 increase of flowstone deposition rates was recorded. During the 650 m long water course between KJ2-4 and KJ2-6, flowstone deposition rate increases for about 3 times to 0.0020 mm/a. Similar but much faster increase of flowstone deposition at nearly the same distance was measured between Kalvarija and Brzice in Križna jama (Chapter 4.1.4). In Križna jama, flowstone deposition rates increase for about 0.0102 mm/100 m in Pisani rov and 0.0085 mm/100 m in Jezerski rov, while in Križna jama 2, increase of flowstone deposition rate amounts only 0.0002 mm/100 m. This huge difference is caused by much weaker outgassing of CO_2 from the water due to higher CO_2 concentration in Križna jama 2, although much higher gradient of water flow in Križna jama 2 offers a better opportunity for outgassing.

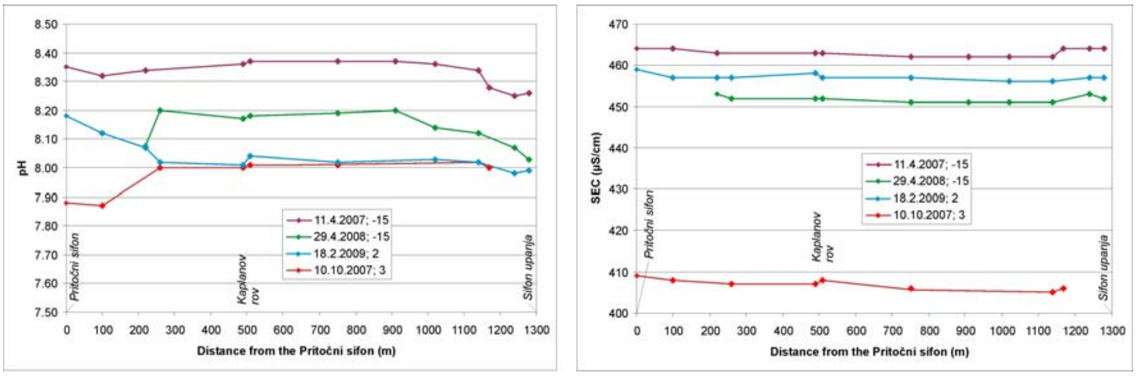


Figure 4.1.9.3: *Change of pH and SEC from Pritočni sifon to Sifon upanja in Križna jama 2 at different water levels as observed at water gauge in Križna jama ($H_{1st\ lake}$).*

Low flowstone deposition rates were measured also with spatial measurement of SEC (Fig. 4.1.9.3). Typical change in SEC due to deposition over the 1,300 m long water course is 2-4 µS/cm, which is much smaller value in comparison with change 5-17 µS/cm along 1,165 m long water course between Kalvarija and Ponor in Križna jama. Low intensity of processes (outgassing of CO_2 from the water or flowstone deposition) can be recognized also from small spatial variability of pH (Fig. 4.1.9.3). Especially in the middle part of Križna jama 2, pH is very stable.

Due to only one known small entrance, Križna jama 2 is poorly ventilated. Measurement of CO_2 concentration near the entrance (see Chapter 4.1.8) shows that the lowest concentration (~900 ppm) can be recorded in summer months, while the highest

(~3,700 ppm) can be recorded in winter months. This corresponds to direction of air masses which in winter time flows from the cave and in the summer time into the cave through the only one known entrance. Two spatial measurements downstream of 1st lake in Križna jama 2 (Fig. 4.1.9.4) show that the CO_2 concentration significantly fluctuates only near the entrance – at Sifon upanja CO_2 concentration is probably nearly constant during the year at about 2,000-2,500 ppm. So high CO_2 concentrations were rarely detected in Križna jama and could be the limitation for intensive outgassing of CO_2 from the water and higher flowstone deposition rates.

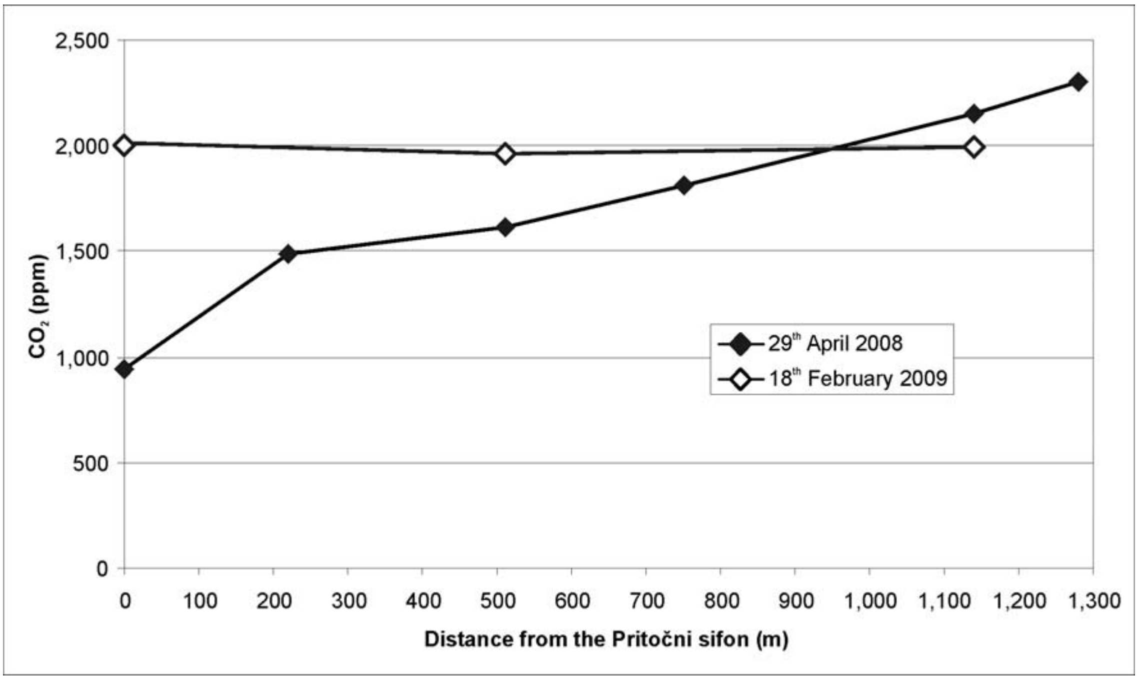


Figure 4.1.9.4: *Change of CO_2 from Pritočni sifon to Sifon upanja in Križna jama 2.*

The morphology of Križna jama 2 is somehow controversial – even more than the morphology of Križna jama. At waterfalls and rapids we can observe fragile flowstone dams. Their fragileness decreases from Pritočni sifon toward Sifon upanja, which corresponds to increasing flowstone deposition rates downstream (Fig. 4.1.9.2). On the other hand, expected flowstone coating is absent and instead of it, walls below and above water level are scalloped. The latter shows net corrosion also below middle water level, but net corrosion was not observed at any measurement point from KJ2-2 to KJ2-6. Close above medium water level, several active-growing stalagmites are corroded at the base and "fresh" at the top. Some of them are located on a ~1 cm high scalloped rocky base – a result of corrosion after the beginning of the stalagmite's growth (Fig. 4.1.9.5). Transition between corroded rock surface (usually covered with scallops) and the base of the stalagmite is sharp. This means that the corrosional episode was followed by period of vadose flowstone deposition – due to decreased aggressiveness of main water flow or suitable hardness of vadose water. After formation of stalagmites, corrosion removed ~1 cm of rock and usually the same amount of the stalagmite's lower parts. In the present-day situation, growth of stalagmites continues while the action of the main water course remains controversial – morphology points out that it can be slightly aggressive while the measurements with limestone tablets suggest slight flowstone deposition.

Figure 4.1.9.5: *Active-growing corroded stalagmite with up to 1 cm high limestone rocky base 0.5 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).*

Although the period of measurement at KJ2-3, KJ2-4, KJ2-5 and KJ2-6 is quite short, all measured values show net flowstone deposition – in spite of some very high discharges with recurrence interval longer than 1 year. Therefore, we are sure that we are not dealing with net corrosion at any location below medium water level through all

Križna jama 2. If we take into account average annual flowstone deposition rate, which was recorded at KJ2-6 (0.0014 mm/a), water needs from 14 to 71 years to deposit a flowstone layer visible with the naked eye (from 0.02 to 0.1 mm). The latter is absent not just in the entrance zone but all through Križna jama. Potential reasons for this discrepancy between actual and potential morphology have been already described in Chapter 4.1.8.

Conclusion

Križna jama-Križna jama 2 cave system is one of the best examples of development of a horizontal cave in the epiphreatic zone. Although the system was at least partly under the influence of allogenic recharge of Bloščica and Farovščica, which have catchment areas on Bloška planota, nowadays tracing tests and physicochemical characteristics of the water indicate diffuse autogenic recharge from the area above and near the cave. Therefore, water rich with carbonates, Ca^{2+} and Mg^{2+} is not a surprise. Due to high total and calcium hardness and a high amount of dissolved CO_2 in water, outgassing of CO_2 from the water leads to oversaturation with respect to calcite in Križna jama-Križna jama 2 cave system. Outgassing of CO_2 from the water and consequential flowstone deposition can be seen through rimstone dams formation, where 0.1 mm/a of flowstone deposition downstream of 1st lake was recorded by Mihevc (1997).

Flowstone deposition occurs only during winter and spring months, when incoming cold air enters Križna jama through the only passable entrance and significantly reduces cave air CO_2 concentration all through the cave and in the nearby vadose zone, from where the percolation water comes. Therefore, outgassing of CO_2 from the water is especially high during winter and spring months and relatively high oversaturation can be reached. Due to all-winter ventilation, the lowest CO_2 concentration in the karst massif is characteristic for spring months, when the seasonal peak in flowstone deposition rates (~0.0006 mm/30 days) was recorded in Križna jama and Križna jama 2. Nevertheless, much higher flowstone deposition rates (up to 0.0170 mm/15 days) were recorded in the most intensively ventilated passages in Križna jama (Jezerski rov and Pisani rov). Here, flowstone deposition rates are the highest during several days in winter months, when outside temperatures do not exceed about -2 ºC. The latter peaks of flowstone deposition are therefore related to the most intense daily winter ventilation. Flowstone deposition rates are mostly independent of low discharges.

In Križna jama-Križna jama 2 cave system, flowstone deposition rates are influenced also from the side of curvilinear branchwork passage and hydrological pattern (the name of pattern after PALMER, 2002, 53) with more and less ventilated passages. Water that enters the cave system is saturated and therefore flowstone deposition cannot be expected. Oversaturation is reached during underground water flow after several tens of metres due to outgassing of CO_2 from the water. The latter process can be observed with downstream stable specific electrical conductivity and rising pH. Due to increased oversaturation downstream, the highest flowstone deposition rates were observed at measurement points which are the furthest from the confluences (e.g. downstream of 1st lake, downstream end of Pisani rov and downstream end of Križna jama 2). Along the water course Pisani rov-Jezerski rov, flowstone deposition rates are reduced between Križna gora and Kalvarija (due to left tributary with significantly lower pH value) and at Kalvarija (because of inflow from Blata passage, which is less ventilated than Jezerski rov and Pisani rov and has therefore also higher pH value).

Differences in flowstone deposition rates can be observed also in micro scale – between lakes and rimstone dames in front of them. During summer and autumn, differences are absent. The only and the highest differences appear during several late autumn and winter days, when the highest flowstone deposition rates were recorded downstream of 1st lake due to the most intensive ventilation. At that time, the ratio of flowstone deposition between rimstone dam downstream of 1st lake (Brzice) and within 1st lake amounts 1:0.08. It is worth stressing that rimstone dams could not be formed without intensive winter ventilation, since flowstone deposition rates are the same out of intensive ventilation.

Corrosion rates are questionable in Križna jama-Križna jama 2 cave system. If they exist, they are very rare, small (up to -0.0003 mm/15 days) and therefore close to the maximum error of measurement (±0.0004 mm). The only corrosion rate (-0.0008 mm/a) out of maximum error was confirmed at tributary in Blata passage, which is hydrologically active only during high water levels. Although the latter corrosion is most probably related to several high discharges, measurement points in Jezerski rov (Križna jama) and near the upstream sump in Križna jama 2 indicate possible but very small corrosion rates in autumn months. Trend of falling flowstone deposition rates

from spring to the end of autumn months is obvious at several measurement points. In autumn, trend of falling flowstone deposition rates can be turned toward slight corrosion (~ -0.0001 mm/15 days); this is close to the average error of measurement. Since the highest cave air CO_2 concentration coincides with detected slight corrosion, the latter is most probably a result of high CO_2 concentration in the karst massif and lower outgassing of CO_2 from the water. Nevertheless, downstream rising of pH during slightly falling specific electrical conductivity points out that outgassing of CO_2 from the water occurs all through the year but it is less expressed in flowstone deposition.
Along main water courses in Križna jama-Križna jama 2 cave system, corrosional and depositional features can be observed. Rimstone dams and flowstone coating on the cave wall suit present-day processes at least in Križna jama. Thickness of rimstone dams and flowstone coating corresponds to about ten thousand years, which shows flowstone deposition during Holocene (MIS 1). In Križna jama 2, discrepancy between measured present-day flowstone deposition (from 0.0006 to 0.0020 mm/a) and lack of flowstone coating is surprising and needs additional study. Flowstone deposition rate at one measurement point in Blata passage points out that low flowstone deposition rates could be related also to the last Ice Age, but changes in rimstone dam's morphology show that changes of discharge or changes of physicochemical properties of water occur at Holocene-Pleistocene transition. The main proof for such changes are scallops, which are numerous in Križna jama-Križna jama 2 cave system but at some places (e.g. in the 1st lake) they do not correspond to present-day hydrodynamic conditions. Most probably they were formed during Würmian stadials (MIS 2-4 & MIS 5a-d), when the snow line at nearby Snežnik mountain was between 1,200 and 1,300 m a.s.l. (ŠIFRER, 1959). Lower annual temperatures reduced the supply of CO_2 from the soil (instead of present-day forest above the cave system we can expect microtermic vegetation (grassland with clumps of trees; ŠERCELJ, 1974), for which lower production of CO_2 is characteristic) and consequently at least strongly reduced possibility for flowstone deposition (FORD & WILLIAMS, 2007, 82). Nevertheless, closure of the main entrance to Križna jama due to breakdown (which is common in such climatic conditions) or changes of catchment area (which already occurred in cave system) would result similarly, that is with lower flowstone deposition rates or even corrosion.
On-going flowstone deposition in Križna jama will not result in vast hydrogeological changes in the aquifer. At some places (downstream ending of Pisani rov, 2nd lake) the

roof of the passage may be reached in about 4,000 years at present-day rate of processes, which will stop ventilation and ventilation-related flowstone deposition in all the cave system. More likely, exponentially smaller flowstone deposition rates are expected due to weaker ventilation and the roof will never be reached. This self-regulating mechanism will equilibrate nowadays disequilibrated flowstone deposition rates on one side and corrosion/corrasion rates on the other.

Present-day climatic changes indicate higher temperatures, especially during winter time. If the same trend continues, we can expect lower flowstone deposition rates, as was recorded in winter 2006/2007 (contrary to colder winter 2007/2008; PRELOVŠEK, 2007).

4.2 Lekinka

Cave Lekinka (Reg. No. 1867) is a 1,032 m long horizontal cave that is situated at the NE edge of Pivška kotlina (=Pivka basin). The latter is, in southern part, made of Cretaceous limestones, which are overthrust onto the Eocene flysch rocks that forms the bottom of northern Pivška kotlina (KOSSMAT, 1897 after ŠEBELA, 1998, 24). Thickness of limestone cover is variable – at some places it is missing and only tectonic windows indicate past coverage with limestone but at some places flysch lies at least 109 m under the basin's surface (KRIVIC ET AL., 1983 after RAVBAR, 2007, 112). Northern bottom of Pivška kotlina is composed of siliceous flysch rocks. Nevertheless outcrops of flysch are rare since the northern Pivška kotlina is covered with fluvial sediments of Pivka and Nanoščica and thick-weathered flysch rocks. Since Pivška kotlina is a closed depression and is bounded mainly with limestones, typical contact karst developed at the edges in the past (MIHEVC, 1991). Typical blind valley is Risnica/Risnik/Risovec, which ends on the surface in breakdown. In the underground, past underground water flow is recognized in Otoška jama (=Otok cave/Cave of Veliki Otok), a part of Postojna cave system. In spite of the fact that we are dealing here with a long geomorphic evolution, some ponors are not formed as blind valleys. Such examples are: present-day ponor of Pivka river into Postojna cave system, ponor of Črni potok (=Black stream) into Lekinka and ponor of stream Osojnica into cave with the same name.

Due to reduction of cross-sectional area of channel under the surface, floods in the northern Pivška kotlina are frequent and sedimentation of suspended and bed load is common in front of caves. Such floods with higher accumulation seem to be more frequent in the past geologic history since we can recognize many accumulation terraces in this part. Thickness of fluvial sediments and weathered flysch rock is such that Nanoščica and Pivka river with more than 3 m deep banks never cut into the flysch rock. Regarding to Gospodarič & Habič (1966), the first terrace should be formed in older Pleistocene and the newest one in Würmian glaciation. For development of cave Lekinka is very important formation of terrace in altitudes between 520 and 528 m, since the catchment area of Črni potok lies on this terrace. Therefore, Lekinka can be simply described as ponor cave with catchment area on Pleistocene fluvial terrace of Pivka and Nanoščica. Altitude of ponor is very low (510.5 m) and for 1 m lower than ponor of Pivka jama (511.5 m) which lies 1 km SE from Lekinka. Because of low hydraulic gradients in the underground, water level in Lekinka lies very close to piezometric level. The latter is defined by underground Pivka river, which flows in Otoška jama at the altitude ~504 m.

Research history of Postojna cave system and Pivška kotlina is relatively long and rich but Lekinka was rarely in focus of cave or speleological research. The first description is known from the time of A. Martel (1894, 442 after GOSPODARIČ & HABIČ, 1966, 13). Although it is very safe even during middle discharge and simple for exploration, the first survey was done by cave club Anthron at the end of 19th century. At that time, 350 m of entrance passages were mapped. More detailed and longer survey was done somewhere around 1926, when they surveyed 387 m of underground passages. Finally, whole cave to the Končni sifon (=Terminal sump) was surveyed by Gospodarič, Habič and Kenda around 1966.

Speleological research of cave Lekinka is even sparser than survey of the cave. Gams (1966a), Michler & Hribar (1959) and Melik (1955) did not pay any attention to Lekinka although they were dealing a lot with karstological and speleological research in Pivška kotlina and its surroundings. Lekinka was studied most intensively by Gospodarič & Habič (1966) in the 1960s, when they make basic geological, geomorphological and hydrological observations. Later, Lekinka was not subject to any research.

Geological and geomorphological characteristics

The catchment area of Črni potok (=Black stream), which sinks into cave Lekinka, extends on Pleistocene accumulation terrace of Pivka and Nanoščica. Fluvial deposits of silicious Eocene flysch are several metres thick and Črni potok nowhere cuts its channel into underlying flysch rocks. Contact between fluvial sediments and limestone is located 50 m before Črni potok disappears into Lekinka. This 50 m long watercourse lies exactly at the thrust fault which is responsible for sharp contact of Eocene flysch with Cretaceous limestone. The thrust fault face is morphologically transformed into a 30 m high steep slope, where small but long-term rock falls have formed a slope with angle 30-35°, this is angle of repose. Angle of slope near ponor is somewhat higher since the debris is washed away by Črni potok. In the stream channel, blocks of limestone with diameter up to 0.5 m are common.

All known passages of Lekinka are developed in Senonian limestones, which are generally inclined for 70-90° toward SW. Toward NE, inclination of strata decreases toward Postojna anticline, which has its axis in NW-SE direction and extends over Postojna cave system. Thickness of strata depends on age – lower (older) Senonian limestones are thick-bedded or even nonstratified while the upper (younger) are developed as stratified limestones with thickness of strata about 1 m (GOSPODARIČ & HABIČ, 1966). All Senonian limestone is very pure and contains small amount of impurities.

Due to thrusting, Senonian limestones are well fractured. Interbed movements at bedding planes are numerous (GOSPODARIČ & HABIČ, 1966). Although the karst massive lies only several hundred metres away from an important thrust, no crushed or significantly broken limestones can be observed in any passage of Lekinka.

All these geological characteristics are expressed in general cave morphology. Since the limestones are not considerably tectonically deformed, 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 rectangular plan of the cave (see Fig. 4.2.5). Deeper in the cave, absence of bedding planes forced passage development along faults and cracks with less expressed geometric pattern. Therefore, the plan of the cave is less rectangular. Unknown water-filled passages between terminal sump in Lekinka and Otoška jama is formed in Turonian strata, which are developed as thick-bedded limestones with rare bedding planes (ŠEBELA, 1998). Rare bedding planes can be resulted in lower possibility for development of free surface flow – therefore, sump is developed at this place.

Contact karst at the NE edge of Pivška kotlina is subject to long-term term geomorphic evolution, where speleogenesis of epiphreatic passages started at least 530 ka ago (ZUPAN HAJNA ET AL., 2007). Such a long geomorphic evolution resulted in some typical underground formations, while superficial contact karst is morphologically relatively poorly developed. For instance, only one blind valley is developed along NE contact (fossil blind valley Risovec), while all other rivers (Pivka) and streams (Črni potok, Osojca) have not developed any blind valley at present ponor sites (MIHEVC, 1991). Contrary to this fact, several nowadays hydrologically active and inactive caves which show characteristics of ponor caves (location, sediments, corrosion-erosion wall notches, incised meanders) are located at the contact. Ponor caves are not dispersed all along the contact – they are concentrated between entrance to Postojna cave and fossil blind valley Risovec (Fig. 4.2.1), this is at only 30 % of the whole NE contact between flysch rocks and limestones in Pivška kotlina. Behind this 1.9 km wide stripe, all known passages of Postojna cave and cave Lekinka are located. This characteristic shows that only this part of contact was under the long-term influence of sinking streams which flow underground toward NE, that is toward Planinska jama. In smaller scale, two locations can be highlighted from this 1.9 km wide stripe: the area near Postojnska jama (=Postojna cave) and area near blind valley Risovec. On the surface, these two sinking areas are divided by the 40 m high erosion terrace of Veliki Otok (545 m a.s.l.). Both ponor areas are characterized by large underground passages (i.e. Postojnska jama and Otoška jama as part of it) and also much smaller caves formed as narrow meanders (i.e. Lekinka, Reg. No. 1867, 511 m a.s.l.; Betalov spodmol, Reg. No. 473, 532 m a.s.l.; Jama 1 nad Lekinko, Reg. No. 1615, 531 m a.s.l.; Jama 2 nad Lekinko, Reg. No. 1616, 549 m a.s.l.; Ciganska luknja, Reg. No. 2172, 539 m a.s.l.). All these caves at various altitudes (from 510 m to 549 m) show similar characteristics, which are much different from the large passages of Postojnska jama (i.e. width-height ratio, presence of wall notches, vadose-phreatic morphology). Therefore we suppose that they were formed in similar ways and that present-day processes and factors in Lekinka are valid also for other, nowadays higher fossil caves. This finding is contradictory to some baseless statements (BRODAR, 1949, 99), that some of these narrow caves were formed as branches of big rivers (i.e. Pivka or Nanoščica).

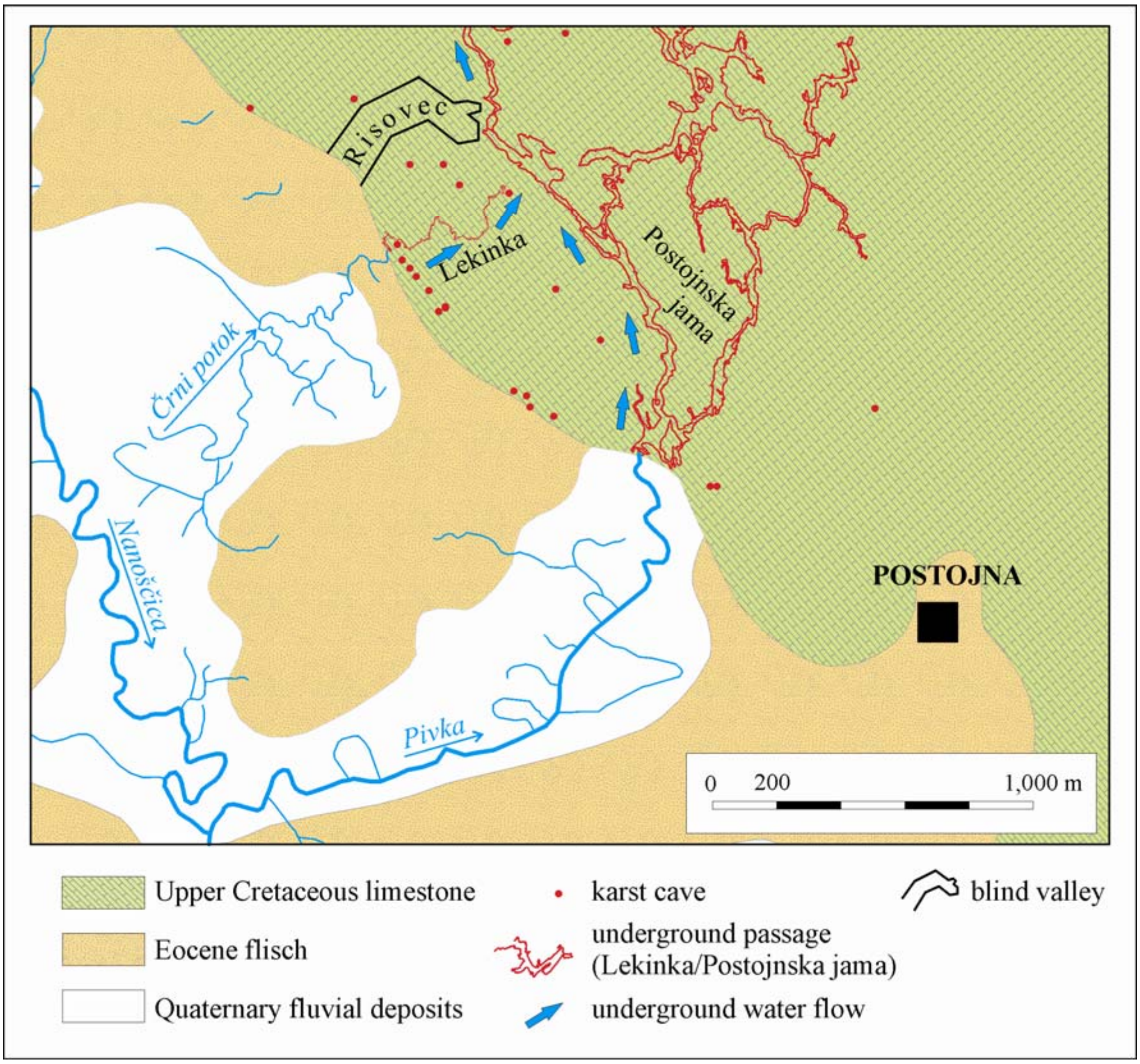


Figure 4.2.1: *General hydrogeological map of karst massive near Lekinka and its superficial catchment area (source of geological data: BUSER ET AL., 1976).*

Gospodarič and Habič (1966) recognized Lekinka as young ponor cave where corrosion still takes place. This statement is based on chemical analyses of water, which showed that total solute load slowly grows from the entrance toward inner parts of a cave, on general geomorphic evolution of terraces in front of ponors and on "freshness" of features. On the other hand, Gospodarič and Habič (1966, 17) were surprised upon low increase in solute load along watercourse – therefore they also state that present-day corrosion is relatively weak or "some unknown chemical processes takes place in Lekinka, which cause increasing or decreasing of solute load along underground water course". Finally, they conclude that the initiation of Lekinka's first passages started during interglacial period Riss-Würm and that formation of 3 wall notches found in the entrance parts of Lekinka correspond to 3 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). A much smaller part of catchment area (~27 %) lies on slope of erosion terrace composed of deeply weathered flysch rocks. Therefore, low maximum relief amplitudes (up to 35 m) result also in very low mean inclination of catchment area (~1º). Some areas, especially near Nanoščica river, can be characterized as marsh from where outflow of water rich in humic acids is common. Catchment area of Črni potok in just half changed from natural forest into meadows since the soils are soaked with water and at some places acidified. According to the pedological map (ŠPORAR ET AL.), soils are mainly brown eutric epi- and hypogleys. This means that the soil contains quite a lot of base cations (mainly Ca^{2+}) and that is at least occasionally soaked with ground or precipitation water – but at some places base cations were already washed out and more acidic soil can be expected. Since the catchment area lies in lowland where the precipitation water with low solute load can be even more acidified with humic acids, quite aggressive water can be expected at the contact with limestone and further into the cave. This was proved also with SEC measurements, which show values mostly between 150 and 200 µS/cm (at high discharge, SEC can be even below 100 µS/cm, while at low discharge it can rise above 400 µS/cm). Although the water has a low solute load and can be very aggressive, intensity of corrosion was never studied in Lekinka.

Discharges were measured 50 m upstream of the Ponor by means of NaCl-solution injection and integration of the specific electrical conductivity as a function of time (salt dilution method). Discharges were estimated using stage-discharge curve (Fig. 4.2.2) and a water gauge 75 m from the entrance. Regarding the relatively small catchment area, mean discharge amounts about 0.04 m^3/s. At low water level, less than 0.01 m^3/s is drained from the catchment area and at such water level all water disappears into the swallow holes at the flysch-limestone contact 50 m from the cave's entrance. Therefore, water flow in the entrance part of the cave is absent. In continuation, some tributaries can sustain very low discharge. Discharge with more than 0.8 m^3/s is rare – it occurs about once per year. At such and even much higher water level, Lekinka is able to conduct all the water without any special damming. Problem in conduction usually occurs in Otoška jama, where oscillations of several metres are common during a year. This leads to backflooding of Lekinka. When the water level in Otoška jama exceeds altitude 509.5 m, backflooding reaches the water gauging station in Lekinka. At even higher water level, when Pivka with Nanoščica floods in front of Postojnska jama and the water level exceeds elevation 518-519 m, water of Nanoščica spills over its banks over Lekinka's catchment area and causes extensive floods in front of Lekinka. At the same time, the outflow of Črni potok is blocked by underground Pivka river. In such situation, Pivka, Nanoščica and Črni potok form the same hydrological system with a little different water flows. Such a situation happened on 12th December 2008 (Fig. 4.2.3).

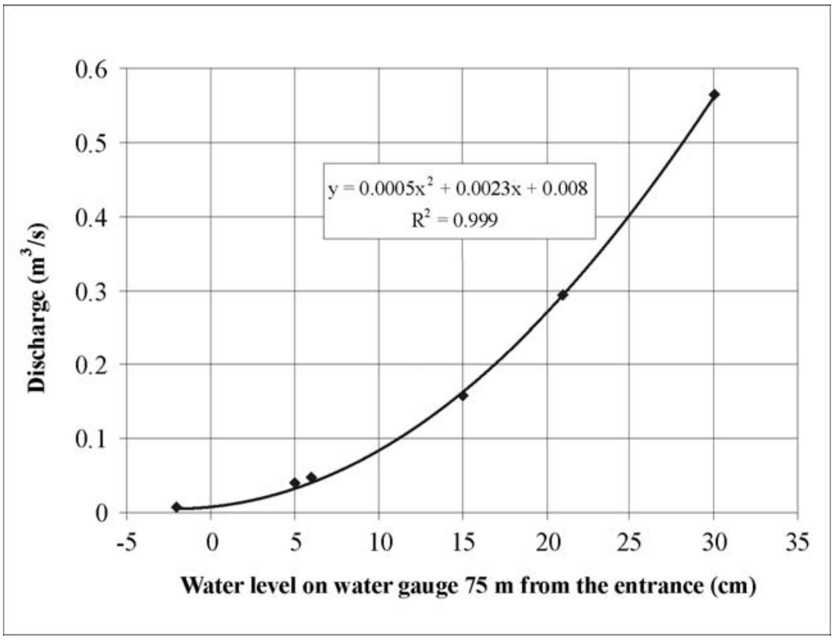


Figure 4.2.2: *Stage-discharge curve for gauging station 75 m downstream of the entrance to Lekinka.*

Figure 4.2.3: *Flood in front of Lekinka (usual ponor is about 6 m under the water level), when Nanoščica river spilled over its banks on 12th December 2008.*

During its 1,032 m long underground course through Lekinka, Črni potok descends for 5 m from 510.5 m to 505.5 m (GOSPODARIČ & HABIČ, 1966). Accordingly, the gradient amounts to 0.48 %, which is slightly less than underground Pivka river to the first sump in Postojnska jama (0.54 %) and underground Pivka river in Planinska jama (0.58 %; HRIBAR & MICHLER). Although the water flows perpendicular to Senonian strata, general deviation from the shortest connection with Otoška jama is quite small (27° toward south, this is upstream to underground Pivka river in Otoška jama; see Fig. 4.2.1). This means that underground Črni potok is taking almost the shortest direction to the confluence with underground Pivka river and that water flow through Lekinka was always directed to Otoška jama. In smaller scale, deviations from direct direction to underground Pivka river up to 160° are possible.

In Otoška jama, Črni potok flows into the underground Pivka river. The confluence was for the first time recognized by Michler & Hribar (1959) when they measured water temperatures along underground Pivka river. Later, caves were never connected due to small and branching passages, which represent a problem for cave divers but probably do not represent a significant hydrological barrier for underground flow of Črni potok. At high water level, the most significant influence to the underground Črni potok is from underground Pivka river which rises in Otoška jama for more than 10 m. Therefore, at such water conditions the water level in Lekinka is more or less defined by underground Pivka in Otoška jama (Fig. 4.2.3).

The main water course, which sinks at the Ponor is fed by several underground tributaries in Lekinka (Fig. 4.2.4). At medium water level, 7 significant tributaries can be visible because of their location above water level. One underwater tributary downstream from Stranski podor (=Side breakdown) was detected from SEC, temperature and pH measurements. Accordingly, 8 tributaries were identified during 790 m long underground water course of Črni potok. Origin of tributary water is unknown – it can be allogenic water connected with two small streams that sink 375 and 700 m NW from the entrance to Lekinka. Both streams have very small mean discharges (several l/s) due to small catchment areas (0.023 and 0.027 km^2) and could correspond to discharges of tributaries in Lekinka. More problematic seems to be high SEC (266-487 µS/cm) at low-middle discharge and relatively constant temperature of tributary water (7.8-11.4 °C), which are more characteristic for autogenic recharge. Therefore, tributary water most likely derives from primary infiltration from the vicinity of cave Lekinka.

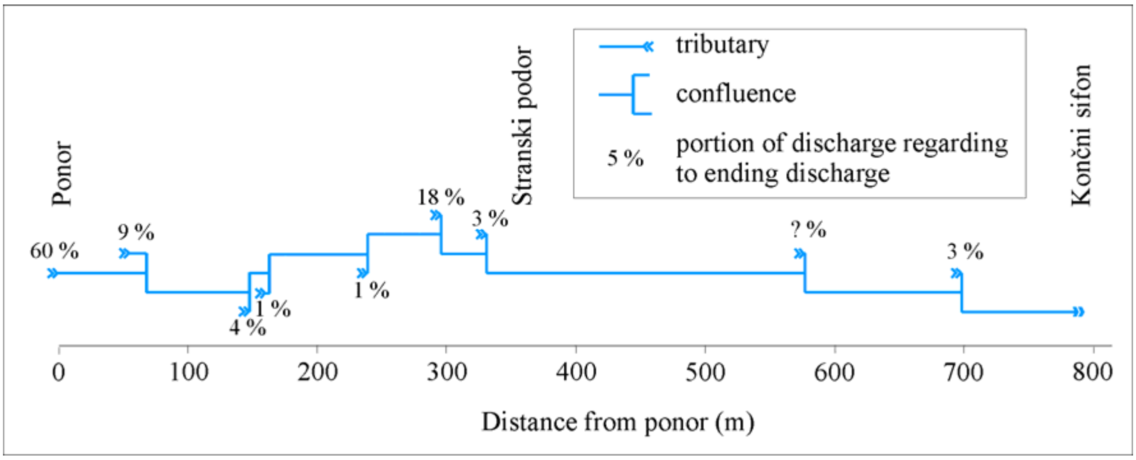


Figure 4.2.4: *Hydrological network of the cave Lekinka regarding to visual observations and SEC, temperature and pH measurements at medium water level (*$H_{\text{gauging station}} \approx +5$ cm*) on 13th February 2008.*

The majority of tributaries are located in the first 300 m of Črni potok underground flow. This can be partly a result of much heavier detection of tributaries in the second part of a cave, where deep and quite long lakes are located. At least 3 tributaries dry out during summer months if precipitations are absent for several weeks. Tributaries contribute variable part of water according to water level. At medium water level ($H_{gauging\ station} \approx +5$ cm), the highest portion is contributed by 5th tributary (28 % of the water that sinks at Ponor or 18 % of the whole water flow at Končni sifon during low-middle discharge). The second most efficacious tributary is the 1st one, which contributes 9 % of the water that sinks at Ponor. The all other tributaries contribute less than 6 % of the water that sinks at Ponor or about 4 % of the whole water quantity at Končni sifon. The whole contribution of tributaries at Končni sifon is estimated to be at least 40 %. At higher water level, contribution is supposed to be smaller since the tributaries most probably represent primary infiltration with more constant discharge. Just the opposite, at low water levels they should contribute much higher portion of water. At very low water level, when all water of Črni potok is drained away from the water channel before Ponor, entrance part of cave Lekinka dries. The only sources of flowing water are some tributaries that do not dry out even at very low water level.

Meteorological characteristics

The only known entrance to Lekinka is located at the ponor of Črni potok. There are actually two entrances, which are connected through a sump even at medium water level. Through the lower entrance, Črni potok disappears into Lekinka. About 3 m above lower entrance, the higher one is located. At its narrowest place, it is about 1.5 m wide and up to 0.6 m high.

Since we know that the whole trunk passage of Lekinka is very well ventilated especially in summer and winter months, the second entrance or connection with ventilated Otoška jama is obvious. Less than 40 m from the Končni sifon, a collapse doline is located. It seems to be very suitable for another entrance, but since even a small ventilating hole is absent on the surface, connection with Lekinka is very questionable. Therefore, more probable is connection with Otoška jama, which was already proposed by Gospodarič & Habič (1966).

Air flow can be felt through the entire cave. Intensity and direction depends on difference between outside air temperature and air temperature in the cave. Change of direction happens when the outside air temperature exceeds/falls below cave temperature (~8 °C that is at the average temperature in Postojna between 1961 and 1990 (CLIMATIC DATA FOR METEOROLOGICAL STATION POSTOJNA 1961-1990). Nonetheless, water flow can cool down or warm up the cave for several degrees and can therefore slightly influence direction and intensity of ventilation. When outside temperature exceeds cave temperature, air flows from Končni sifon toward Ponor. When temperature difference is reversed, outside air flows in the opposite direction. If temperature is lower than 0 °C, freezing of the entrance part is common. In such a situation we can observe also weakly expressed mechanical weathering in the entrance part of Lekinka. Before 2nd World War, ventilation was even stronger since the entrance was not so artificially modified, partly blocked by gravel.

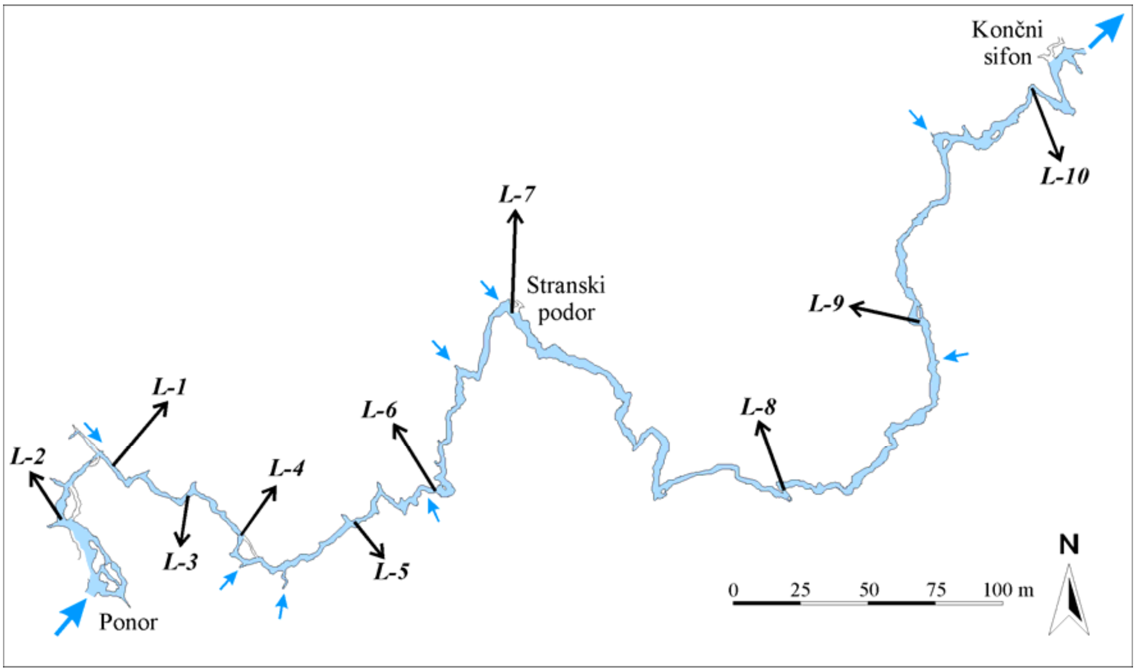


Figure 4.2.5: *Plan of Lekinka with measurement points.*

Corrosion rate measurements and their relation to key factors and forms

4.2.1 Measurement place L-1 – temporal variability of processes 75 m from the ponor

Since the Lekinka cave is a typical ponor cave with catchment area in partly carbonate accumulation terrace and show low solute load at the entrance, we should expect relatively high corrosion rates – at least in the entrance part of the cave. High corrosion rates in similar environment were confirmed also in other karst areas (DROPPA after GAMS, 1985, 368) and were expected in Lekinka already by Gospodarič & Habič (1966). Contrary to expectations, mean corrosion rates calculated from water hardness were surprising – corrosion rates seemed to be not as big as they expected (GOSPODARIČ & HABIČ, 1966). Since we know the actual yearly corrosion rates from Lekinka (Chapter 3), we can understand why Gospodarič and Habič were so confused about corrosion. The most probable reason for low corrosion rates measured by Gospodarič and Habič (1966) is probably low water level, during which the water was analysed (at higher water level caving is very difficult and much more dangerous than at lower water level). To confirm this idea and to get some new insights into seasonal variations in corrosion rates, precise short-term measurements with limestone tablets are an excellent opportunity to make measurements of corrosion rates and their relation with discharge. This was already 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 scale are possible". He advised usage of micrometer or limestone tablets.

Measurements of temporal variation in corrosion rates started on 25th September 2006 and finished on 5th April 2009. Measurement point named L-1 was located 75 m downstream from Ponor about 7 m downstream from the 1st left tributary (Fig. 4.2.5). Water flow was always turbulent with mean water velocities about 0.5 m/s. At very low water levels ($H_{water\ gauge}$ = -5 cm), water flow was absent. We used 22 limestone tablets for corrosion rate measurements – 11 limestone tablets were exposed at measurement points and another 11 tablets were at the same time dried in chemical laboratory at Karst Research Institute ZRC SAZU. In this chapter we used only average value of the lower two limestone tablets at $H_{water\ gauge}$ = -7.5 cm and $H_{water\ gauge}$ = -2.5 cm, since they under the water level during low-medium water level. Limestone tablets were fixed on stainless steel screws with stainless steel nuts and two felted stainless steel washers.

Tablets were exchanged after 15 days of drying/exposure. Such a period was long enough to get some reliable values considering precision of methodology and previously measured values (Chapter 3). At high water levels, we supposed that the measurement interval could be much shorter (even less than one day) but since such intensive measurements are very time consuming we decided for a more simple approach – for the same interval as in Križna jama (Chapter 4.1). Since Črni potok transports some bed and suspended load, corrasion could be possible at higher water level.

Figure 4.2.1.1: *Measurement point L-1 at very low water level ($H_{water\ gauge}$ = -5 cm; the lowest limestone tablet is under the water level).*

Results from measurement place L-1 are represented in Fig. 4.2.1.2. As expected, course of corrosion rates corresponds to rain-snow discharge regime (KOLBEZEN & HRVATIN, 2001, 58), which is typical for central part of Slovenia. Therefore, high corrosion rates were detected at generally higher discharges, which occur in autumn and spring. Low discharges are characteristic for summer and winter. The latter usually depends on snow retention, which is a consequence of precipitation that falls as a snow and low-temperature conditions – if they overlap, snow retention is possible. Quite warm winters 2006/2007 and 2007/2008 without significant snow retention caused joining of high autumn and spring corrosion rates. Only absence of precipitation in two cold periods during winter 2007/2008 led to two low corrosion rates and partial separation of autumn and spring period of corrosion. During winter 2008/2009, the situation was similar. Nevertheless, low corrosion rates during winter do not significantly influence yearly course of corrosion rates, generally represented as polynomial function (Fig. 4.2.1.2). Corrosion at L-1 out of maximum error of measurement (±0.0004 mm) appears when the water level exceeds at least $H_{water\ gauge}$ = +5 cm (Q = 0.04 m^3/s).

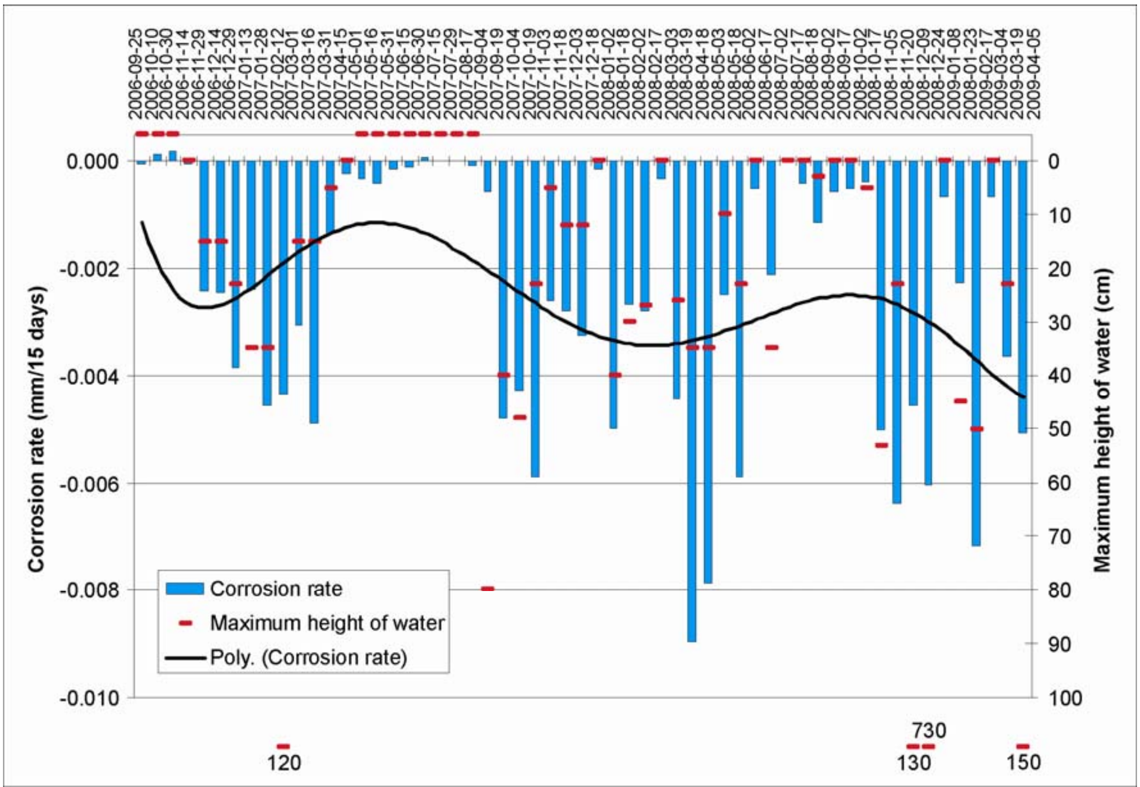


Figure 4.2.1.2: *Corrosion rates between 25th September 2006 and 5th April 2009 at measurement point L-1 in Lekinka.*

Total corrosion rate during 15 days of exposure depends on two phenomena:

- corrosiveness/aggressivity of water and
- time of exposure to individual corrosiveness of water.

The first is defined as facility or power of water to dissolve calcium carbonate (SWEETING, 1972, 26) and depends mostly on Ca^{2+} and H^+ concentration. The latter concentrations depend on interaction with soil carbonates and soil CO_2 in the catchment area. In swampy catchment areas (i.e. Črni potok), we should take into account also enhanced acidification of water caused by humic acids. In Lekinka, high concentration of organic matter in the water can be clearly seen in a brownish colour. Since the soil CO_2 concentrations are strongly related to microbial activity, which is higher 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 is expected during summer and lower during winter months. Some authors (e.g. SWEETING, 1972, 219 and 226) affirm quite the contrary – corrosiveness of water should be higher in winter due to lower temperatures of water, which enhances higher solubility of CO_2. Special attention was dedicated to decay of organic matter, which can, with decomposition of organic mater to CO_2 (BRAY, 1977) and organic acids, form complexes with Ca^{2+} ions (the latter reduces activity of Ca^{2+} ions and therefore influences equilibrium; ROQUES, 1969, 144) and consequently enhance corrosion rates. Concentration of humic acids is hard to measure since it involves many complex organic compounds; usually concentrations are estimated using total organic carbon (TOC) or dissolved organic carbon (DOC) concentrations. According to Butturini & Sabater (2000), the highest DOC concentrations are observed at flood events and in autumn and winter months. According to all these data, the highest aggressiveness of water is expected at high water level without clear evidence on seasonal variations. The longer are the high water levels, the higher corrosion rates are expected within 15 days.

According to results in Fig. 4.2.1.2, higher corrosion rates are evidently related to higher water levels, although the highest corrosion rates are not always related to the highest water levels. For example, during periods 12th February 2007 – 1st March 2007 and 4th September 2007 – 19th September 2007, two flush floods did not result in significant corrosion rates. Even more, another two periods of the highest water level (20th September 2007 – 9th December 2008 and 9th December 2008 – 24th December 2008) did not result in the highest corrosion rates. Therefore, only high water levels with high discharges are not so important for high (and the highest) corrosion rates, which can be recognized also from relatively low Pearson product moment correlation coefficient (-0.56) and low R^2 (0.31; Fig. 4.2.1.3). The highest corrosion rates were recognized at medium water levels (from $H_{water\ gauge} \approx 20$ cm to $H_{water\ gauge} \approx 35$ cm) if such water levels last long enough (several days). Therefore, much higher correlation was found between corrosion rates and total amount of precipitation within 15 days (from meteorological station Postojna). If we exclude results obtained during warm months (May, June, July, August), when evapotranspiration importantly reduces runoff, Pearson product moment correlation coefficient (0.78) and R^2 (0.61; Fig. 4.2.1.3) are quite high. High positive correlation between corrosion 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).

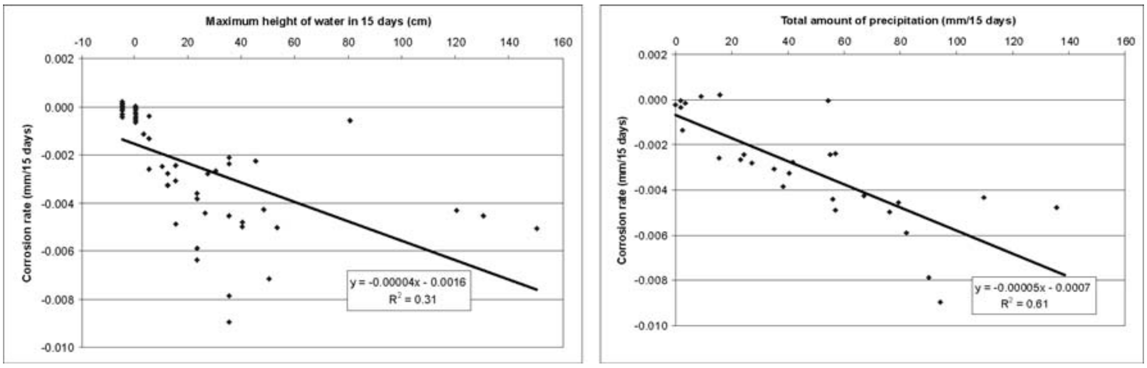


Figure 4.2.1.3: *Correlation between corrosion rate and maximum height of water during 15 days and between corrosion rate and total amount of precipitation during 15 days*[1].

Although correlation between corrosion rates and maximum water height or total amount of precipitation in 15 days is lower that should be expected, equations that describe correlation with corrosion rates (Fig. 4.2.1.3) makes it possible to calculate potential corrosion rates according to maximum height of water or total amount of precipitation. Differences between predicted corrosion rates and actual corrosion rates behave very similar in both examples (Fig. 4.2.1.4) and therefore show quite a high degree of relationship (Pearson product moment correlation coefficient amounts 0.77). With maximum height of water or total amount of precipitation unexplained difference shows no seasonal variations (Fig. 4.2.1.4) and therefore neglects strong seasonal

[1] In the correlation between corrosion rates and amount of precipitation, data from May, June, July and August are excluded, while in the correlation between corrosion rates and maximum height of water, result during exceptional high water ($H_{water\ gauge} \approx 730$ cm) is excluded.

influence of organic acids. Lack of seasonality of deviations also neglects influence of water temperature, which was predicted by Corbel[1] (1959 after WHITE, 1986, 261), Moore[2] (1964 after WHITE, 1986, 261) and observed by Gams (1966b, 13) on bare rock surface or in superficial stream (1966b, 35-37; in the latter case, differences in hardness along the watercourse are extremely small and can be therefore attributed to errors). This does not mean that these factors do not influence corrosion rates but that their seasonality cannot be observed or is very low.

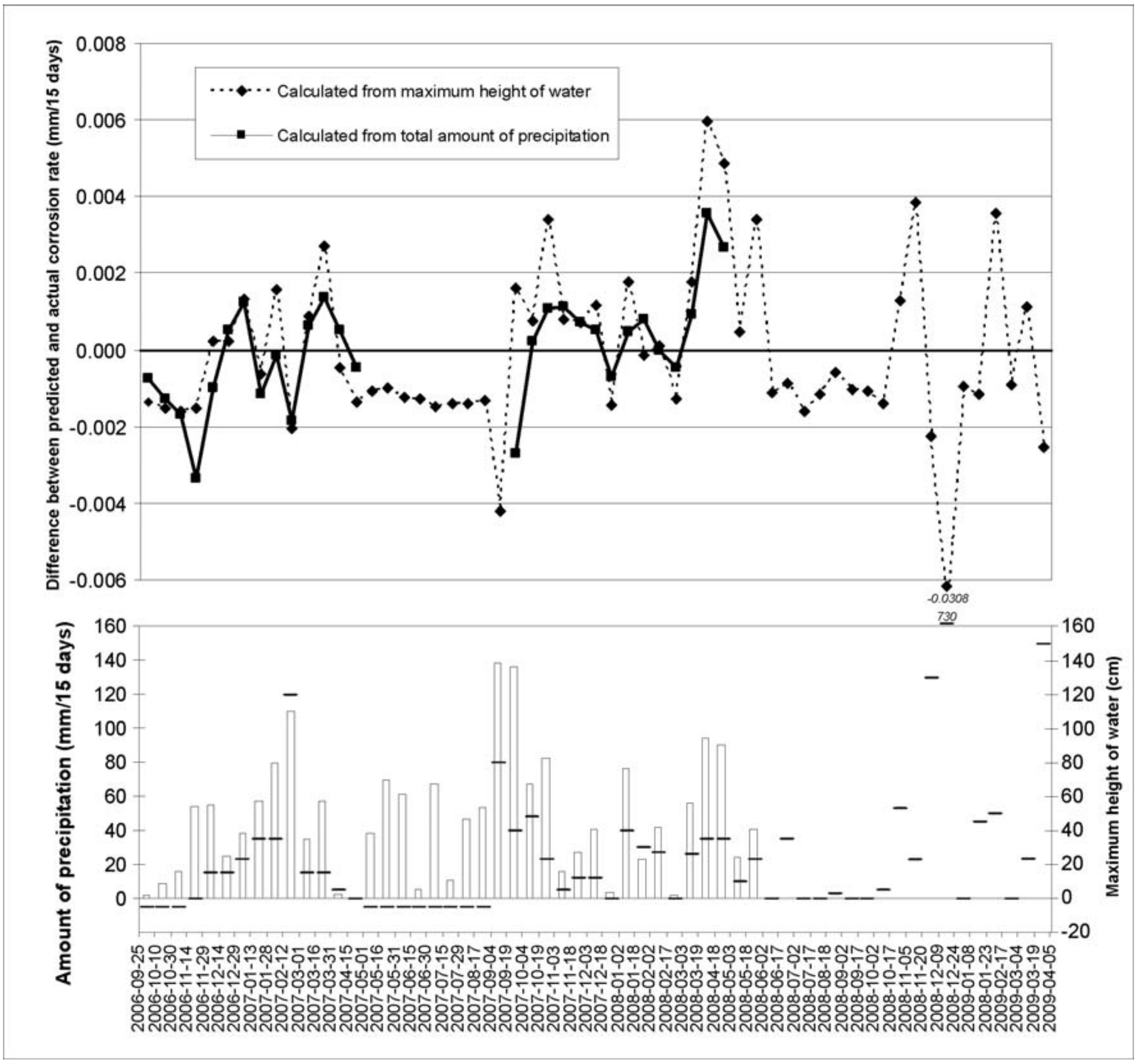


Figure 4.2.1.4: *Difference between predicted and actual corrosion rates with regard to comparison between maximum height of water and total amount of precipitation. After 1st June 2008, data for amount of precipitation are not available.*

[1] Higher aggressiveness is expected in winter time since the CO_2 is more soluble in cold water.
[2] Higher aggressiveness is expected in summer time since the biological production of CO_2 is the highest in warm months.

Another seasonal factor that should affect corrosion rates is cave air CO_2 concentration. During corrosion, CO_2 concentration in the water falls. In Lekinka, the system is open, which means that CO_2 can be taken from the atmosphere. The best opportunity for this is in summer time, when the cave air CO_2 concentration amounts up about 1,360 ppm. In winter time, CO_2 concentration at L-1 can is equal to outside concentration since the entrance part is cooled and very well ventilated. Since the summer corrosion rates most commonly are very low and also below mean annual predicted corrosion rates (Fig. 4.2.1.4), high CO_2 concentration in summer does not play important role at corrosion rates – at least not at L-1.

Caves develop under a variety of processes, among which the corrosion and corrasion are usually highlighted. Delineation of corrosion and corrasion was often a challenge for geomorphologists and a source of many discussions. Generally accepted belief is that corrasion takes minor role at "normal" water levels but can be strong speleogenetic factor at high water levels. In floods both accelerate but corrasion exceeds corrosion (NEWSON, 1971). Nevetheless, distinction between them is quite complicated, since the corrosion is usually incomplete and the remnants of corrosion (i.e. big crystals) are often torn away by force of flowing water (ZUPAN HAJNA, 2003) – with or without bed load or suspended load. In Lekinka case, high water transports rather small amount of siliceous bed load but a lot of siliceous suspended load (sometimes visibility of water is less than 5 cm – especially during flush floods). Such composition of transported material is a result of gently sloping relief in catchment area of Črni potok, where a small amount of bed load material is available. Since a lot of suspended sediment is transported at higher water level, we would expect some corrasion as peaks in thinning of limestone tablets, when maximum water levels are high (HABIČ, 1966, 18). But several high water levels represented in Fig. 4.2.1.2 are not usually connected with high thinning of limestone tablets since backflooding occurs when the water level exceed $H_{water\ gauge} \approx +40$ cm (Fig. 4.2.1.5). The only hint to corrasion can be slight decline in "corrosion" rates at L-1, when the water level exceeds $H_{water\ gauge} \approx +50$ cm (see Fig. 4.2.3.2 in Chapter 4.2.3). At this water level, velocity of flow is significantly lower due to backflooding and transport of sandy material is highly reduced. Besides lower corrasion, slightly lower weight loss of limestone tablets can be also a result of lower corrosion rates due to diffusion boundary layer, which is thicker when the water flow slows down due to backflooding. Therefore, clear distinction between corrosion and corrasion is almost impossible due to smooth transition between both processes. According to slight decline in weight loss of limestone tablets when the water level exceeds $H_{water\ gauge} \approx +50$ cm, velocity of water flow most probably influences corrosion and/or corrasion process. Since the majority of bed load is transported close to the channel bed and we do not see any difference in weight loss between limestone tablet at $H_{water\ gauge} \approx -7.5$ cm and $H_{water\ gauge} \approx -2.5$ cm, influence of bed load transport to corrasion seems to be rather small.

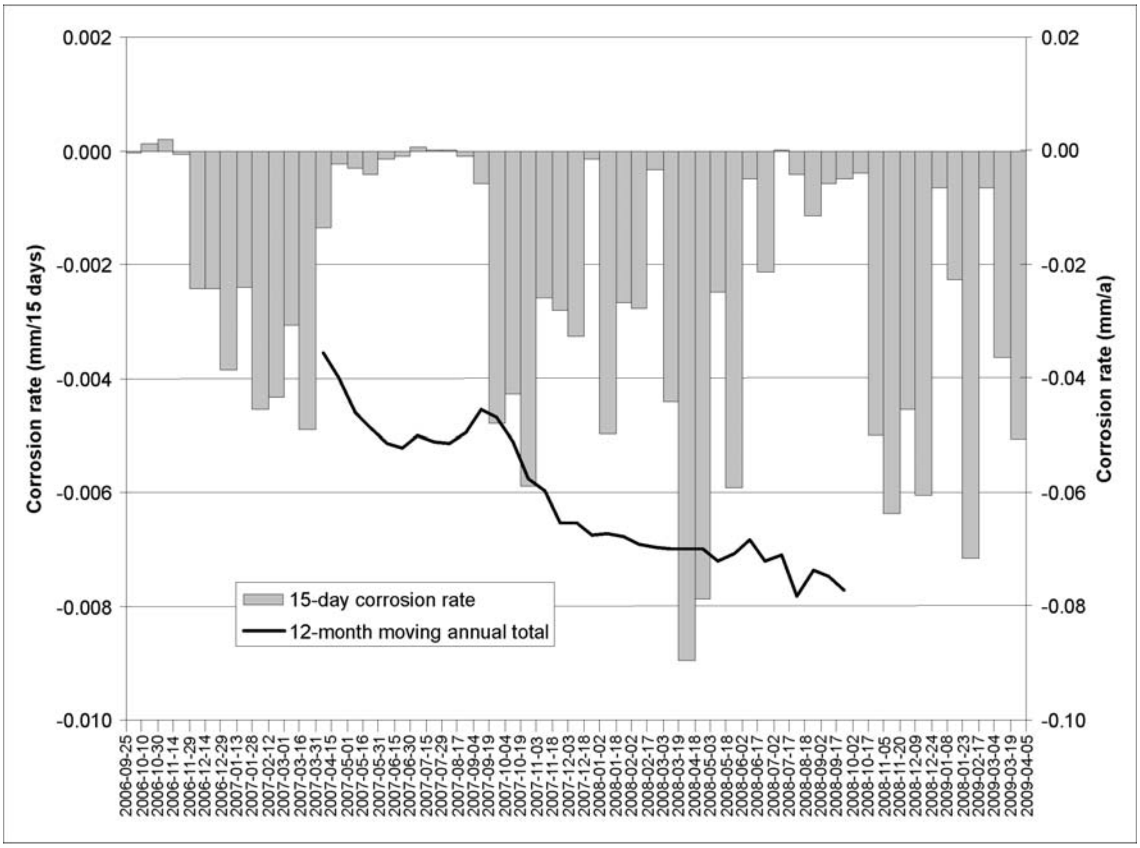


Figure 4.2.1.6: *Corrosion rates measured in 15 days and their 12-month moving annual total from measurement point L-1 (average of the lowest 2 limestone tablets).*

Results obtained at L-1 give us also important information about changeable annual corrosion rates (Fig. 4.2.1.6), which can be represented as moving annual total (annual moving sum of 24 corrosion rates obtained in 15 days (≈1 year). According to moving annual total, minimum annual corrosion rate of -0.0356 mm/a and maximum corrosion rate of -0.0781 mm/a was obtained. Difference between these two values and also standard deviation of annual corrosion rates is relatively high (±0.0118 mm/a), which shows strong variation in annual corrosion rates. Nevertheless, average annual corrosion rate of -0.0611 mm/a and standard deviation (±0.0118 mm/a) are thought to be at least a relatively good approximation of magnitude of annual corrosion rates. If we assume similar corrosion rates in the last 10,000 years, from 36 and 78 cm of corrosion can be expected (corrosion rates in Senonian limestone from Lekinka are almost the same – see Fig. 2.1.3.11). If we take into account that corrosion rates observed with micrometer are on average 56 % higher (Figure 2.1.3.12), incision of the meander amounts from 56 to 122 cm. Using the same rates corrected with micrometer measurements, actual 4 m high meander at L-1 could be developed in 33,000-72,000 years.

High corrosion rates in Lekinka (will) have some hydrological, geomorphic and speleological consequences. In comparison with Postojnska jama (Chapter 4.4), Lekinka has lower entrance (510.5 m *vs.* 511.5 m). Water divide between Črni potok and Nanoščica river seems to be stable for several 10.000 years. However, continuous widening and lowering of Lekinka's entrance passages due to high corrosion rates and consecutive downcuting of Črni potok will result in more and more often spilling of Nanoščica's water into catchment area of Črni potok. In December 2008, we were lucky to observe consequences of such, nowadays occasional, spilling (Fig. 4.2.1.5). On 11th December 2009, rise of water level started with very quick rise of waters (1.2 m/h), when the water level in Lekinka was medium high ($H_{water\ gauge} \approx +35$ cm). High rise of water level was actually backflooding in Lekinka cave, which happened due to increasing water level in Otoška jama. After 6 hours, surface channel of Črni potok was full and rising was slowed down due to spilling of water over the banks of Črni potok to extensive flood plain, which can accumulate big amounts of water without significant water level rise. At that time, water flow in Lekinka might be reversed and Lekinka act as a spring since the water level in Otoška jama was still increasing but in Lekinka, water level stagnated. After 4 hours of relatively slow rising, another steep rise of water happened. This was spilling of Nanoščica river into Črni potok catchment area over 518-519 m high water divide. Due to huge amount of Nanoščica's water, water level rise was quite fast – up to 1.4 m/h. The highest water level was reached after 30 hours from the first rise at $H_{water\ gauge} \approx +730$ cm, when Nanoščica reached its maximum. Declining of water level was slow at the beginning and even faster than rising at the end (more than 2.5 m/h). This confirms supposition about good hydraulic permeability of Lekinka, which can transfer all the water from Črni potok without significant damming.

Although the water level was higher than $H_{water\ gauge}$ = +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 corrosion rates (-0.0061 mm/15 days). We have to stress that similar corrosion rates were reached one month before when the highest water level did not exceed $H_{water\ gauge}$ = +23 cm (Fig. 4.2.1.2). Therefore we can conclude that all the corrosion in that 15 day measurement period happened before and after Nanoščica river intrusion. At the time of spilling over, Nanoščica could cause minor corrosion rates, which are supported also with corrosion measurements in Postojna cave system (Chapter 4.4.1). Nevertheless, corrosion rates of Nanoščica river are much lower in comparison with Črni potok even at high discharge and will, at the time of permanent spilling over, decrease deepening and probably also enlargement of Lekinka. We can expect also major modification of Lekinka – meander pattern of passages will change toward more laterally extensive (Chapter 4.2.2), since much lower corrosion rates will be observed especially at low and medium water levels and since we can expect some deposition of bed load material in the cave.

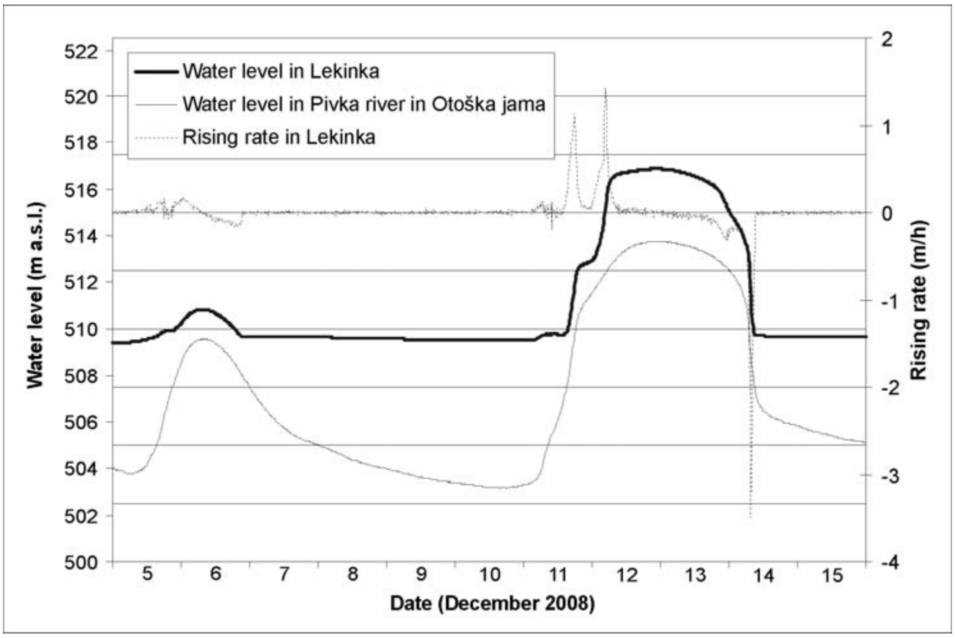


Figure 4.2.1.5: *Water height in Lekinka and Pivka river in Otoška jama and rising rate in Lekinka, when Nanoščica river spilled over its banks and flowed into Črni potok catchment area between 11th and 14th December 2009. See first flush flood event, when Nanoščica did not spill into Črni potok catchment area, for comparison.*

4.2.2 Measurement place L-1 – vertical variability of processes

At measurement point L-1, water fluctuation was observed from $H_{water\ gauge}$ = -5 cm to up to $H_{water\ gauge}$ ≈ +730 cm. Lower section of passage is under the influence of low and high discharge, while the upper part of a passage is influenced only by high discharge. Therefore, corrosion rates should decrease with height – to what extent we tried to find out with a vertical set of limestone tablets located at measurement point L-1. We also tried to find out if the actual morphology of passage corresponds to present-day corrosion rates.

Vertical changes in corrosion rates were measured at measurement point L-1, where we installed 11 limestone tablets on the water gauge. In the lower section, distance between limestone tablets was set to 5 cm, while in the upper section the vertical distance was smaller (Fig. 4.2.1.1). The procedure and duration of measurement was the same as was described in Chapter 4.2.1.

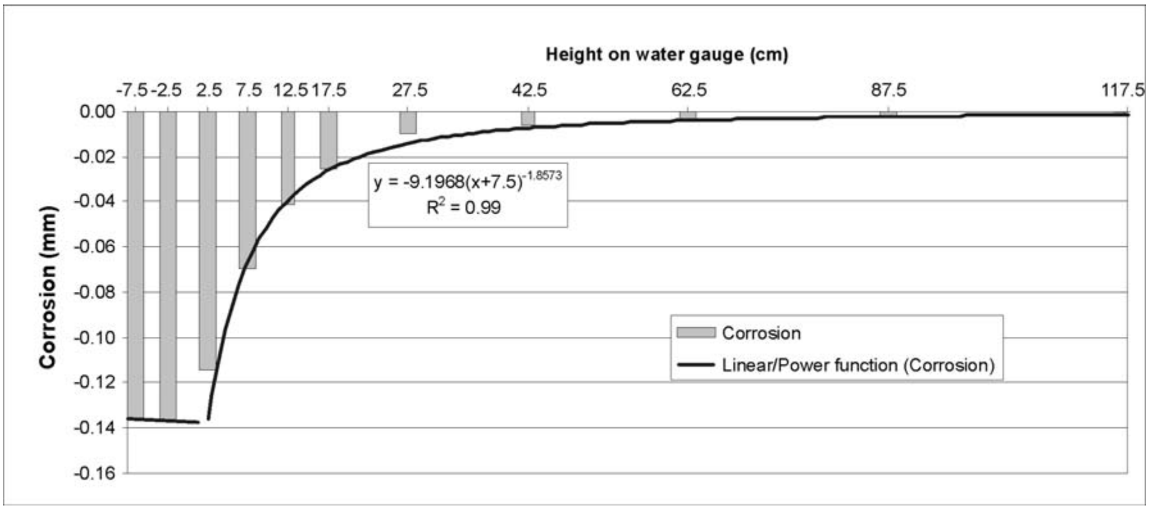


Figure 4.2.2.1: *Decrease of corrosion with height measured at L-1 from 14th November 2006 to 8th January 2009 (786 days).*

Results of measurements at L-1 are represented in Fig. 4.2.2.1. Corrosion at $H_{water\ gauge}$ = -7.5 cm and $H_{water\ gauge}$ = -2.5 cm are nearly equal as was already mentioned in Chapter 4.2.1. This means that when the water level falls below $H_{water\ gauge}$ = 0 cm, water is not corrosive any more. Above $H_{water\ gauge}$ = 0 cm, steep decline of corrosion rates, which can be the very accurately described with power function (R^2 = 0.99), can be observed. This is a result of exposure time – in the measurement period, the highest limestone tablet was exposed to high water levels for only several hours, while the lower limestone tablets were corroded at all water levels. At $H_{water\ gauge}$ = +7.5 cm, corrosion drops to the half of that one, recorded at $H_{water\ gauge}$ < 0 cm. At $H_{water\ gauge}$ = +25 cm, exposure time is so short that only 10 % of corrosion is observed in comparison with $H_{water\ gauge}$ < 0 cm. At $H_{water\ gauge}$ = +120 cm, corrosion drops to less than 1 % (Tab. 4.2.2.1).

Table 4.2.2.1: *Portion of corrosion at different height at measurement point L-1 in comparison with the lowest two limestone tablets at L-1. Data based on results of measurements between 14th November 2006 and 8th 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 corrosion in comparison 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

Decrease of corrosion according to height represented in Fig. 4.2.2.1 and Tab. 4.2.2.1 is a sum of corrosion rates measured in 15 days. If we take into consideration average corrosion rates measured in 15 days in relation to maximum height of water, we notice quite big differences (Fig. 4.2.2.2). Due to 49 individual measurements of corrosion rates in relation to height, results are averaged within 4 different vertical zones of maximum water levels. When the maximum water level within 15 days stay below $H_{water\ gauge}$ = +1 cm (18 measurements; vertical zone 1), the biggest vertical differences are noticed. From Fig. 4.2.2.2 we can see that when the maximum water level stays below $H_{water\ gauge}$ = +1 cm, corrosion above $H_{water\ gauge}$ = +1 cm amounts close to the zero (which is logical since these limestone tablets were not exposed to water flow). Drop of corrosion from $H_{water\ gauge}$ < +1 cm to $H_{water\ gauge}$ = +2.5 cm is huge but such water levels within 15 days are rare (4 %), weak in corrosion even below $H_{water\ gauge}$ = +1 cm and therefore less important.

Very steep decrease in corrosion with height is observed within 2nd vertical zone, where the maximum water height fluctuated between $H_{water\ gauge}$ = +1 cm and $H_{water\ gauge}$ = +22 cm; 11 measurements). In the time of such water level fluctuation, 21 % of all measured corrosion at two the lowest limestone tablets occurred.

The most efficient and therefore representative is 3rd vertical zone (15 measurements), where 59 % of all measured corrosion at two the lowest limestone tablets occurred. If the maximum water level exceeds $H_{water\ gauge}$ = +50 cm (4th zone; 5 measurements; 17 %

of all measured corrosion at two the lowest limestone tablets), corrosion in the lower part is not much higher in comparison with 3rd zone. Even more, corrosion below $H_{water\ gauge}$ = +2.5 cm slightly falls down due to slower water flow which influences corrasion rates, rate of tearing away partly corroded crystals and reduces corrosion rates with thickening of diffusion boundary layer. But above $H_{water\ gauge}$ = +12.5 cm, differences exceed 10 % and therefore further decline in corrosion with height is much lower. The latter characteristics indicate that oscillation of discharge has an important influence on vertical distribution of corrosion – small differences in discharge will result in moderately high maximum height of water and high differences in vertical distribution of corrosion can be expected. On the contrary, high oscillation in discharge (i.e. many flush floods) will not significantly transform the lower part of a passage (in comparison with moderately high maximum height of water) but they will more severely corrode upper parts of a passage. Therefore, differences in corrosion in relation to height are much lower.

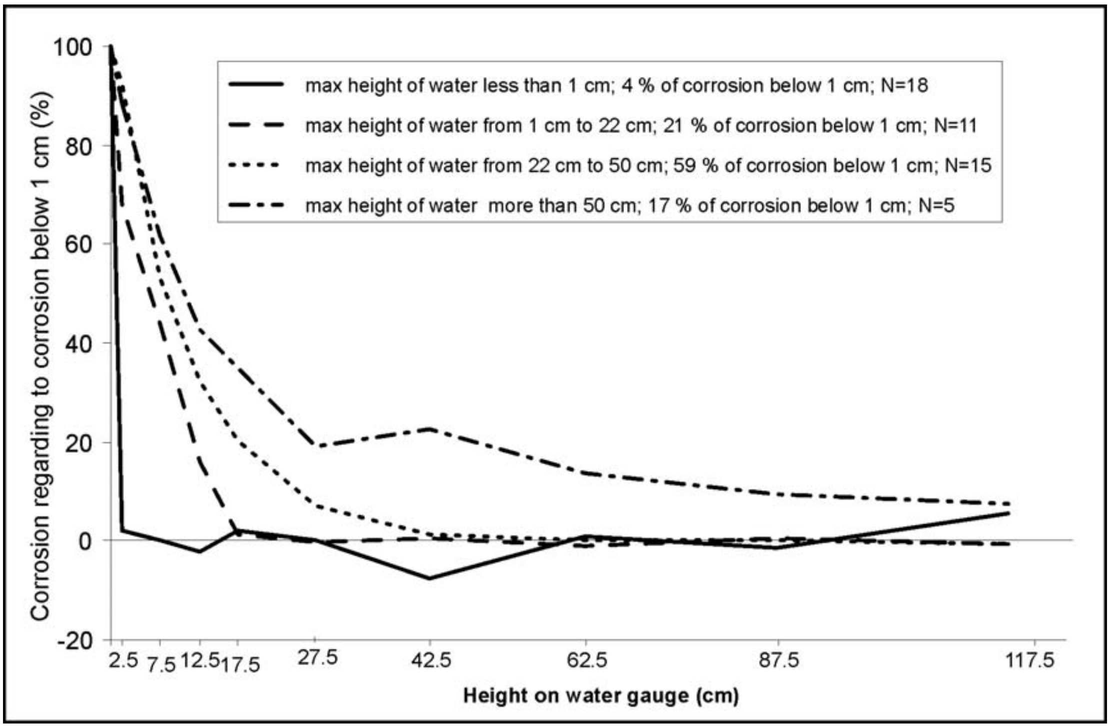


Figure 4.2.2.2: *Comparison between average corrosion at individual height and corrosion $H_{water\ gauge}$ < +1 cm with regard to 4 different zones of maximum height of water. Data represented in this figure were obtained at measurement point L-1 from 14th November 2006 to 8th January 2009.*

Changes of corrosion with height (Fig. 4.2.2.1) and different maximum height of water (Fig. 4.2.2.2) has an important speleogenetic consequence – the upper part of a passage suffers almost no corrosional transformation while the lower part widens and incises. Ratio between widening and incising depends on morphology of a passage and fluvial transport of bed load material. The latter protects the bed of a passage against corrosion or at least severely decreases incision of passage, while the widening of the passage still goes on in both lateral directions. Long term continuation of such a process would result in vast lateral extension in the lower part of a passage. Since such morphology is absent in Lekinka, deeper accumulation of bed load material seems to be very limited in Lekinka – partly due to small availability of such material and partly because of high corrosion, which can rapidly reduce the amount of bed load.

Lateral extension of lower part of a passage is possible also without accumulated bed load if the walls are perpendicular to water level. In such case, water widens the passage below $H_{water\ gauge} = 0$ cm twice as quickly as it incises (since the widening takes place in two directions and incision only in one). However, long-term widening has limits if the stream transports some material – when the ratio between depth and width of water channel decreases, friction increases, transport ability of stream decreases and braiding appears (SKINNER ET AL., 2004, 365). If the stream starts to deposit more and more material, corrosion is more or less limited to just one wall or even neither. Height and shape of lateral extension is related to oscillation of water level – lateral extension will be vertically short and laterally deep if the oscillations of discharge will be low and *vice versa*.

For simple incision of a vadose meander, equilibrated shape of the lower part of the meander has to be established (Fig. 4.2.2.3). Due to high corrosion rates even at lower and medium water levels and quite low at high water levels, quite sharp transition between vertical walls and horizontal bottom is expected in Lekinka if the processes are equilibrated with cross-sectional morphology. Sharpness of transition between vertical walls and horizontal bottom depends also on differences between corrosion rate at low water level and corrosion rate at middle water level (and is therefore related also to oscillation of discharge) – sharper transition is expected if oscillation of discharge is low. Equilibrated shape of meander can be observed in Lekinka but it is quite rare due to often noticed heterogeneity in karstified massive. Usually it is formed at spillways, which are not covered with bed load material and not influenced by downstream damming of water. In the case of Fig. 4.2.2.3, transition between the bed of a channel and vertical walls is sharp, which proves that majority of corrosion occurs during low and middle water levels. Otherwise, downward incision of a vadose meander cannot be possible.

Figure 4.2.2.3: *Typical meander cross-section about 300 m from the Lekinka's entrance, where cross-sectional area reflects uniform incision of meander without significant widening. Therefore, width of a passage remains more or less stable.*

Actual cross-sectional morphology at L-1 (Fig. 4.2.1.1) is influenced by described relations (corrosion rates below $H_{water\ gauge}$ = 1 cm, vertical changes of corrosion, oscillation of discharge, height of water oscillation, initial morphology) and artificial influx of bed load material. At L-1, walls are perpendicular to water level since the bottom of the passage is filled with bed load material. Since the corrosion acts more or less laterally, a wall notch is developing in present-day situation. Due to longitudinally and transversally changeable dimensions of the wall notch (which are the result of lateral changes in water flow and heterogeneity of rock), exact dimension of lateral extension are hard to obtain. Generally, the wall notch is incised for about 14 cm into the lateral direction, which would correspond to 2,300-1,500 years of corrosion at annual corrosion rates -0.0611 mm/a (rate obtained by limestone tablets) and -0.0953 mm/a (rate obtained by limestone tablets corrected with micrometer measurements – see Fig. 2.1.3.12 in Chapter 2.1.3). Simple comparison between cross-sectional shape and vertical distribution of corrosion points out that present day morphology corresponds to the last modifications of passage's shape.

Above $H_{water\ gauge}$ = +75 cm, a fossil wall notch can be recognized. According to Gospodarič and Habič (1966) this wall notch could correspond to the lowest accumulation terrace of Črni potok. Another higher two wall notches, which are mildly developed at L-1 but exist in some other entrance part of Lekinka, should correspond to two young higher accumulation terraces in Črni potok catchment area (GOSPODARIČ & HABIČ, 1966, 27). According to Gospodarič and Habič, development of wall notches should correspond to accumulation of bed load material inside and outside the cave, which could be climatically driven in Würmian glaciation. According to our measurements, corrosional development of a wall notch because of bed load accumulation is possible since the accumulation holds up incision and leads to lateral extension of passages. Decreased supply of bed load material is followed by gradual complete removal of bed load material and subsequent incision of new vadose meander, whose width corresponds to the most effective width of channel regarding to discharge. According to present-day corrosion rate (from -0.0611 to -0.0953 mm/a), the end of fossil wall notch development and beginning of incision would date to 9,400-14,700 years B.P. This roughly corresponds to transition between Holocene and Pleistocene. Formation of the fossil wall notch can be therefore attributed to Würmian glaciations.

Can wall notches be also a result of higher annual discharge without accumulation of bed load material? According to our results (Fig. 4.2.2.2), higher discharge would strongly increase corrosion rates in the upper part of a cross-sectional profile but also incision of the channel. This leads to disequilibration of the old profile and establishing of new one, which is necessarily wider than the previous one. When the new equilibrium profile is formed, incision of wider lower part of a passage lasts so long as higher discharge continues. If annual discharge is reduced again to primary values, incision of passage goes on in a narrower (primary) passage and formation of the wall notch is finished. In the case of enlarged annual discharge, the corresponding wall notch should be higher and transitions between wall notch and vertical walls would be much more gradual in comparison with higher influx of bed load material at unchanged hydrological conditions. Therefore we suppose that wall notches in Lekinka do not fit this way of formation since the actual wall notches in Lekinka are vertically lower and transitions between walls and wall notches are relatively sharp. Higher influx of material is possible also because of several terraces in front of Lekinka, which undoubtly shows higher influx of weathered material from the catchment area or limited transport of material into the cave. If the latter occurs, simple incision of the passage would go on.

4.2.3 Measurement places L-2, L-1, L-3, L-4, L-5 and L-6 – longitudinal variability of processes in the entrance part of Lekinka (along 250 m long watercourse)

Decrease in corrosion rates from the entrance to the inner part of a cave is common and should be expected in all kinds of ponor caves where the water is aggressive at the entrance. It is common also on the surface, when the water from non-karstic rocks flows over karstifiable rocks. Such a case was studied by Droppa in the valley of Demänova (GAMS, 1985, 368), where the corrosion rates in the middle of limestone valley fall to 14 % of corrosion rates detected at the first contact with limestones. Such a drop in corrosion rates is common at contact karst, since the water is far from equilibrium with respect to Ca^{2+}. Downstream, where the river leaves the limestone valley, corrosion rates were only slightly lower (12 % of corrosion rates detected at the first contact with limestones). At such locations (when the H^+ ions are rapidly consumed for reaction with $CaCO_3$), transition of CO_2 to the water can be a limiting factor for corrosion rates (ROQUES, 1969, 158). But in general, decline in corrosion rates is related to increasing saturation of water after it starts to flow over the karstifiable rocks. Bray (1972; 1977) asserts that decrease of corrosion rates in downstream direction in ponor caves can be reduced due to gradual decay of organic mater that increase concentration of H^+ in the water. All these phenomena can be expected in Lekinka. With longitudinal corrosion measurements, we tried to prove decreasing corrosion rates with longitudinal set limestone tablets, quantify decreasing corrosion rates at different discharges, to find out the most relevant factors, which control corrosion, and find out logical morphological consequences.

Longitudinal variability of karst processes was studied at 6 locations using 12 limestone tablets. The procedure and interval of measurement was the same as at L-1 (Chapter 4.2.1). The first measurement point (L-2) was located 40 m from the entrance/ponor, the second (L-1; only the lowest limestone tablet) 75 m, L-3 115 m, L-4 145 m, L-5 205 m and L-6 250 m. The biggest hydraulic differences existed between L-4 and all others measurement points – measurement points L-2, L-1, L-3, L-5 were characterized by fast flowing supercritical turbulent flow with velocities about 0.5 m/s during middle discharge. Measurement point 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 other locations. In the time of very low discharge, limestone tablets were mostly under the water level but the water flow was absent. At very high discharges limestone tablets were under the slow flowing water since the Pivka river in Otoška jama partly dammed water flow in Lekinka and caused backflooding. Measurements at L-2, L-1, L-3, L-4 and L-5 started on 15th April 2007 and finished on 5th April 2009.
Spatial measurements of physicochemical properties of water (SEC; T and pH) were done using WTW Multiline P4 at different hydrological conditions.

The highest corrosion rates most probably take place 30 m before the entrance to Lekinka, where the stream Črni potok meets the first limestone blocks in the water channel. Further corrosion rates are represented in Fig. 4.2.3.1. It can be seen that corrosion rates decrease between first (L-2) and last (L-6) measurement point, which is as expected. The biggest deviation is noticed at L-4 placed in slowly flowing water, which reduces R^2 from 0.99 to 0.97. Nevertheless, the difference is relatively small (10 % between predicted and actual corrosion). According to Fig. 4.2.3.2, the highest deviation between L-4 and all others measurement points appears at middle water level (between $H_{water\ gauge} \approx +10$ cm and $H_{water\ gauge} \approx +45$ cm), when differences in flow velocity are the highest. At lower water levels, corrosion is absent downstream of L-1, while at higher water level, flow velocities are quite similar at all measurement points due to backflooding. Therefore, low velocity of water flow seems to be the most relevant factor, which reduces corrosion rates in pools in the entrance part of Lekinka. The most appropriate processes (corrasion and transport of ions through diffusion boundary layer), which cause lower corrosion rates, therefore rely on flow velocity.

Thickness of diffusion boundary layer has important influence in water with low pH, where the transport of H^+ ions through DBL is the main factor that is controlling dissolution rates (FORD & WILLIAMS, 2007, 66). Experiments done by Liu and Dreybrodt (1997) show that corrosion rate can be strongly related to thickness of DBL. Nevertheless, we should take into account also the force of flowing water and suspended load, which can tear away small partly dissolved calcite crystals at the surface of incompletely dissolved limestone tablet. Mechanical tearing of partly dissolved crystals is definitely higher at places with faster water flow.

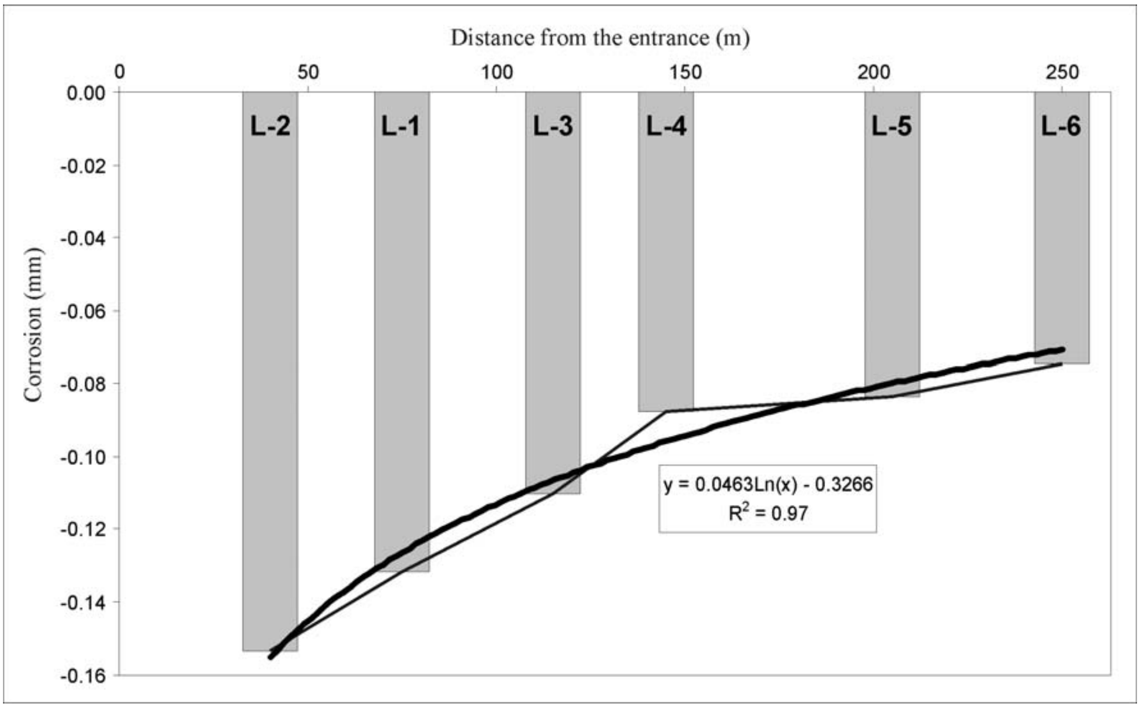


Figure 4.2.3.1: *Corrosion at L-2, L-1, L-3, L-4, L-5 and L-6 from 5th April 2007 to 5th April 2009.*

Decrease of corrosion from L-2 to L-6 can be easily described with a logarithmic equation, which fits the real data quite well (R^2 = 0.97; Fig. 4.2.3.1). This means that drop of corrosion rate is the largest near the contact (for 37 % per 100 m of water course between L-2 and L-3), while further from the contact, drop of corrosion rates is much lower (for 27 % per 100 m of water course between L-3 and L-6). In spite of this, drop of corrosion rates during first 250 m of underground flow is very high (54 %). Regarding to equation in Fig. 4.2.3.1, at the end of a Lekinka (after 790 m of water flow) corrosion rates about -0.018 mm are expected, which is only 12 % of corrosion rate measured close to the entrance (L-2).

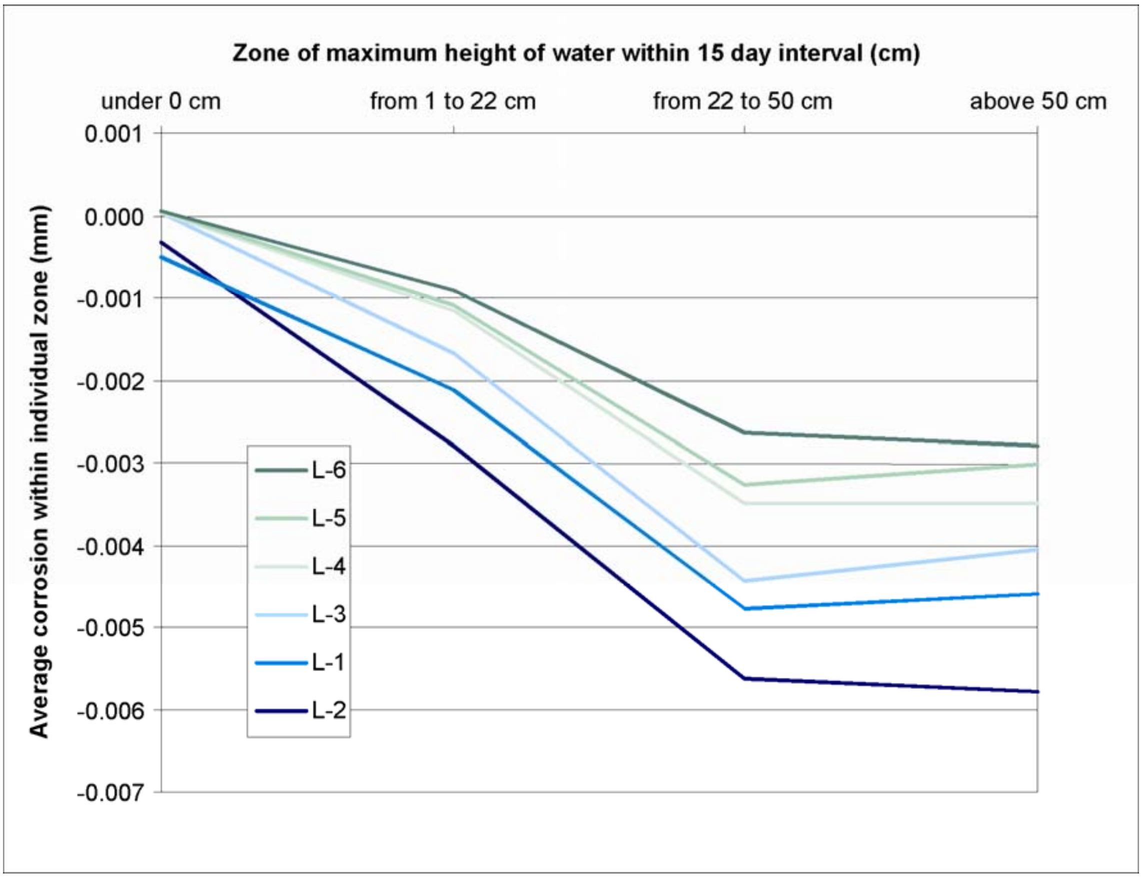


Figure 4.2.3.2: *Average corrosion within zones of maximum height of water (defined in Chapter 4.2.2) with regard to different measurement points in the entrance part of Lekinka. Data are calculated from measurements that began on 15th April 2007 and ended on 5th April 2009.*

Decrease of corrosion rates represented in Fig. 4.2.3.1 is not constant but fluctuates significantly during different discharges (Fig. 4.2.3.2). At very low water level ($H_{water\ gauge}$ < 0 cm), water is already saturated before Črni potok enters Lekinka. During such low water level, corrosion in Lekinka is not increased even from the side of decay of organic matter or higher CO_2 concentrations (up to 1,440 ppm) during summer months. At measurement place L-2 and L-1, first corrosion rates were detected when the water level exceeded $H_{water\ gauge}$ = 0 cm (Q ≈ 7 l/s). During such water levels, differences in corrosion rates between L-2 and L-1 on one side and all other measurement points on another side are the biggest, since the corrosion is absent downstream of L-1 (Fig. 4.2.3.2; groups of averaged values correspond to zones already defined in Chapter 4.2.2). Downstream of L-2 and L-1, corrosion appears at slightly higher discharge, when the water level exceed $H_{water\ gauge} = +10$ cm. If the maximum height of water exceed $H_{water\ gauge} = +10$ cm but remains below $H_{water\ gauge} = +22$ cm, corrosion at L-6 amounts 32% of corrosion measured at L-2. Further rise of maximum height of water leads to higher absolute but lower relative differences between measurement points, but only to the $H_{water\ gauge} \approx +50$ cm, when absolute differences remain the same even at higher water level. This is related to backflooding, which with bigger cross-sectional area obstructs further increase of water velocity through the cave. Lower velocity of flow reduces weight-loss of limestone tablets due to:

- lower corrasion rates and lower degree of tearing away weakly bonded incomplete corroded crystals,
- thicker diffusion boundary layer and
- reduced ratio between reaction surface and quantity of water.

Lower corrosion rates due to decreased velocity of flow were confirmed also with measurement at L-4 (Fig. 4.2.3.1).

In the entrance part of Lekinka, several tributaries, fed by percolation water, join the main water course. It seems that they represent autogenic recharge of the area nearby Lekinka since they have high SEC and very stable temperature during a year. All are characterized by lower corrosion rates than Črni potok since they cannot compete in present-day channel incision. The first right tributary also deposits some flowstone, when it starts to degas at transition from the corrosionally enlarged fracture to the well ventilated main passage. All this indicates higher CO_2 concentration in their catchment area, saturation state of these waters and possible outgassing of CO_2 from the water when they reach main passage – especially during low discharge of main water course. From Fig. 4.2.3.3 we can see that these tributaries do not hold up corrosion even at low discharge, when the total hardness of Črni potok is relatively high (~217 μS/cm, which is ~100 mg $CaCO_3$/L; after Eq. 4.1.4.1 in Chapter 4.1.4). Increase of SEC due to corrosion was recorded even further downstream, when even higher SEC was recorded (~250 μS/cm, which is ~117 mg $CaCO_3$/L). Although corrosion is hardly detected with limestone tablets at so low water level due to average error, growing SEC shows on slight corrosion during all discharges before and after confluences with tributaries

(Fig. 4.2.3.3). However, it is questionable how high would corrosion be without tributaries. Higher or lower?

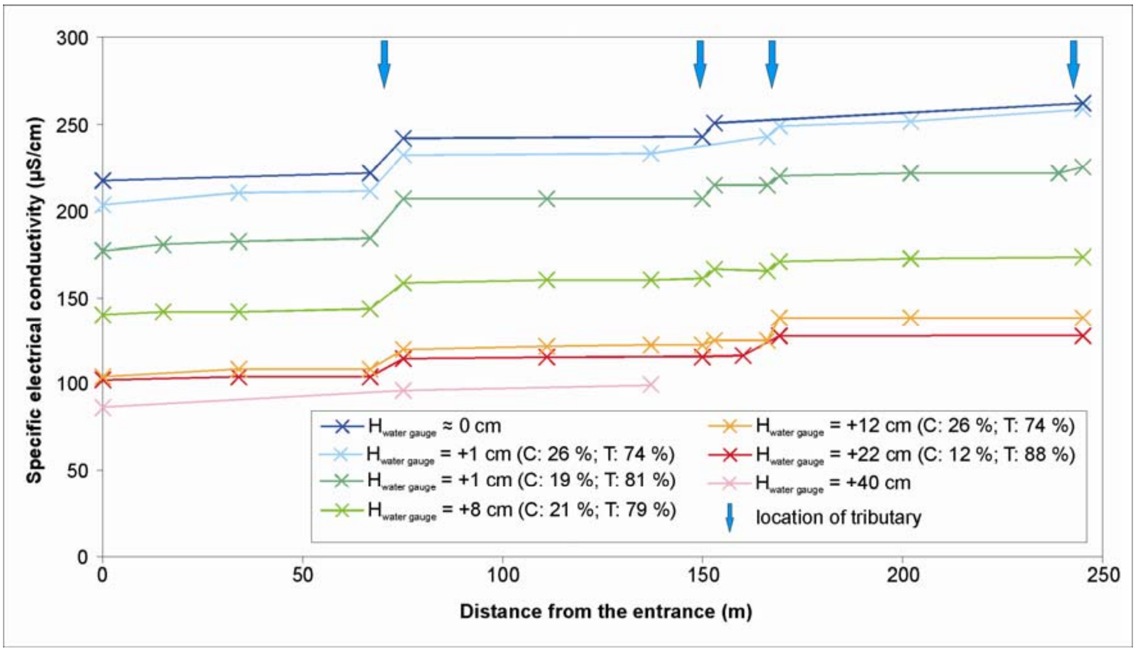


Figure 4.2.3.3: *Growth of SEC as a result of corrosion (C) and influx from tributaries (T) with high total hardness.*

Mixing of two saturated waters with different CO_2 concentration and different hardness results in undersaturated water due to mixing corrosion. In the Lekinka case, at least one water is usually highly undersaturated (Črni potok) and therefore even higher corrosion can be expected. However, because of several tributaries, total CO_2 concentration and hardness increase and if CO_2 concentration is too high, outgassing of CO_2 can lead also to flowstone deposition. According to spatial and temporal measurements of SEC (Fig. 4.2.3.3), the latter increases the most due to several tributaries, which cause the biggest changes of SEC (much higher than corrosion itself) – independently on recharge. Their contribution to total hardness rises with increase of discharge of the main water course, when the transfer of water is very fast through the entrance part of Lekinka, contact with limestone wall the shortest and quantity of water of main water course the highest. During such high discharge, rise of SEC in first 250 m of the cave amounts up to 3 µS/cm (12 %), while the rise of SEC as a result of tributaries amounts about 23 µS/cm (88 %). During low discharge, changes in total hardness are much bigger due to long contact of water with limestone walls. During such discharge, corrosion is responsible for 26 μS/cm (26 %) rise of SEC, while the tributaries contribute up to 74 μS/cm (74 %). Beside increasing hardness in the main water course, tributaries also raise total CO_2 concentration. Such a junction is usually suitable for higher corrosion rates but in open system with high turbulence in water course, such as Lekinka is, excellent possibilities for outgassing of CO_2 can lead to saturation (or even oversaturation) of water. According to our measurements, evaluation of influence of tributary cannot give us final conclusion. Nonetheless, measurement represented in Fig. 4.2.3.3 shows that even tributaries raise total hardness; their influence is too small for stopping corrosion, at least along first 250 m of underground passage. However, if the ponor water would have higher SEC, tributaries would have higher discharge and higher degree of oversaturation, and their influence on corrosion rates would be much higher – at least far downstream from confluence, where the water would be sufficiently outgassed with respect to CO_2.

According to our results, decreasing corrosion rates from the entrance to the cave's interior should result in decreasing dimensions of passages. At the places where meanders are developed, more intense deepening at the entrance would result in lowering of gradient. This is in agreement with present-day morphology (GOSPODARIČ & HABIČ, 1966) since the height of passages generally decreases from the entrance. In detail, the situation is much more diverse since the meander is incised in previously phreatically enlarged faults/fractures and bedding planes with different spatial positions, dimensions, heights above present-day middle water level etc.

During incision, the meander cuts also several small phreatic tubes, which were developed in the past near the contact with flysch rocks (and are probably still growing now under the present-day water table). At such places, pools are located instead of meanders. If we take into account decreasing corrosion rates from the entrance, pools should be wider near the entrance and narrower in the inner part of a cave – at least theoretically. Practically, the real situation is much more complicated due to different time of development, coupling of two parallel passages into one and heterogeneity of already karstified massive. Moreover, total amount of corrosion in phreatic passages, which has slower enlargement rates due to slower water flow, depends on the downstream meander, which defines local water level and incises faster than the upward pool (during incision of lower meander, deeper pools should be therefore transformed into shallower pools or even into meanders). It seems that width of phreatic passages enlarges downstream, which is in contradiction with higher corrosion rates observed at the entrance but in agreement with higher exposure time (primary due to slower incision of meander downstream of phreatic passage). Downward incision further from the entrance is also under the influence of backflooding from the side of underground Pivka river in Otoška jama.

Gospodarič and Habič (1966) were the first who noticed three wall notches which gradually disappear about 300 m from the entrance. According to them (GOSPODARIČ & HABIČ, 1966) wall notches disappear due to appearance of sumps, which transferred a limited amount of water in the past. Due to backflooding, wall notches were formed at the time of high discharges. However, this is illogical if we take into account high rise of water due to backflooding, which would tend more to phreatic enlargement of passages. According to our observations, wall notches develop if water is corrosive at low and middle discharge, at places with small vertical oscillation of water level and because of transport of bed load material, which at least partly protects the cave floors against corrosion. The first condition is very evident near the entrance and diminishes to the inner part of Lekinka. Along the 250 m water course, water is corrosive during medium discharge but not during low discharge. The second condition was also observed near the entrance, but the further we go into the cave, the more frequent is the influence of backflooding. When the backflooding occurs, water level rises a lot and corrosion is responsible for phreatic development of passages. Since the backflooding in Lekinka seems to be a quite long-lived and stable phenomenon, absence of wall notches 300 m from the entrance due to significant rise of water level is possible. Accumulation of bed load material is also a crucial factor for wall notch development. Due to slow mobility of bed load material in the cave, which even diminishes during the time of high discharge (due to backflooding), present-day accumulation of bed load material is possible just in the first 250 m. If the hydrological conditions were similar in the past, wall notches could develop in the same was as today at measurement point L-1. Therefore, formation of past wall notches is related to the same factors as are observed in the present-day situation. Disappearance of wall notches 300 m downstream from the entrance is related to higher fluctuation of water level, lack of bed load material and most probably lack of corrosion at low-middle water level.

4.2.4 Measurement places L-2, L-1, L-3, L-5, L-6, L-7, L-8, L-9, L-10 – longitudinal variability of processes all along underground water course in Lekinka (from the entrance to the sump)

In Chapter 4.2.3, measurements were done only in the first 250 m of Lekinka. Further into the cave, several lakes make access more complicated and measurements harder. Therefore, a much longer interval was chosen for corrosion measurements. Data were obtained all along the main water course to the narrow place several tens of metres before the terminal sump, that is all along 790 m of underground water flow.

Corrosion measurements on L-7, L-8, L-9 and L-10 started on 13th February 2008. Data were obtained when the limestones tablets were replaced, that is on 5th September 2008 (after 205 days of exposure) and on 17th April 2009 (after 255 days of exposure). The procedure of weighing and fixing was the same as at L-1 (Chapter 4.2.1); only the exposure time and number of exposed limestone tablets at each measurement point were different (3 *vs.* 1). Measurement point 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 discharges (supercritical turbulent water flow). At the time of higher water levels, backflooding started from L-10 and sometimes reached also L-2. At low water level, all limestone tablets were below the water level but water flow can be absent at some locations.
Data from measurement points L-2, L-1, L-3, L-5 and L-6 are the sums of data from the 15-day-long measurements during the same interval as at L-7, L-8, L-9 and L-10.

Results of measurement are represented in Fig. 4.2.4.1. Decrease of corrosion from the entrance to the Končni sifon is not surprising – during 460 days long measurement period, 45 % of corrosion was detected at L-10 in comparison with L-2. This is much higher in comparison with calculations done by using equation from data L-2 to L-6 (12 %; Fig. 4.2.3.1). Decrease of corrosion rates is higher during 1st measurement period (36 % of corrosion at L-10 regarding to L-2; Tab. 4.2.4.1) but much lower during 2nd measurement period (51 % of corrosion at L-10 regarding to L-2). This is a result of much higher discharge during 2nd measurement period, which can be observed also in higher corrosion rates in the entrance part of Lekinka (Tab. 4.2.4.1).
Two longitudinal zones of dissolution can be distinguished: from 0 to 250 m and from 250 to 750 m from the entrance. The entrance zone is characterized by steep decrease of corrosion rates since diffusion of H^+ ions across diffusion boundary layer plays an important role during the beginning of corrosion (DREYBRODT, 1988, 113). Therefore, differences regarding the flow velocity appear between L-4 and all other measurement

points in the entrance zone (Chapter 4.2.3). The second zone extends downstream of L-6. In this zone, corrosion rates are more or less controlled by reaction on the calcite surface and can be suitably described by linear function (DREYBRODT, 1988, 116). Steep decrease of corrosion rates that follows linear decrease, which was observed experimentally, is not observed along 750 m of underground water course. For sure it exists at low discharge and possibly at middle discharge, but finally it is overwhelmed by relatively high dissolution rates at high discharge. Nevertheless, logarithmic function describes relation between corrosion and length of underground quite well since R^2 amounts 0.84 (Fig. 4.2.4.1).

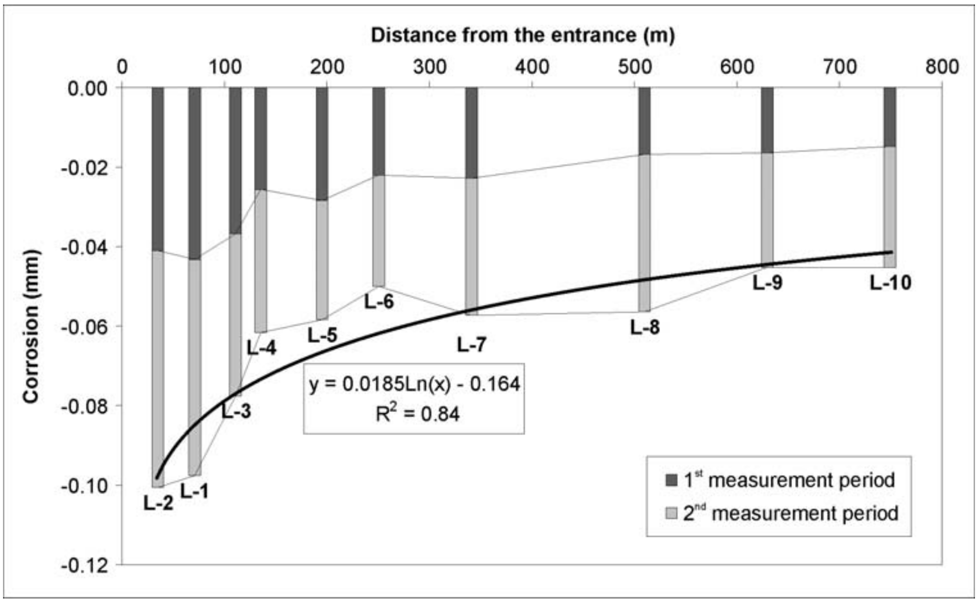


Figure 4.2.4.1: *Corrosion from cave Lekinka measured out from the Ponor (entrance) to the Končni sifon (=Terminal sump) from 13th February 2008 to 17th April 2009. Corrosion at L-2, L-1, L-3, L-4, L-5 and L-6 is sum of 15 day corrosion during the same measurement period.*

Although corrosion decreases relatively constantly between L-2 and L-10, some results also show some other factors that can increase or decrease corrosion rates along water course. The most obvious such increase of corrosion happens between L-6 and L-7. It was detected during both measurement periods, especially during 2nd measurement period. Since the increase of corrosion rates occurs at transition between short-term and long-term measurements and can be therefore connected with methodology, differences in corrosion seem to be too high to be a result of methodology. The most relevant factor seems to be a quite big tributary several tens of metres upstream of L-7 (see Fig. 4.2.4). The catchment area of this tributary is not known but physicochemical measurements at low and middle discharge indicates that the water is most probably of autogenic origin since it has high SEC (~400 μS/cm), relatively high temperature in winter time (8.9 ºC) and low pH (7.58). During high water level, which is by far the most relevant, physicochemical properties are not known due to inaccessibility.

Table 4.2.4.1: *Corrosion rates in Lekinka measured out from the Ponor (entrance) to the Končni sifon (=Terminal sump) from 13th February 2008 to 17th April 2009.*

	L-2	L-1	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10
1st measurement period (mm/a; % of corrosion at L-2)	-0.0729	-0.0769	-0.0655	-0.0454	-0.0507	-0.0389	-0.0407	-0.0301	-0.0295	-0.0264
	100%	106%	90%	62%	69%	53%	56%	41%	40%	36%
2nd measurement period (mm/a; % of corrosion at L-2)	-0.0853	-0.0777	-0.0584	-0.0515	-0.0430	-0.0402	-0.0542	-0.0568	-0.0408	-0.0432
	100%	91%	69%	60%	50%	47%	64%	67%	48%	51%

In Lekinka, water flow stays relatively highly aggressive all along the underground water course, most probably all the way to the confluence with Pivka river in Otoška jama. Aggressiveness of water supports growth of the underground passage all along the water course at high rates (-0.0774 mm/a at L-2 and -0.0357 mm/a at L-10 – according to measurements with limestone tablets). Direction of passage enlargement depends on the morphology of present-day passages – in phreatic ones, corrosion takes place in lateral and downward direction, while in vadose meanders, predominant downward incision is expected. Therefore, phreatic passages are wider but lower in comparison with meander-type of passages. 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 of passages close to the entrance, although corrosion rates are much higher at the entrance. Direction of enlargement of downstream passages in Lekinka also depends on the height of Pivka river in Otoška jama.

Nevertheless, both factors (corrosion rate and backflooding in Lekinka from the side of Pivka river) result in some general transition of morphology from the Ponor to the Končni sifon. Meanders can be found in the entrance and final downstream part of Lekinka but they are taller and more common in the entrance part. Near measurement point L-10, the bottoms of meanders are not smoothened but rather dissected along fault lines and joints. The latter morphology is a result of backflooding from the side of Pivka, which inhibits predominantly downward incision of meanders and supports widening of passage under phreatic conditions. A logical consequence of backflooding is also a reduction of flow velocity, which is reflected in quite rare and over 5 cm long scallops found close to the terminal sump. Scallops in the entrance part of a cave are usually up to 5 cm long. The longest (~350 m with very short phreatic passages) and the tallest meanders are developed in the entrance zone, while the downstream part of Lekinka is mostly formed in several metres wide phreatic passages. The latter are often completely filled with water; even Črni potok is low but Pivka river is high. At many places, incision from the initially phreatic passage can be observed (Fig. 4.2.4.2), which can demonstrate an incision of passage due to lowering 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). Nevertheless, gradual incision due to gradual adaptation and enlargement of initially disoriented phreatic passages toward meanders (PALMER, 2002) is more possible – especially in Lekinka, where the water course has a possibility to incise.

Figure 4.2.4.2: *Incision of vadose meander in initially phreatic passage.*

Conclusion

Lekinka drains a marshy catchment area about 1 km^2 wide with low inclination and quite low carbonate content in soils. Therefore water of Črni potok that flows into Lekinka is highly undersaturated with respect to Ca^{2+}, which leads to high corrosion rates at the entrance and further toward the Končni sifon (=Terminal sump).

The rate of corrosion mainly depends on discharge, which is a function of amount of precipitation, evapotranspiration and snow retention. Therefore, the highest corrosion 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. During low discharge, corrosion rates are absent all through the cave, while at high discharge, corrosion rates can amount up to -0.009 mm/15 days. The latter high value was not characteristic for very high discharge but rather for long-lasting middle-high discharge. Influence of other properties of water (temperature, content of organic matter, other seasonal influence) and air (cave air CO_2 concentration) is of minor importance, which was recognized already by Williams (1964 after SWEETING, 1972, 219 & 226) for western Ireland. Corrasion seems to be relatively low although high turbidity of water can be observed at high-middle discharge.

Upward decrease of corrosion is sharp, which indicates relatively constant discharge and the most expressed corrosion during low-middle water levels. Therefore an upper part of passage remains almost uncorroded, while the lower part incises downward or laterally. Prevailing direction of enlargement depends on 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 formation of wall notches. Formation of wall notches is not possible in the case of very high water fluctuation or absence of aggressiveness during low-middle discharge. In the entrance part, recent wall notch formation can be observed due to artificial supply of bed load material. Without this artificial supply of bed load material, incision would prevail most probably during all the Holocene, following lateral extension of the passage during the Würmian glaciation. Lateral and downward enlargement of passages is characteristic for passages that have walls perpendicular to water level at low-middle water level. By far prevailing downward incision is characteristic for meander-type of passages, which are mainly vertical in upper part but rounded in the lowest part of cross-section. At middle water level, when the corrosion is the most expressed, walls form with water level an angle higher than 90º. This supports subvertical enlargement of passages at the contact between water level and walls, but together with downward incision in the middle part of passage, downward incision is a final result of corrosion in meander-type of passages.

Downstream, corrosion rates decrease. In the first 250 m of underground water flow, the decrease of corrosion rates can be described with exponential function. Downstream of 250 m, decrease of corrosion rates can be described by low-inclined linear function. This means that in the first entrance zone rates are mostly controlled by diffusion of H^+ ions across diffusion boundary layer. Therefore, differences in corrosion rates are observed also due to velocity of flow, which has an important influence on thickness of the diffusion boundary layer. Further downstream, slow decrease of corrosion rates was observed. Some increases of corrosion rates in the downstream zone are most probably caused by tributaries, which usually supply the main water course with more than 40 % of water that sinks into the Končni sifon.

Downward incision in the downstream part of Lekinka is influenced by the Pivka river in Otoška jama. Pivka river causes backflooding and therefore hinders 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. Ongoing incision will result in lowering of the water divide with Nanoščica river, which can use Lekinka as a shortcut to Otoška jama due to its lower entrance in comparison with the entrance to Postojnska jama. If capture does occur, corrosion rates will be significantly reduced in Lekinka. Changed physicochemical properties of water will result also in hindered downward incision. (Over)saturated water at low and middle discharge and slightly aggressive water at (very) high water level will enhance passage enlargement at phreatic conditions and obstruct wall notch formation.

4.3 Škocjanske jame

Škocjanske jame (=Škocjan caves; Reg. No. 735) present the biggest natural curiosity of the whole Classical Karst between the Gufl of Trieste and Vipava valley. Together with the blind valley of Vreme and Divaški Kras along the narrow ponor border of the Reka river they make part of typical morphogenetical unit of contact karst, unique in Europe regarding to its phenomena and dimensions (GAMS, 1983). Due to scenic view over the ponor area, the area above collapse dolines was already populated in the Copper Age and reach special prosperity in the Bronze Age (LEBEN, 1983). The first real exploration of the entrance part along underground water course started in the 1st half of 19th century, when 500 m of cave was known (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 started in 1884 by DÖAV from Trieste ended in 1890 at the terminal siphon in Martelova dvorana (=Martel's chamber). The latter was successfully dived in 1991, but a connection at least 900 m long with downstream Kačna jama (MIHEVC, 2001, 52) is still unknown. Due to extreme dimensions and unique karst landscape with early and rich history of explorations, Škocjanske jame were listed in 1986 as a natural and cultural heritage of the world at UNESCO. Škocjanske jame are known also because of one of the largest underground chamber in the world (Martelova dvorana), which is 308 m long, up to 123 m wide and up to 146 m high. The volume of this chamber, through which Reka river flows, is estimated to be 2,100,000 m^3 (MIHEVC, 2001, 79).
In Škocjanske jame, scientific research started already 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 started in the 1980s. Geological structure, long-term speleogenesis and first datings were made 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 should be related to colder climate due to huge production of gravel while the warmer periods should correspond to gentle development of Škocjanske jame with accumulation of flowstone (GOSPODARIČ, 1983; GOSPODARIČ, 1984). Transport of sediment through Škocjanske jame was studied by Kranjc (1986). In 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, lithological structure with emphasis on initial development of channel along bedding planes was investigated by Knez (1996). Speleogenesis of the whole system and first measurements of processes were done by Mihevc (2001), while Slabe (1992; 1995, 109) paid attention to micro-morphology of the water channel. Lastly, scientific research brought some new information on water oscillations and physicochemical characteristics of underground water flow, which was carried out with monitoring of 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

All passages of Škocjanske jame are located relatively close to the contact between Eocene flysch rocks and older Cretaceous limestones. A whole stratigraphic sequence of Carboniferous rocks is located in a low tectonically deformed monocline, which is inclined for 20-35º toward SSW (GOSPODARIČ, 1983, 165). Therefore, the youngest sediments (Eocene flysch rocks) are found in the SSW and the oldest (thick- to non-bedded Turonian limestones) are found in the NNE (GOSPODARIČ, 1983; KNEZ, 1996). Between them, very pure (portion of $CaCO_3$ usually exceed 99.5 %; KNEZ, 1996) micrite bedded Senonian and thin-bedded Paleocene limestones are developed. All known passages of Škocjanske jame are located within thick- or non-bedded Senonian and Turonian strata, except Tiha jama (=Silent cave; southwestern nowadays dry passage of Škocjanske jame) is developed in thin-bedded limestones. Thick-bedded carbonate rocks are nowhere highly tectonically damaged, which supports development of wide or long tall passages without significant collapses. Recognized faults cross Škocjanske jame in WNW-ESE or NNE-SSW direction (GOSPODARIČ, 1983, 165).

From a speleogenetical point of view, the most important geological structures for formation of Škocjanske jame are 5 tectonized bedding planes, where the initiation of the first phreatic passages took place (KNEZ, 1996). Later, development of Škocjanske jame is characterized by incision of vadose meander in the epiphreatic zone. 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, called 300 (KNEZ, 1996, 23-24). In continuation, the passage incised for about 90 m to the stratigraphically lower bedding planes (400 and 500, in Martelova dvorana also 600, 700; MIHEVC, 2001, 60) and formed deep meander with subhorizontal walls. Hankejev kanal is narrowest at the bottom (about 10 m) and wider at the top (15-20 m; MIHEVC, 2001, 74). Lack of significant lateral extension in the cross-sectional profile indicates regular incision without interruptions (MIHEVC, 2001, 83) in tectonically low-deformed non-bedded limestone (GOSPODARIČ, 1983, 164). Finally, present-day keyhole passage formed.

Underground active passages of Škocjanske jame are rich in corrasional and corrosional micro-features, which spatially alternate between each other. Corrasional features (potholes, polished surfaces, scratches) are related to the exceptionally high transport of allochtonous material from the Reka river catchment area (KRANJC, 1986). Corrasion rates were measured by Mihevc (2001, 65) with micrometer at 17 points. In 6 years of measurements, the highest values were found at places where the pebbles are hitting the wall (from -0.16 to -0.04 mm/a) while much lower values were measured at places of polishing (about -0.02 mm/a). Corrosional features (scallops) show that we can expect also some corrosion rates, but results of measurements done by Mihevc (2001, 64) show that they are close to measurement error of micrometer (about -0.01 mm/a). Corrosional and corrasional features are developed just 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 flowstone deposition, which takes place even at the bottom of Hankejev kanal (SLABE, 1992, 198; MIHEVC, 2001, 74). Location of flowstone suggests that flowstone deposition is higher than corrosion – at some places even higher than corrasion.

Enlargement of passages in Škocjanske jame are crucial for development of the superficial upstream catchment area and downstream karst aquifer. They are the only points where an upstream water and sediment (about 242.4 m^3 of limestone and much more flysch rocks!; GAMS, 1962, 267) can be drained from the superficial catchment area and seem to act as a restriction for equilibration of longitudinal cross-section since the highest gradient is observed here. Where the Reka river flows over flysch rocks, average gradient is 2.8 ‰. Between lithological contact of flysch with limestone and Ponor (hydrological entrance to Škocjanske jame), this is along 7.1 km water flow through the narrow gorge, 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 average gradient of 6.3 ‰. Therefore, the critical point for water flow and also erosional base for the catchment area of 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 corrosional power of Reka river plays an important role in underground gradient, since it defines how fast and where the restrictions can be removed.

Hydrological characteristics

Free-surface underground course of Reka river is 2.7 km long and usually 3-15 m wide at medium water level (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 from the ponor to the Škocjanske jame. About 1 m^3/s is lost in the water channel immediately downstream of the contact between flysch rocks and Paleocene limestone and some more water further downstream (RADINJA, 1967 after MIHEVC, 1991). This subparallel 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 level (MIHEVC, 2001, 62). In the case of strong precipitation, 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 recurrence period of 100 years is estimated to be 453 m^3/s (ZVSS, 1978 after MIHEVC, 1991).

Škocjanske jame are a typical example of contact karst since all the water originates in a superficial catchment area and sinks at one point – close to the contact with soluble rocks. This 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 discharges while the narrows in the cave (in this case probably the sump named Ledeni dihnik – see Fig. 4.3.1.1) function as restrictions at high water level. Therefore, several tens of metres high floods in Martelova dvorana are usual every year. At the highest discharge (for example in 1826), water can rise for 132 m above medium water level in the final lake in Martelova dvorana (BOEGAN, 1938 after HABE, 1966, 47) and floods the bottom of all passages except Tiha jama. At high water level, water flow velocity at wider places decreases significantly since the cross-sectional area of water flow becomes much bigger. This leads to decreased power of water flow and sedimentation of fine-grained suspended material, especially at the sides of wider chambers (i.e. Martelova dvorana).

Therefore, characteristics of catchment area are extremely important for geomorphic activity in Škocjanske jame. According to several sources (ROJŠEK, 1983, 52; KRANJC & MIHEVC, 1988 po MIHEVC, 2001, 52; HABIČ ET AL., 1989, 10; UHAN, 2007), the catchment area of Reka river extends over 332 to 378 km^2. This surface span-width is due to partly karstic area, where delineation is hardly determinable and also varies in time due to different hydrological conditions in the autogenously recharged aquifer of Snežnik mountain (1797 m a.s.l.). Karstified carbonate rocks (mainly Cretaceous limestones) cover about 28 % of the catchment area, especially in the SE part, from where Reka river gets some important springs at the contact with flysch rocks. The latter extend over 60-74 % of the catchment area, mainly at Brkini mountains (KRANJC,

1986, 112; HABIČ ET AL., 1989, 10; KRANJC & MIHEVC, 1988 after MIHEVC, 1991). For 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 consequence on the discharge duration curve, which (with very concave form) shows big differences in discharge with a relatively small percentage of medium discharges. Torrential character of Reka river can be seen also from comparison of the lowest (0.16 m^3/s; UHAN, 2007) and the highest observed discharge (305 m^3/s; UHAN, 2007) since it amounts 1: 1,906. Streams from Brkini mountains decrease total hardness of Reka river downstream of karst springs from Snežnik mountain. None the less, decrease is not so important since the total hardness fall from 10.7 ºNT to still high 10.3 ºNT between springs below Snežnik mountain 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 Reka river and its tributaries.

Another very important influence of Reka river is 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 River reka valley was washed away through the cave. In present-day situation, on average 30,000 m^3 of material is transported every year trough the Škocjanske jame (KRANJC, 1986). Such a movement of material is possible due to quite high slope inclination on fluvial-denudational relief – regarding to Rojšek (1983, 54) average inclination is 14.3 º. 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, percentage of flysch pebbles strongly decreases (for 8.5 % per km of water course; KRANJC, 1983 after MIHEVC, 1991). It is very important that the percentage of flysch pebbles is not reduced just due to rounding, which would indicate only corrasion, but rather due to crushing, which was confirmed with almost longitudinally stagnant index of roundness (KRANJC, 1986, 114). Although crushing of pebbles is recognized as an important process, which leads to reduction of flysch pebbles downstream of lithological contact, longitudinally stagnant index of roundness could not be possible without rounding of freshly crushed pebbles. Transport of flysch material can be an intensive process for high corrasion rates, if the crushing and rounding occurs at the contact with limestone water channel. Since the superficial and underground water channel is mostly formed in solid limestones (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), transport of flysch material definitely is an important process responsible for high corrasion rates, which has been already confirmed by Mihevc (2001, 65). Another important process is mechanical erosion and transport of limestone blocks, since the percentage of limestone increases from 0 % at the lithological contact to 20 % at Škocjanske jame (KRANJC, 1986, 114).

Corrosion is a much less known process in Reka river in comparison with corrasion. Regarding high oscillation of discharge and catchment area in mostly quartzitic flysch rocks expected corrosion rates could be high, especially at high discharge. Occasional spatial measurements of water total hardness in Reka river gorge at middle water level (GAMS, 1962, 1966b) do not prove this. Even at high discharge, corrosion seems to be low since Gams (1966b) detected relatively high total hardness (9.7 ºN) and Mihevc (2001, 64) very low corrosion rates measured by micrometer. This is a result of karst springs that feed the main water course of Reka river under Snežnik mountain and a result of dissolution of cement between particles in flysch (pebbles, sand, silt and clay), which constitutes from 20 to 24 % of the flysch rock. Nevertheless, the cement in the catchment area can be siliceous or calcitic (ŠIKIĆ & PLENIČAR, 1975, 22); therefore high differences can be expected in total hardness among tributaries from Brkini mountains.

Meteorological characteristics

Due to its two big entrances, all passages of Škocjanske jame (except Tiha jama) are very well ventilated. Especially in summer and winter time, when temperature differences with outside temperature are the highest, strong air currents can be felt all along the water channel. In winter, cold air is entering the cave through the lower entrance and if the outer temperatures stay for several days below 0 ºC, which is common due to temperature inversion in the collapse doline, freezing in the lower part of the cave is common. Warmer air exits the cave under the roof. In summer time, 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 can be observed 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 ºC (KOGOVŠEK, 1983 after HABIČ ET AL., 1989, 13).

Corrosion rate measurements and their relation to key factors and forms

4.3.1 Measurement place S-1 and S-2 – temporal variability of processes at Swidovo razgledišče

First measurements of corrosion in Škocjanske jame that were done by Mihevc (2001, 64) with micrometer showed low corrosion rates close to the measurement error (-0.01 mm/a). Therefore, usage of micrometer for measurements of corrosion rates is inappropriate for short time intervals. Measurements with limestone tablets seem to be a good solution for more accurate measurements, if we are able to fix limestone tablets at more calm (noncorrasional) places. Therefore, position is a crucial factor to succeed in such rugged environment, which was recognized already by Gams (1996, 103), who failed in measurements with limestone tablets in Škocjanske jame. Because of better and more suitable fixation we were able, during 440 days long measurements with corrosion rates in Hankejev kanal (Chapter 3), to confirm low corrosion rates (together with corrasion rates less than -0.0016 mm/a), but in that period discharge was quite low and without any important flash flood, when higher corrosion is expected. Therefore we continued with measurements at the same location, here named as S-1 and S-2 and extended our measurements all along the underground water course.

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. 4.3.1.1). Only 1.5 m away, corrasion rates -0.02 mm/a high were measured with micrometer by Mihevc (2001, 65). Since the limestone tablets were placed in the middle of water channel, where the velocity of water flow exceeds even 5 m/s and water transports a lot of bed load material, a microlocation of measurements was chosen with great caution. Nonetheless, corrasion can be expected at least from the side of suspended load. Measurement points S-1 and S-2 were under the water when the discharge of Reka river exceeded ~3 m^3/s. Since the lower discharge is characteristic for about 60 % of a year (REKA DISCHARGE DATA FOR 2006, 2007, 2008 AND 2009), limestone tablets were under the water for 40 % of their exposure. They were fixed with iron screws, nuts and felted washers. Misleading corrosion due to iron oxide seems to be (almost) absent at S-1 and S-2 as was proved by low rate of overall corrosion during 440 days of measurement in "8-month" period (Chapter 3; Appendix I). At S-1 and S-2, measurements were taken in 4 measurement periods: From 1st February 2006 to 17th April 2007 (440 days), from 17th April 2007 to 27th February 2007 (316 days), from 27th February 2007 to 14th October 2008 (230 days) and from 14th October 2008 to 4th March 2009 (141 days).

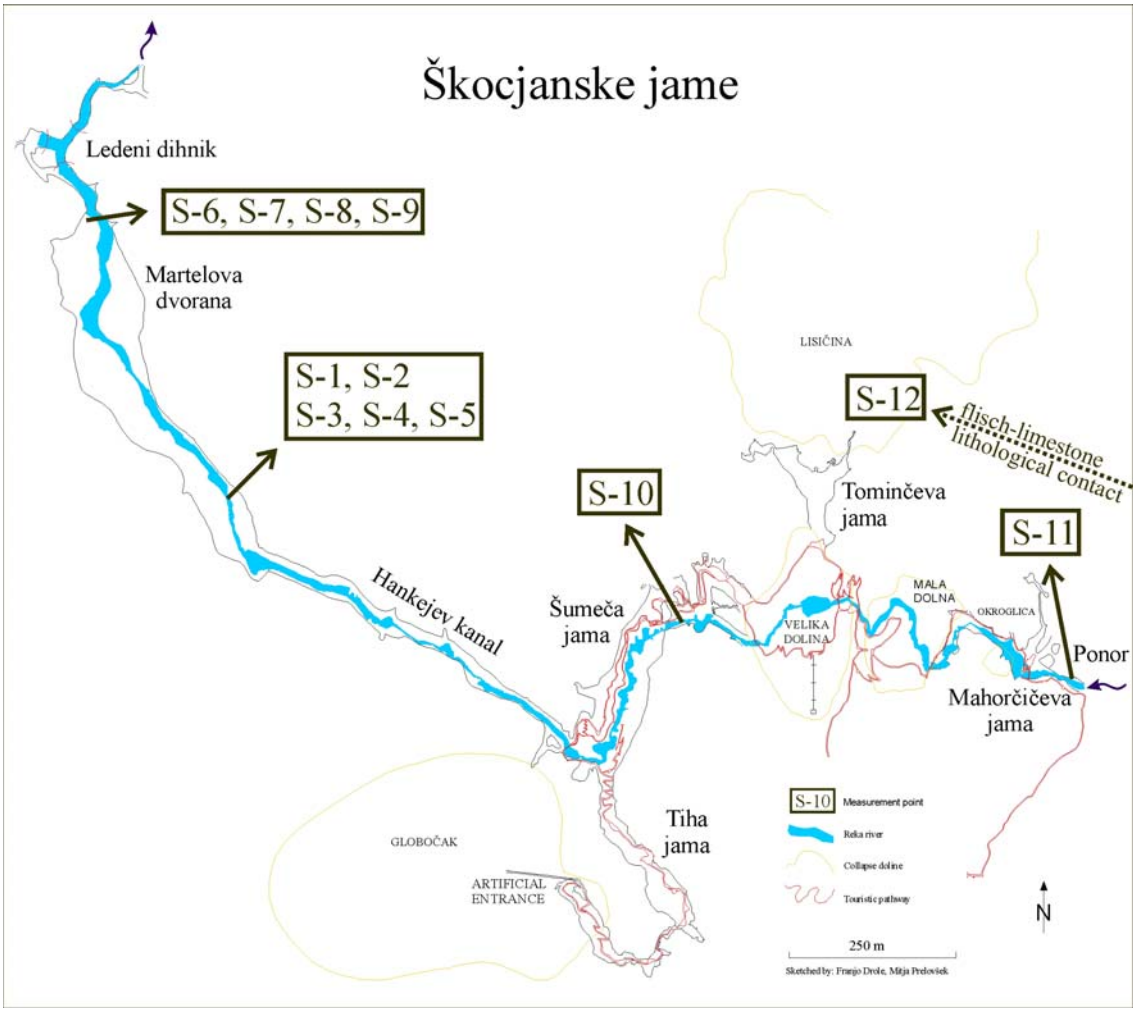


Figure 4.3.1.1: *Position of measurement places from S-1 to S-12 in Škocjanske jame and on Reka river upward from the caves (source of plan: Archive at IZRK ZRC SAZU).*

Results from measurement points S-1 and S-2 are represented in Fig. 4.3.1.2. In the 1st measurement period, several discharges reached 50 m^3/s. Although discharge was quite high, corrosion/corrasion rates are relatively small (on average -0.0012 mm/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. 4.3.1.3). Therefore corrosion rates are even smaller, if they exist at all. During 2nd and 3rd measurement period, discharges were quite low. Thus there was only weak mobilization of bed load material and the limestone tablets showed no corrasional damages. Average rates show weak corrosion (-0.0002 mm/a) or slight deposition (0.0008 mm/a). The highest corrosion/corrasion rates were detected during the 4th measurement period, which was characterized by two strong flash flood events with discharge more than 100 m^3/s.

Limestone tablets were strongly damaged due to crumbling and grinding – corrosion rates therefore can not be determined.

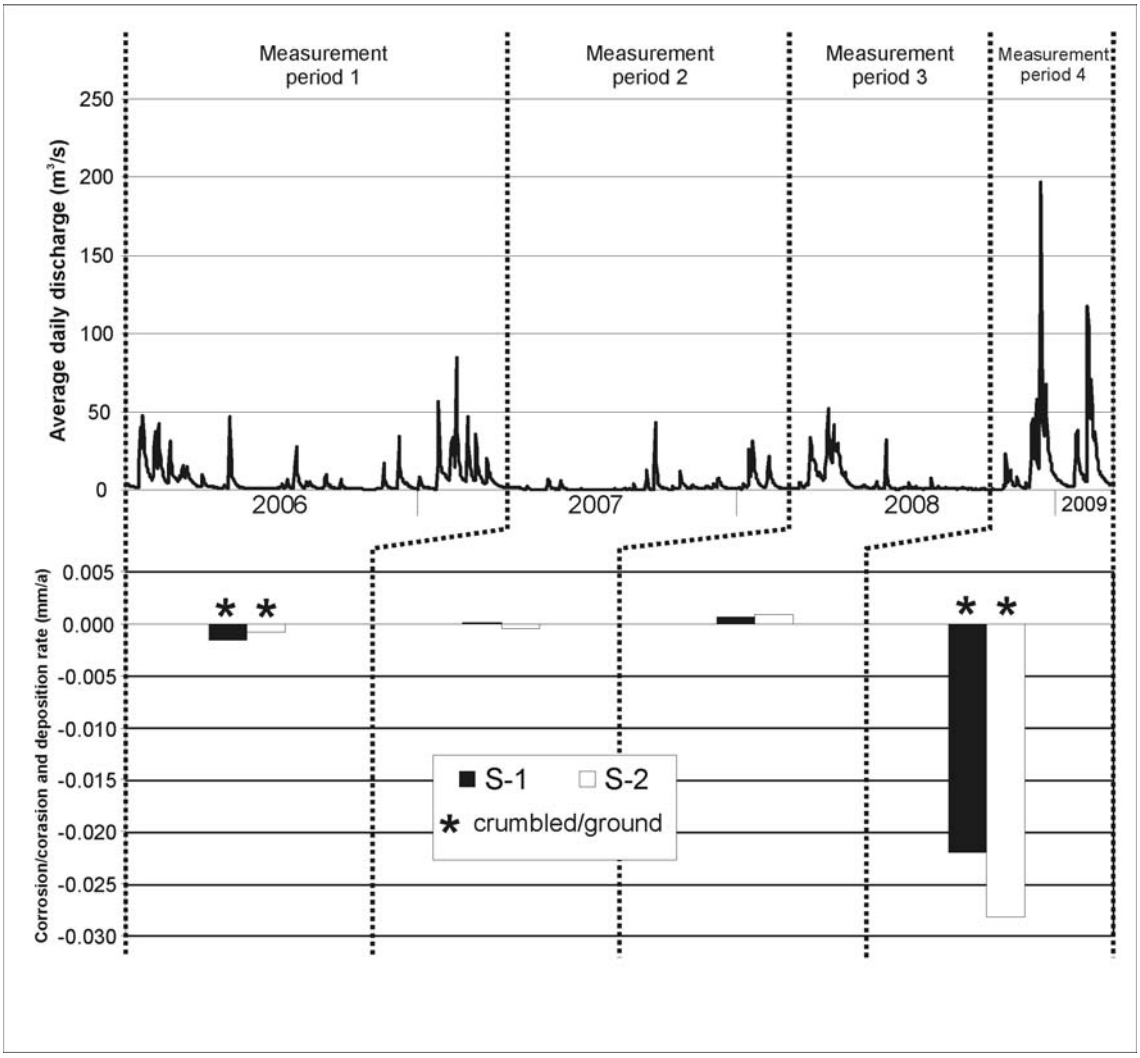


Figure 4.3.1.2: *Corrosion/corrasion and deposition rates at S-1 and S-2 in 4 measurements period between 1st February 2006 and 4th March 2009 together with average daily discharge (source of hydrological data: REKA DISCHARGE DATA FOR 2006…).*

Although measurement points S-1 and S-2 were located away from the obvious corrasional places, crumbling and grinding strongly deformed the limestone tablets. From Fig. 4.3.1.2 it is obvious that weight loss during flash flood with over ~50 m^3/s shows the degree of corrasion, but the values cannot be taken as strictly representative since limestone tablets are exposed to much higher corrasion than the bed of a channel.

However, they represent degree of corrasion, which seems to be a positive function of discharge. This can be seen in Fig. 4.3.1.2, where detectable corrasion appears at discharges ~50 m^3/s and slightly increases at discharges up to ~100 m^3/s. Discharges higher than ~100 m^3/s result in very high corrasion rates.

Due to crumbling and grinding, we were not able to observe corrosion 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 3rd measurement period suggest that (flowstone) deposition is possible during low discharge.

Figure 4.3.1.3: *Crumbled and ground edge of limestone tablet at S-1.*

From a morphological point of view, three different types of surfaces can be exposed in the water channel: surfaces with black coating, polished surfaces as a result of corrasion and surfaces with scallops as a result of corrosion. Black coating is several millimeters 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 places where corrasion is evident (polished surfaces, potholes, surface with scallops). If it is located on collapse blocks, the black coating usually sticks together collapse material. This proves that sticking of blocks is younger than collapsing or moving of collapsed blocks. Reaction of black coating with 10 % solution of HCl is strong, which indicates calcite (flowstone). Beside calcite, 13 % of impurities (weathered flysch rock, organic material) are common. If we take into account results from 2nd and 3rd measurement period, when the limestone tablets were not damaged by corrasion, average net flowstone deposition rate of 0.0003 m/a could be responsible for at least 3 mm thick black coating, if we suppose the same rate of process during the Holocene. Potential thickness of black coating roughly corresponds to its actual thickness. Since the overall (net) process in the lower portion of the water channel at places without corrasion shows flowstone deposition, corrosion rate seems to be up to -0.0003 mm/a high.

The second type of surface, corrasional surface, is developed at places, where vast bed load transport takes place. Corrasion rates are very different and strongly depend on microlocation. From our measurements we can conclude that they are usually higher than flowstone deposition rates, where they appear. The only reliable results are given by Mihevc (2001, 65) – from -0.02 mm/a at polished surface to -0.16 mm/a at places, where bed load is hitting the wall. Nevertheless, corrasion can be extremely weak in some places and there flowstone deposition prevails.

Surfaces with scallops are relatively rare. On the walls, scallops are usually absent. The most characteristic are on the tops of big collapse blocks in water channel, which are flooded when discharge exceeds ~10 m^3/s. Morphology of scallops is interesting, since they are long and narrow. Transitional angle between scallops is very low and amounts 75-90º (SLABE, 1992, 31). It seems that they form at places with relatively small corrasion and within a zone between flowstone deposition and back flooding (Fig. 4.3.2.4). This statement was tested with measurement of vertical variability of processes (Chapter 4.3.2).

4.3.2 Measurement places S-3, S-4, S-5 and S-6, S-7, S-8, S-9 – vertical variability of processes at Swidovo razgledišče and at Martelovo jezero

Measurement places S-1 and S-2 shows flowstone deposition at low (and medium) water level. At high water level, limestone tablets suffered corrasion. The latter blurred possible corrosion rates, which are probably the highest at very high water level and were as such also in the focus of our interest. To avoid corrasion and detect corrosion, we start to measure with two vertical sets of limestone tablets: at Swidovo razgledišče

(=Swida's viewpoint; 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 level. At Martelovo jezero, water flow is slightly less turbulent. During very high discharges, velocity of flow reduces significantly at both places since the backflooding causes vast enlargement of cross-sectional profile of water flow. At each measurement point, 3 limestone tablets were exposed. They were fixed with stainless steel screws, nuts and felted washers. Measurement point S-3 was fixed 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 higher vertical span. Measurement point S-6 was located 0.4 m above geodetic point 58 (located at the shore of Martelovo jezero) and seems to be out of 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 weighted at the same time as S-1 and S-2 (Chapter 4.3.1).

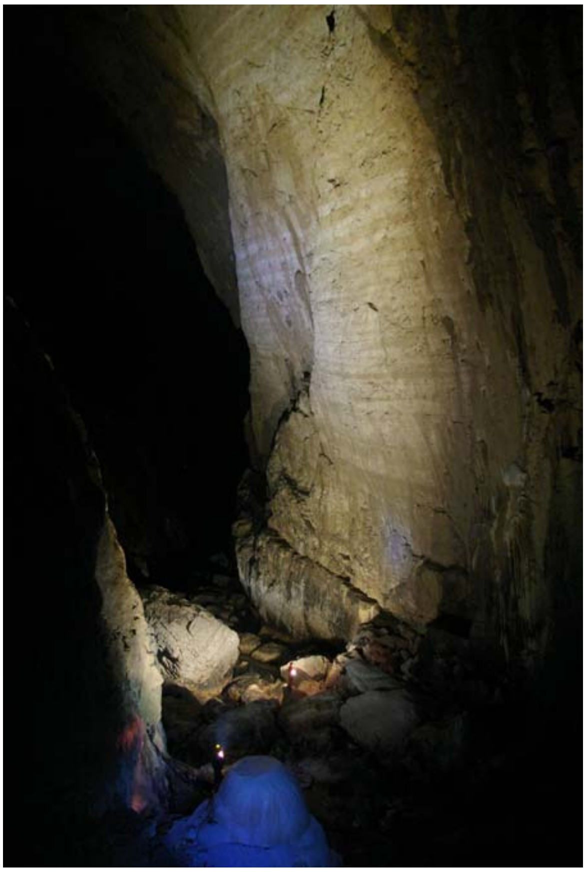


Figure 4.3.2.1: *Cross-section through Hankejev kanal at Swidovo razgledišče. Note traces of past flood events on several tens of metres high right wall and about 2 m high stalagmite in the water channel (photo: Borut Lozej, conservationist at Park Škocjanske jame).*

Results of measurements from vertical set at Swidovo razgledišče are represented in Fig. 4.3.2.2. Measurement point S-3 was, similarly as S-1 and S-2, exposed to corrasion. Corrasion was much more expressed between 14th October 2008 and 4th March 2009 since two flush flood events with more than 100 m^3/s occurred within this measurement period. Corrasion reduced the weight of limestone tablet at S-3 also between 27th February 2009 and 14th October 2009, 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. 4.3.1.2). Corrasion at S-3 overwhelmed chemical processes and nothing can be said about them.

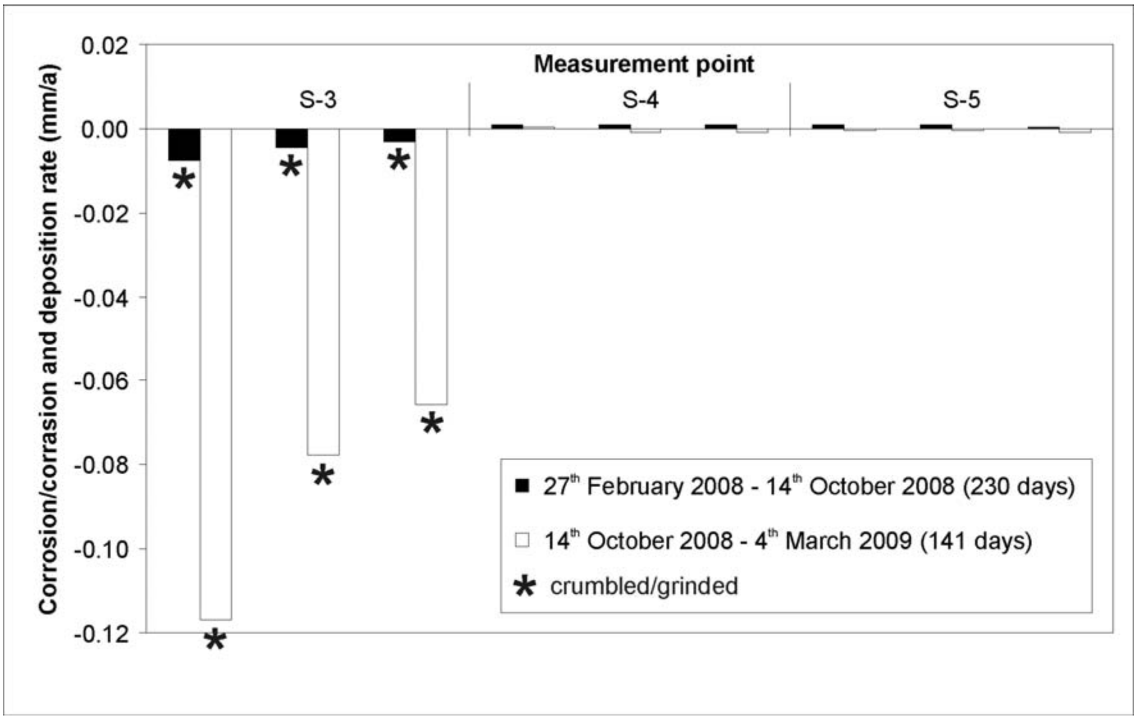


Figure 4.3.2.2: *Corrosion/corrasion and flowstone deposition rates measured at Swidovo razgledišče between 27th February 2008 and 4th March 2009.*

On the contrary, corrasion was absent 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 fast rising of water that flooded both measurement points almost simultaneously or simply too weak difference in rates. During the first measurement period, slight flowstone deposition (0.0007 mm/a) was detected at S-4 and S-5. Since original value (0.0004 mm) is at the edge of maximum error, slight deposition is possible even at middle-high discharge.

During the last measurement period, slight corrosion (-0.0006 mm/a) was detected. The original value (-0.0002 mm) is at the edge of standard error of measurements which makes the final conclusion about corrosion rates in one year uncertain. Low corrosion rates within measurement error are surprising since two very big flash flood events are characteristics for this the last measurement period. Results prove that aggressiveness of Reka river is very low or almost absent even at very high discharge since the average value at S-4 and S-5 is even positive (0.0002 mm/a) in the whole measurement period (from 27th February 2008 to 4th March 2009). It is interesting that suspended material, which is abundant in water at high discharges, did not cause important corrasion rates. Therefore, only bed load is responsible for corrasion rates.

Measurement place at Martelovo jezero was chosen due to lack of corrasional morphology at all measurement points. Therefore some more can be said about flowstone deposition at low discharge and slight or absent corrosion at high water level. Result of measurements at S-6, S-7, S-8 and S-9 (Fig. 4.3.2.3) confirmed lack of corrasion even at the lowest measurement point. Weight loss at one limestone tablet during the 1st measurement period is a result of artificial damage during fixation. Although values are rather small, evident transition from net flowstone deposition at S-6 toward corrosion at higher measurement points can be observed. The highest average corrosion rates (-0.0004 mm/a) were detected at S-8, which is located 6.1 m above measurement point S-6. Upward, corrosion rates are smaller due to shorter exposure time. Downward (1.6 m above S-6 at S-7), net corrosion rates are smaller most probably due to deposition during middle water level. Flowstone deposition is even bigger at the lowest limestone tablets (measurement point S-6), which were exposed to corrosion and deposition. Deposition prevails over corrosion, since the weight of limestone tablets increased. Deposition was very obvious during 2nd measurement period, which was characterized by low discharges – even not sufficient to reach measurement points S-8 and S-9. From the viewpoint of corrosion it is interesting that 1st measurement period shows even higher corrosion rate than 3rd measurement period although the highest discharges were far the highest during 3rd measurement period. However, the difference is very small (0.0002 mm/a) and usually even smaller than differences between limestone tablets placed at the same measurement point.

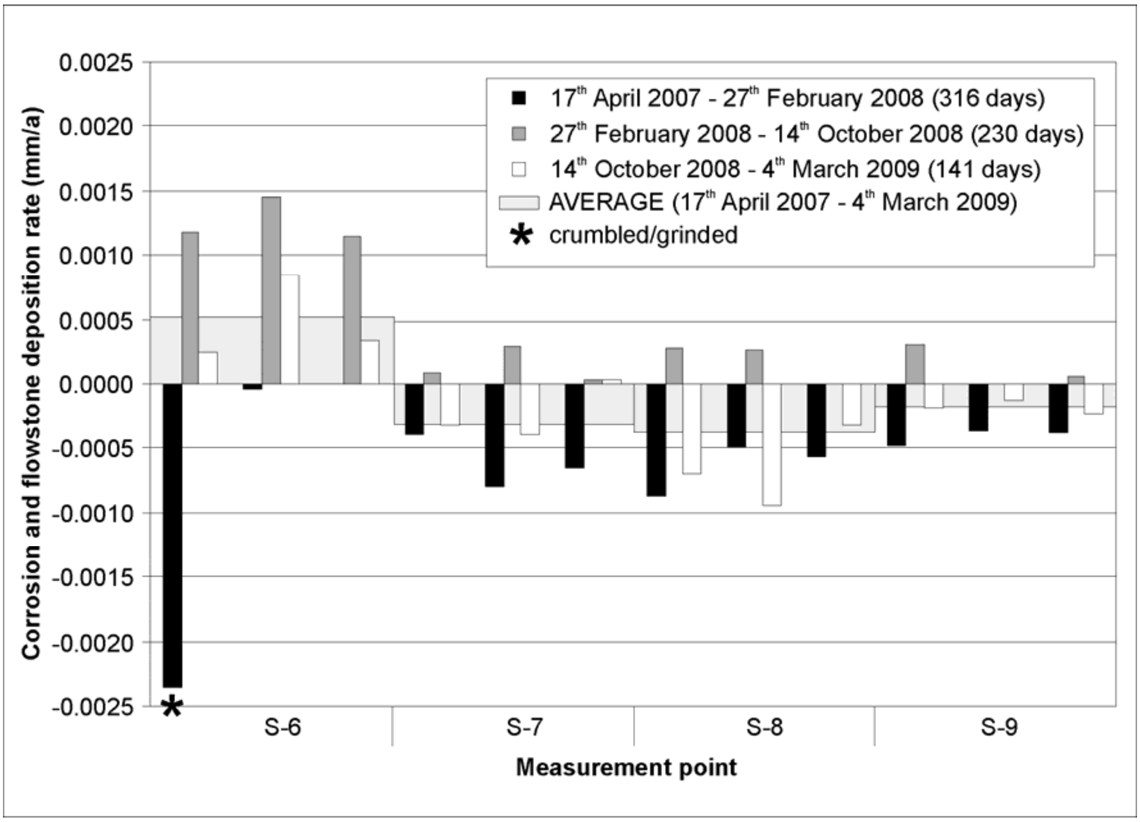


Figure 4.3.2.3: *Corrosion and flowstone deposition rates measured at Martelovo jezero between 17th April 2007 and 4th March 2009.*

Results of measurements at Swidovo razgledišče and Martelovo jezero show that we can expect deposition at low water level and corrosion at high water level. Change from net deposition to net corrosion seems to occur when the water level in underground channel rises 1.5 m above low water level (Q ≈ 20 m^3/s; GABROVŠEK & PERIC, 2006, 40) usually all along the underground water channel. 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 places. At higher water level, backflooding prevents development of scallops due to decrease of water flow velocity.

Corrosion rates in upper portions of the underground channel decrease due to shorter exposure time. Morphology of temporarily flooded passages rarely shows corrosional features. More often can be seen disintegrated rock surfaces, which are slightly blurred by corrosion.

At low water level, the prevailing process is deposition, although corrosion can be expected at high water level. Although we have no direct proof that we detected deposition of flowstone and deposition of organics is possible, flowstone deposition seems to be possible since Mihevc (2001, 67) already observed thin flowstone coating in the underground water channel. Prevailing carbonate composition of coating (83 % of carbonates) was confirmed with dissolution in HCl. Thickness of actual black (flowstone) coating roughly corresponds to the rate of 0.0005 mm/a during Holocene (12,000 years bp).

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 present-day micromorphology of the water passages. Nevertheless, some features (i.e. scallops) can be also inherited from the past and are just sustained in present-day conditions. Processes, key factors and features can be therefore summarized in the general scheme represented in Fig. 4.3.2.4. Thin flowstone coating indicates that saturation of water should be lower before Holocene. Regarding to Gams (1996, 103), higher aggressiveness in Ice Ages can be expected due to frozen ground, which promoted superficial runoff without interaction with carbonates within the soil. Another explanation is lower CO_2 concentration in the karst water due to smaller biological productivity. Such water could not be able to deposit tufa due to lower (over)saturation.

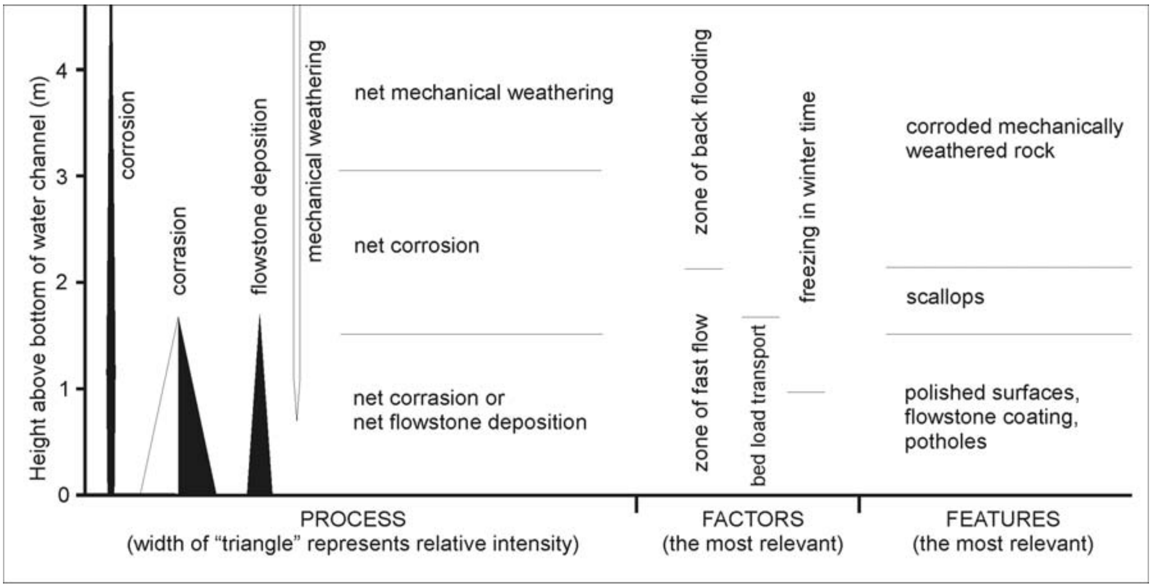


Figure 4.3.2.4: *The most relevant present-day processes, factors and features characteristic for Škocjanske jame.*

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

Low aggressiveness that leads to low corrosion rates in the inner parts of Škocjanske jame can be a result of gradual saturation of Reka river along more than 7.5 km long water course between the lithological contact flysch-limestone or already saturated water at the lithological contact flysch-limestone. Although both explanations are related to more or less superficial stream upstream of Škocjanske jame, they are crucial for development of Škocjanske jame and worthy of more detailed observation. Therefore we decided to measure processes in a longitudinal section from the contact flysch-limestone to the downstream sump Ledeni dihnik in Škocjanske jame.

Limestone tablets were placed at 5 different measurement points. The most upstream one (S-12) was located at the lithological contact of limestone with flysch, S-11 was located at the Ponor (location, 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 already described Swidovo razgledišče (S-3; Chapter 4.3.2) and Martelovo jezero (S-6; Chapter 4.3.2). At each point, measurements were done using 3 limestone tablets. They were fixed with stainless steel screws, nuts and felted washers at non or weakly corraded surfaces. All measurement points demonstrate very similar hydraulic conditions – turbulent supercritical water flow with velocities usually several m/s. Results are available for two measurement periods: 1st one from 27th February 2008 to 14th October 2008 (316 days) and 2nd one from 14th October 2008 to 4th March 2009 (141 days).

Although limestone tablets were fixed at places where the corrasion supposed to be weak, corrasion is obvious especially at measurements place S-10 and S-3 (Fig. 4.3.3.1). Corrasion was observed also at S-12 and S-11, especially during 2nd measurement period, when discharges exceeded 100 m^3/s. Since the corrasion rates strongly differ spatially and do not represent actual rates of corrasion, if they are measured by limestone tablets, we excluded limestone tablets with observed corrasion from further evaluation.

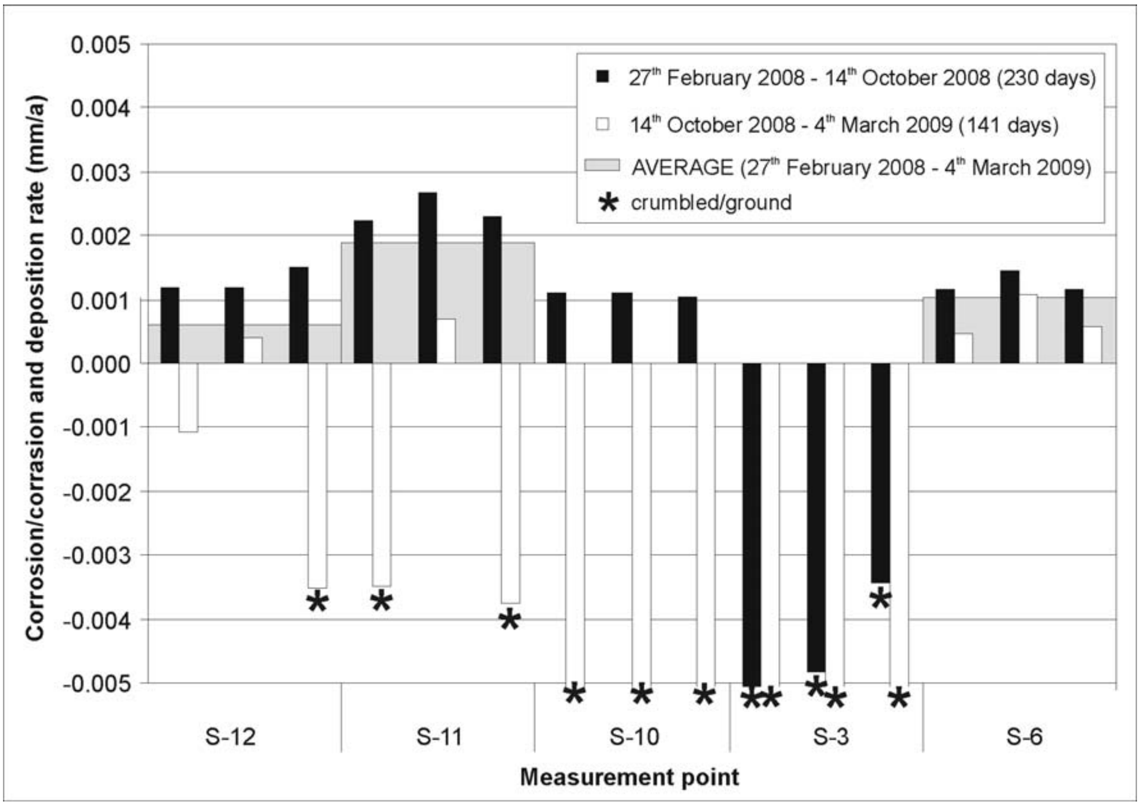


Figure 4.3.3.1: *Corrosion/corrasion and flowstone deposition rates measured between flysch-limestone contact (S-12) and Martelovo jezero (S-6) between 27th February 2008 and 4th March 2009. On average, crumbled and ground limestone tablets are not included. Average was not calculated for S-10 and S-3 since all limestone tablets from one measurement period were damaged by corrasion.*

In the first measurement period which is characterized by relatively low water level, deposition was measured at all measurement points. Deposition rates from the lithological contact (S-12) remain more or less constant at ~0.0012 mm/a all the way to Martelovo jezero (S-6). Only at the Ponor (S-11), they are one time higher (0.0024 mm/a) due to some unknown reason. At high discharge that was characteristic for the 2nd measurement period, the Reka river seems to be slightly corrosive at the lithological contact (-0.0003 mm/a). Downstream, measured corrosion rates are smaller or even turn to flowstone deposition either because of contact with limestone or because of higher flowstone deposition rates during low discharges. Nevertheless, although the Reka river is slightly aggressive at high discharges, average value at each location shows that flowstone deposition prevails over corrosion. Therefore on average, slight net flowstone deposition can be observed all along superficial and underground water flow from the lithological contact to Martelovo jezero in Škocjanske jame. Net flowstone deposition rates ranges between 0.0006 and 0.0019 mm/a.

The reason for low aggressiveness of Reka river in Škocjanske jame therefore does not exist in superficial flow of Reka river over limestones 7.5 km from the Ponor but in the catchment area. The most reliable explanation can be found in karst springs that feed Reka river and are oversaturated with calcite at open atmosphere conditions. Some of them deposit tufa in high quantities (e.g. Podstenjšek; KOGOVŠEK, 2006) and are therefore oversaturated. Many tributaries from Brkini mountains decrease total hardness of Reka river (GAMS, 1962, 278) but they are too weak to turn the water toward aggressiveness. The latter is almost absent even at very high discharge, which was characteristic for the last measurement period at all measurement points.

Conclusion

If we take into account just chemical processes, flowstone deposition can be defined as the strongest geomorphic process in the epiphreatic part of Škocjanske jame. The most characteristic is for low discharges. During medium discharges, flowstone deposition rates are lower but still exist. According to measurements at Martelovo jezero and measurement point at the lithological contact limestone-flysch, net flowstone deposition amounts to 0.0010 mm/a in the lower portions of the water channel. Morphologically, flowstone deposition can be seen as black flowstone coating, which covers and sticks together collapse blocks in the water channel of Škocjanske jame. Slight corrosion (up to -0.0004 mm/a) appears at high water level, when discharge exceeds about 20 m^3/s. Corrosion rates most probably rise with higher discharges, but the most problematic for high corrosion rates is time of exposure, which is quite low at high water level.

About 1.5 m above low water level ($Q \approx 20\ m^3/s$), slight net corrosion rates become higher than net flowstone deposition rates. This is also the lowest vertical point, above which the corrosional forms can be observed. The most obvious are scallops, which disappear upward because of backflooding and consequential decrease of flow velocity due to increase of cross-sectional area of water flow. Walls in flooding zone are characterized by corrosionally blurred mechanically weathered rock. Here, slight corrosion due to flooding is accompanied also by condensation corrosion. Distinction between them is impossible.

Due to vast transport of flysch material 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 bed load material, while the geomorphic action of suspended load is absent. Rates of corrasion done by bed load transport were measured by Mihevc (2001) and are compared with other processes in this Thesis. Measurements and morphological observations reveal that they can be much stronger than flowstone deposition, but also much weaker at calm places.

Present-day processes correspond to present-day factors and actual microfeatures along water course in Škocjanske jame. Nevertheless, thickness of flowstone cover (several millimetres) shows that intensity of processes was different before the Holocene. At that time, flowstone deposition rates were smaller or corrosion rates higher, since we lack thicker flowstone coating. Deep vertical incision of the meander (Hankejev kanal) suggests that lateral extension of meander due to corrosion was extremely weak. This is proved also with lack of wall notches, which could form in a water channel that is partially blocked by collapse material or where deepening of meander is slowed down due to collapse blocks accumulated at the bottom of the passage due to mechanical breakdown. Corrosional features of fast water flow at vertical walls are also absent. The most probable cause for the incision of meander is corrasional activity of water, which is the strongest at the bottom of passages and leads more toward incision than toward lateral extension of passage. This differentiates Škocjanske jame from Lekinka (Chapter 4.2).

4.4 Postojnska jama-Planinska jama cave system

Postojnska jama (=Postojna cave; Reg. No. 747) and Planinska jama (=Planina cave; Reg. No. 748) belong to one of the most extensive hydrologically active cave systems in Slovenia which is connected with superficial Pivka river at Pivška kotlina (=Pivka basin) and Unica river at Planinsko polje (=Planina polje). Postojnska jama and Planinska jama have together 27,226 km of known underground passages – some of them are characterized by underground Pivka river flow while the other passages are at present-day conditions dry (Fig. 4.4.1). The vast majority of passages is horizontal and supposed to be formed in epiphreatic conditions by the Pivka river. Planinska jama is accessible through one entrance and ends in upstream direction in an over 25 m deep sump (VRHOVEC, 2000). Passages of Postojnska jama 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. 4.4.1). Some of the listed parts of Postojnska jama were after 1st World War connected by diving or with artificial tunnels.

Nowadays, Postojnska jama is famous due to the highest biodiversity of underground species (troglobionts) in the world (84; 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, Postojnska jama takes the first place among all touristic attractions in Slovenia and is the most recognized show cave in Europe. Prosperity of tourism started with discovery of inner parts of the cave behind Pivka ponor in 1818, construction of single-track underground railway in 1872 and double-track underground railway in 1964 (GAMS, 2003, 297).

First scientific research of Postojnska jama started with archeological investigations in the entrance part of Postojnska jama soon after the finding of inner parts. Work was done by very famous people 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 last two were also the first who touched the question about formation of underground passages. Between 1st and 2nd World War, detailed mapping, speleogenetic and hydrologic investigations were done by Italians (L. Bertarelli, E. Boegan, R. Battaglia, S. Gradenigo; for details see GOSPODARIČ, 1976, 12). Some important work was done also by A. Perko. After 2nd World War, new era of research started with archeological investigations (BRODAR, 1951; BRODAR, 1966), hydrological investigation of underground Pivka river (MICHLER & HRIBAR, 1959), study of wider hydrological conditions between Postojna, Planina and Cerknica (GAMS, 1966a) and geological investigations (PLENIČAR, 1961; ŠEBELA, 1998). The knowledge of geology and speleology was substantially deepened by Gospodarič (1976), who comprehensively studied the whole Postojnska jama-Planinska jama cave system from the viewpoint of allochtonous sediments, speleogenesis and related age of sediments (1980). The age of much older sediments was studied recently and published by Zupan Hajna et al. (2008). Geomorphological evolution of the underground passages connected with development of superficial relief was done by Gams (1965).

From the viewpoint of processes, Gams (1966b, 34) studied corrosion rates with a hydrochemical method and later (GAMS, 1996) with limestone tablets in the entrance part of Postojnska jama. His results show that corrosion is absent or very low. Further from the entrance, the situation in not known.
Although Postojnska jama is among the most speleologically studied caves in the world, the exact speleogenesis seems to be very hard task due to complicated long-term evolution and much oversimplification in the past.

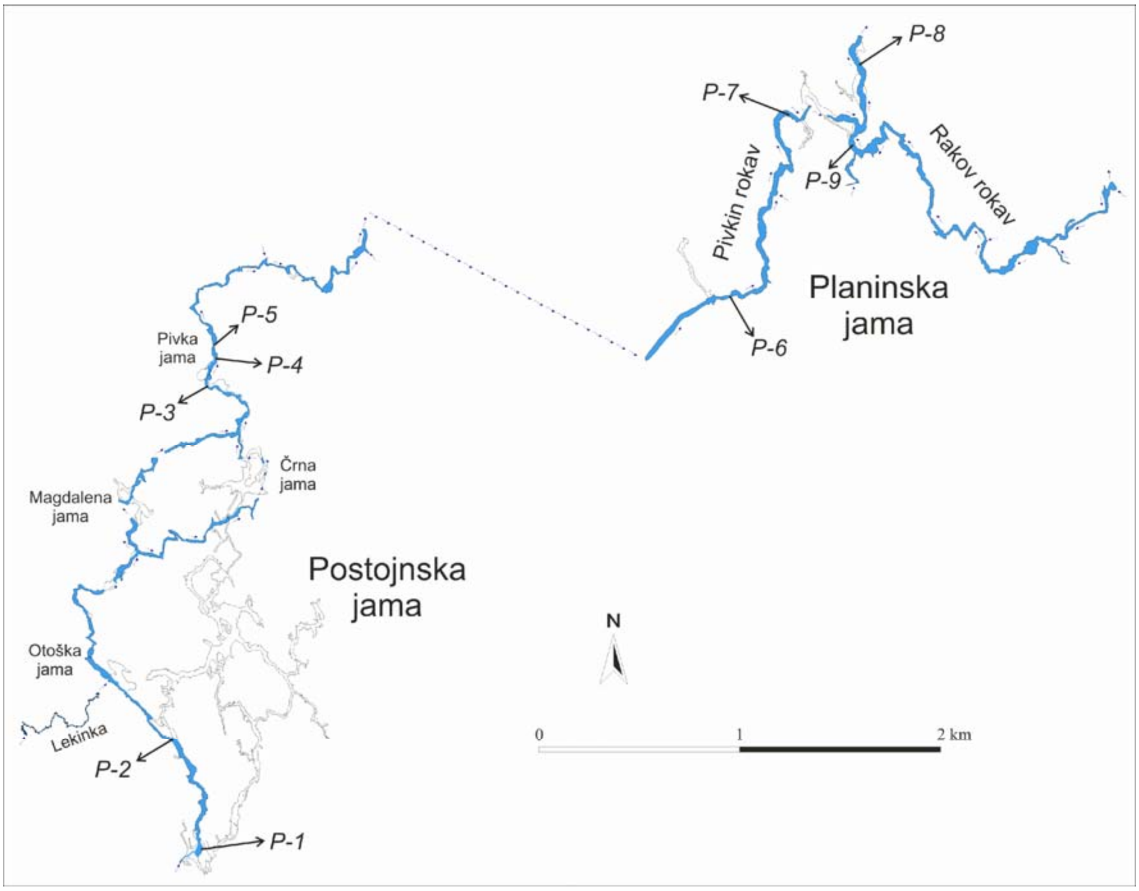


Figure 4.4.1: *Plan of Postojnska jama-Planinska jama system.*

Geological and geomorphological characteristics

Postojnska jama and Planinska jama are located between Pivška kotlina (~530 m a.s.l.) and Planinsko polje (~450 m a.s.l.). Pivška kotlina is a closed depression composed of flysch rocks in the northern part and of limestone in the southern part. Relief of Pivška kotlina is characterized by small vertical amplitude due to long-lasting geomorphic evolution and low nearby hydraulic gradients. Low vertical amplitudes are especially characteristic for the northern part of the basin since it is composed of mechanically less resistant flysch rocks. Gentle slopes are characteristic also for southern part of Pivška kotlina, which is composed mainly of Cretaceous limestone. The main reason for flattened relief is most probably long-term evolution near the water table, where downward lowering is limited by the water table. The same factor seems to be responsible for the flatness of Planinsko polje, which can be characterized as the most typical karst polje of all (closed depression, occasionally flooded, flat bottom, inflow from karst springs, outflow through karst ponors and without superficial inflow or outflow). In present-day morphological situation, more or less the only possible drainage of Pivška kotlina can be through Postojnska jama toward Planinsko polje. This underground water flow takes place under the karst surface with elevation from ~580 m a.s.l. to ~750 m a.s.l. Karst surface is characterized by several conical and elongated hills, which are incorporated within the system of elongated ("dry") valleys and dolines (GAMS, 1965). Due to sometimes thin and heavily fractured roof, several collapse dolines developed especially in the area of Postojnska jama. In Pivka jama, collapsing formed a new entrance to the cave system.

General geological structure of the karst massif, where Postojnska jama and Planinska jama are located, is very simple. It is composed of Upper and Lower Cretaceous limestones, which are folded in SW-NE direction (Fig. 9.4.2). The most SW fold is Postojna anticline, in which the majority of passages of Postojnska jama are developed. The northeast, Studeno syncline is developed, where the downstream passages of Postojnska jama, and the unknown connection with Planinska jama are formed (GOSPODARIČ, 1976, 21). Water flow between Pivška kotlina and Planinsko 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 the general pattern of folded structure.

The youngest lithified sediments are Senonian layers (K_2^3), which are developed as thick-bedded limestones. At the contact with Eocene flysch rocks ($E_{1,2}$), dip of the strata can be almost 90º toward SW. Toward the axis of the anticline, the dip of strata is reduced to about 45 º. Entrance part of Postojnska jama and Pivka jama passages are developed in the Senonian limestones.

Upper layers of Turonian limestones (K_2^2) are similar to Senonian – they are thick-bedded or even non-bedded. Lower Turonian limestones are usually characterized by thinner layers and they can be rich with up to a decimetre thick layers of chert. Passages that are developed in Turonian limestones are responsible for a higher portion of pipe flow in the sumps. In Turonian limestones, the majority of now dry passages in Postojnska jama are formed.

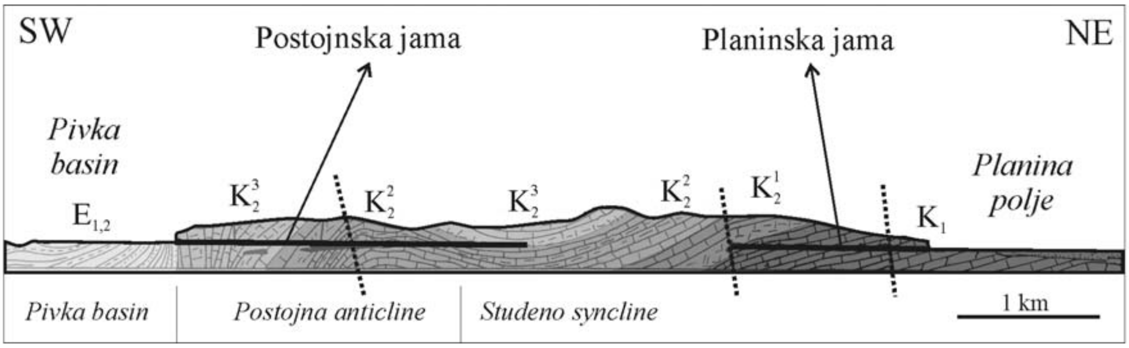


Figure 4.4.2: *General geological SW-NE cross-section between Pivška kotlina and Planinsko polje with Postojnska jama and Planinska jama (modified after GOSPODARIČ, 1976, 25).*

Cenomanian limestones (K_2^1) are non-bedded and can be reached just at the downstream end of Pivka jama and the upstream dry passage named Paradiž (=Paradise) in Planinska jama. The non-bedded structure of these limestones is most probably responsible for development of deep sumps between Postojnska jama and Planinska jama although some passages support free-surface flow (VRHOVEC, 2000). It seems that horizontal free-surface water passages are developed at all places where development of such passages was possible and that pipe flows developed where there was no other choice.

Lower Cretaceous limestones (K_1) can be thick-bedded or thin-bedded. They contain layers of dolomite and brecciated limestones. At the transition with Cenomanian strata, layers of chert can be found. Passages that are developed in limestones with cherts are smaller. Almost all passages of Planinska jama are formed in Lower Cretaceous limestones. (GOSPODARIČ, 1976)

The first comprehensive speleogenesis of Postojnska jama was given by archeologists (e.g. BRODAR, 1951; BRODAR, 1966) since they were the first one who studied cave sediments from scientific point of view and therefore paid attention to accumulation and erosional phases during speleogenesis. Later, this very schematic interpretation, which is strongly related to misinterpreted formation of a lake in Mindel-Riss interglacial (MELIK, 1955), was later criticized as an oversimplified, too short and not wide-spread over the whole Postojnska jama-Planinska jama cave system. Subsequent more detailed interpretations that were given by Gams (1965) and Gospodarič (1968) were later (even by the same authors; GOSPODARIČ, 1976) again recognized as too simplified. At present, even so abundant knowledge about Postojnska jama and Planinska jama, which was accumulated by Gospodarič, and additional datings made by Zupan Hajna et al. (2008), are not enough to interpret temporal and spatial speleogenesis of the whole cave system. From this point of view we should agree with Gospodarič (1976, 15) who states that different parts of the cave system were influenced by very different speleogenetic processes and factors even at the same time and that we are dealing with many erosion-accumulation phases even within individual passages.

The present-day situation in the cave system surely confirms Gospodarič's statement (1976, 15) since some passages develop under the influence of vertical percolation at one side and underground water flow of Pivka river on other. The activity of the latter was of measured only by Gams (1966b, 35). Although he strongly supported the idea of corrosional formation of passages along the underground Pivka river, his measurements only partially confirmed his expectations; his hydrochemical measurements between entrance to Postojnska jama and Spodnji Tartar confirmed downstream increase of hardness just in 11 cases while in about 14 cases he got no increase or even a decrease of hardness. Nevertheless, downstream increase of hardness was almost always within or very close to the range of error. This was confirmed also with further measurements in the entrance part of Postojnska jama, which were done with 3 limestone tablets (GAMS, 1996). Downstream, aggressiveness or underground Pivka river all the way to Planinsko polje remains unknown.

Hydrological characteristics

The hydrological backbone of the Postojnska jama-Planinska jama cave system is the Pivka river, which joins the underground Rak river in Planinska jama. Together they are named Unica river, which flows over Planinsko polje. Along this main underground water flow, several tributaries join the main water course but they are relatively unknown since they are hardly recognizable during low water level and the most interesting point of confluences lies in unexplored passages between Postojnska jama and Planinska jama (VRHOVEC, 2000).

Pivka originates from a karst spring located 16 km south from the entrance to Postojnska jama. During middle and high water levels, several karst springs mainly from the east (Javorniki mountains) feed the superficial Pivka river course. Tributaries from the western side are also numerous, but they are relatively small. Their catchment area extends over impervious flysch rocks. During middle water levels, discharge of Pivka river at the lithological contact limestone-flysch (11 km downstream of source) amounts 2.86 m^3/s (KOLBEZEN & PRISTOV, 1998). During low water levels, all the water from the upper Pivška kotlina, which is made up of Cretaceous limestone, flows toward Malni springs and Planinska jama (HABIČ, 1989, 240), while during high water level, discharge reaches up to 26.4 m^3/s (KOLBEZEN & PRISTOV, 1998) due to abundant karst springs below Javorniki mountains.

Between lithological contact limestone-flysch and ponor of Pivka river, the most important tributary of Pivka river is Nanoščica river, which contributes 1.41 m^3/s during middle water level and up to 15.9 m^3/s during high water level (KOLBEZEN & PRISTOV, 1998). The catchment area of Nanoščica river extends over the lower Pivška kotlina, which is formed by impermeable flysch rocks. Therefore Nanoščica river is fed mainly by superficial runoff. However, it is fed also by several small karst springs under Nanos mountain and from karst spring Korentan, which drains the partly isolated karst of Orehek (GOSPODARIČ ET AL., 1970; PETRIČ & ŠEBELA, 2004). During low water level, the contribution of Nanoščica river is higher in comparison with Pivka river since all the water from the upper Pivška kotlina flows toward Malni spring and Planinska jama (GAMS, 1966B, 35).

Only 2.3 km downstream of confluence of Pivka river and Nanoščica river, the ponor of Pivka is situated at 511.5 m a.s.l – several metres below the dry entrance to Postojnska jama. During summer months, when low discharges usually appear, discharge can amount to several tens of l/s. High water level is characteristic for 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). Consequently, the majority of water passages in Postojnska jama are completely filled with water.

Water flow in the Postojnska jama-Planinska jama cave system is characterized by water gradient that is perpendicular to strata dip (perpendicular flow is characteristic also for Lekinka; Chapter 4.2). However, water flow is not straightforward but rather zigzagged since the water flow chooses the most effective way through widened bedding planes and faults/cracks. Even more, water gradient is perpendicular to main tectonic structures (crushed zones), which can obstruct direct water flow toward Planinsko polje (ŠUŠTERŠIČ ET AL., 2001). Where the underground Pivka river flows along strata dip, 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 allochtonous flysch material. The latter is brought into the cave by sinking Pivka river and consists mainly of clay and silt, while sand and pebbles are less common (KRANJC, 1989, 65).

Along water flow in Postojnska jama, several tributaries were recognized, both visually (MICHLER & HRIBAR, 1959; GAMS, 1966A) and with tracing tests (HABIČ, 1989; KOGOVŠEK, 1999). The first one is underground Črni potok, which joins underground Pivka river in Otoška jama from the left side through cave Lekinka. 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. It is possible that they are active just during higher water level, when they can contribute significant amount of water, but they can dry up during low water level. A quite small left tributary was observed downstream of the downstream sump of Pivka jama, which could be underground water flow of superficial streams sinking northern of Postojnska jama-Planinska jama cave system (VRHOVEC, 2000, 167). Another very strong tributary (20 % of Pivka river) was observed by divers, who dived the sumps between Postojnska jama and Planinska jama (VRHOVEC, 2000, 168). This tributary can have its catchment area at Javorniki mountains or in upper Pivška kotlina, since some tracing tests confirmed connection of these areas with passage between Pivka jama and Pivka branch in Planinska jama (HABIČ, 1989; KOGOVŠEK, 1999, 184-185). In this section of water passages, we can expect also tributaries from the northern area, where some sinking streams near Studeno are located. The latter can flow also toward Vipava spring, but such conditions are less probable. Nevertheless, along the underground water flow of Pivka river we can count on several tributaries of allogenic or autogenic origin, which are the most characteristic for the passages downstream of Otoška jama and especially downstream of Pivka jama.

Hydrological connection of Postojnska jama with Pivka branch in Planinska jama was confirmed by several tracing tests (PERCO & BOEGAN, 1928 after GOSPODARIČ, 1976, 37; HABIČ, 1989, 240). It is interesting that all of them deny any loss of water between these two points (tracer did not appear anywhere else except in Pivka branch in Planinska jama). This means that underground Pivka river represents more or less the lowest point of underground drainage and that collects water from the surrounding area, although it is partially filled with allochtonous and collapse material (GAMS, 1966A, 12). Water channels are well developed and are able to conduct even high discharges without significant damming. Damming occurs just during very high water level but at rare narrow places (e.g. in Magdalena jama) and in some collapse chambers (e.g. Martelova dvorana). Therefore, the general gradient between ponor of Pivka river in Postojnska jama and spring of Unica river from Planinska jama (455 m a.s.l.) amounts to 10.6 ‰ (D = 5,270 m; ΔH = 56 m).

In Planinska jama, the Pivka river gets the strongest tributary – Rak river. Hydrology of the latter is much more complicated than the hydrology of Pivka river, since the most interesting part lies in a huge and up to 18 m deep sump at the end of Rak branch, where the waters from Javorniki mountains and Rakov Škocjan mix (MOREL, 2000). The catchment area of Rak branch extends at least over three directions: Rakov Škocjan (Cerknica polje), Javorniki mountains and upper Pivška kotlina. Therefore, mixing of two types of water (diffuse and concentrated autogenic) is characteristic for Rak in Planinska jama. From this point of view, Rak in Planinska jama is similar to Malni springs (Chapter 4.6). During low water level, Rak in Planinska jama dries up since all the water flows toward lower Malni springs (MICHLER, 1955).

The Postojnska jama-Planinska jama system drains the area of Pivška kotlina, which is quite densely populated near the entrance to the cave system (Postojna). In the 1970s, Pivka river was so polluted that the divers in Pivka jama were strongly threatened by infections due to some pollutants (SKET & VELKAVRH, 1980, 30). Construction of water treatment plants reduced pollution in the last decade. Nevertheless, pollution can be observed even nowadays, especially in the summer months during low discharge. Pollution can change some physicochemical characteristics of water that influence corrosion (or flowstone) deposition rates.

Meteorological characteristics

Due to many entrances to Postojnska jama, the latter is very well ventilated (GAMS, 1970). Less ventilated are only smaller passages close to the sumps, while the majority of water passages are characterized by intensive air flows (e.g. between entrance to Postojnska jama all the way to the Magdalena jama, entrance part of Pivka jama). Therefore, CO_2 concentration is relatively low even during summer months (GAMS, 1974; our measurements).

On the contrary, Planinska jama is well ventilated only in the entrance zone due to its big entrance, which enables two contrary wind directions in vertical cross-section. Inner passages (above Sotočje) are less ventilated, especially in the Pivka branch. The latter statement was confirmed also with CO_2 measurements, which ere relatively high even at the end of winter (~1.150 ppm).

Corrosion rate measurements and their relation to key factors and forms

4.4.1 Measurement point P-1 – temporal and vertical variability of processes in the entrance part of Postojnska jama

The first person, who started to measure corrosion rates in Postojnska jama was Gams (1966b, 35). Regarding several measurements of differences in water hardness between Veliki dom (=Big chamber) and Spodnji Tartar (=Lower Tartar) he concluded that corrosion rates are small. Most often they occur at low water level between January and March, when the majority of water comes from Nanoščica river. Therefore, the limiting factor for higher corrosion rates seems to be Pivka river. Later, Gams (1996) measured corrosion rates also with 3 limestone tablets placed in the Pivka river in Veliki dom. His results show that corrosion rates are extremely low, if they exist at all.

During 8-month-long measurements we tried to verify Gams's conclusions (1966b, 1996), since we are using a slightly modified technique. Unfortunately, the lower limestone tablet (measurement point 78) was broken due to transport load of Pivka river. About 1 m higher limestone tablet (measurement point 52) showed slight corrosion (-0.0001 mm/a) but we do not know for how long the limestone tablet was exposed to water flow and how reliable so low corrosion is. In 2007 we continued with measurements at more appropriate location (measurement point P-1), which is less influenced by the transport load of the Pivka river. Simultaneously, the water level was measured at a nearby location by Janez Turk, young researcher at Karst Research Institute ZRC SAZU.

Measurement point P-1 was located about 150 m downstream of the ponor of Pivka river in Postojnska jama in Veliki dom on the right side of underground Pivka river. The whole set of 16 limestone tablets was arranged in subvertical position (Fig. 4.4.1.1), where the vertical distance between limestone tablets amounted 6 cm. At the lower position ($H_{\mathrm{Veliki\ dom}}$ = 0 cm), 3 limestone tablets were installed to obtain better precision for longitudinal measurement of karst processes (Chapter 4.4.2). Therefore, 32 limestone tablets (pairs of 16 limestone tablets) were used to get insight into the vertical variability of processes and to evaluate influence of different discharges within 78 cm high zone. The lowest 3 limestone tablets were located always under the water, while the upper tablets were temporarily above water level. Limestone tablets were fixed with stainless steel screws, nuts and felted washers. Due to big cross-sectional area of chamber, water flow can be defined as low turbulent and subcritical at low and middle discharges. At

high discharge, water flow can be more turbulent. During very high discharge, backflooding results in lower velocity of water flow, which amounts about 0.5 m/s during high water level. During low and middle water level, velocity of flow is much smaller.
Measurements at P-1 started on 26th September 2007 and finished on 26th March 2009 (547 days). Due to change of limestone tablets on 20th February 2008 and on 18th September 2008, results are available for 3 measurement periods (lasting 147, 211 and 189 days).

Figure 4.4.1.1: *Limestone tablets at measurement point P-1 in Veliki dom in Postojnska jama during low water level.*

Average corrosion or deposition rates per year are represented in Fig. 4.4.1.2. It is clear that corrosion is absent during low, middle and high discharges. Even during very high discharge, which was characteristic for the middle of December 2009, we did not detect any corrosion rates within vertical zone of measurement. The main process seems to be deposition, which can be observed at limestone tablets as blackish material most probably related to organics. Blackish material was not deposited above $H_{\text{Veliki dom}}$ = +36 cm – therefore, deposited material can be also thin layer of flowstone. The highest deposition (0.0041 mm/a) was observed at limestone tablets, which were most of the time below water level (below $H_{Veliki\ dom}$ = +10 cm). Upward, deposition decreases logarithmically toward 0 mm/a at $H_{Veliki\ dom}$ = +79 cm. Differences between theoretical logarithmic function and real data are very low, since the R^2 amounts 0.89. Very rarely, differences are higher than maximum error of measurements with limestone tablets. Where differences are higher, difference can be attributed to deposited material that can not be cleaned with usual procedure (Fig 2.1.3.1 in Chapter 2.1.3).

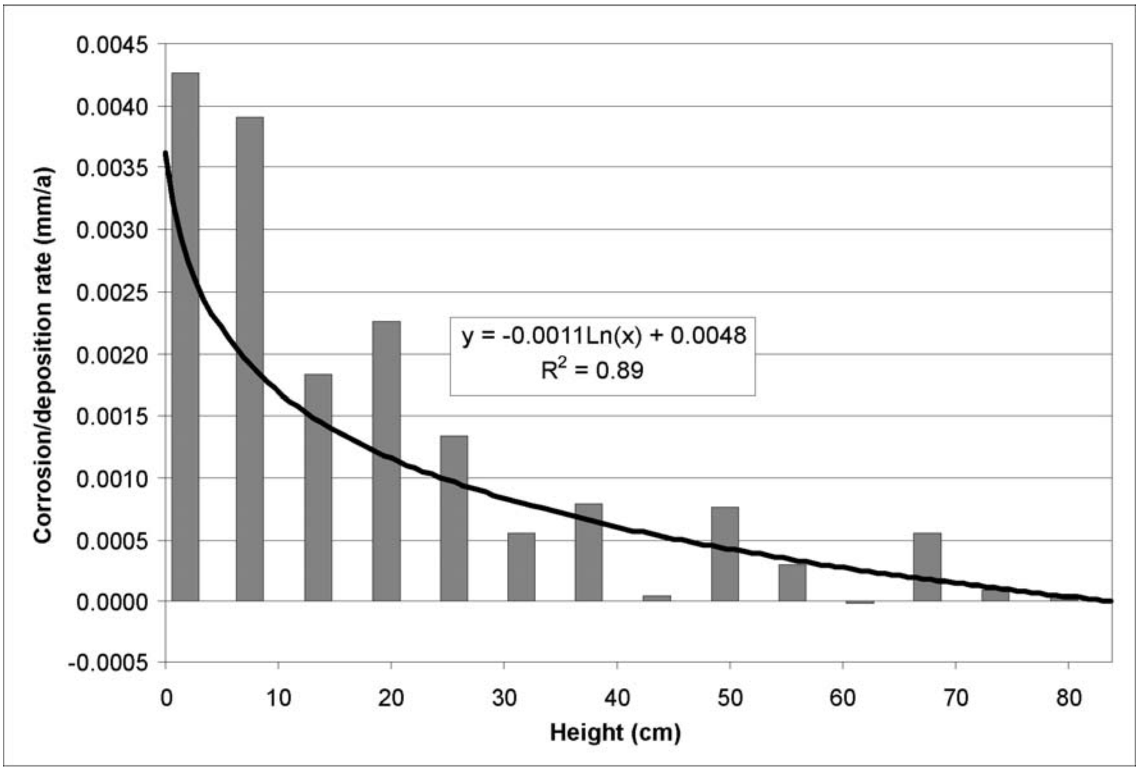


Figure 4.4.1.2: *Average corrosion and deposition rates at measurement point P-1 between 26th September 2007 and 26th March 2009.*

More detailed insight at measurement point P-1, which is possibly due to 3 measurement periods (Fig. 4.4.1.3), shows much more diverse situation with comparison with average values (Fig. 4.4.1.2). During 1st measurement period, water most probably flooded all limestone tablets (Fig. 4.4.1.4) but the source of water seems to be diverse since we observe first peak up to $H_{Veliki\ dom}$ = +70 cm with corrosion rates and additional higher one without corrosion rates several hours later during all three flood events in 1st measurement period. The first peak should be related to the fast superficial runoff from the nearby area covered by flysch rocks, while during the second one prevailing runoff from karst area should prevail (HABE, 1966, 50). Therefore, corrosion rates observed up to $H_{\text{Veliki dom}} = +70$ cm could be related only to the superficial runoff from flysch rocks, while additional karst water caused no corrosion – although is was higher. Below $H_{\text{Veliki dom}} = +70$ cm, corrosion rates decreases due to higher deposition rates downward. Deposition prevailed over corrosion below $H_{\text{Veliki dom}} = +27$ cm. The highest deposition was recorded on the lowest two places, where amounts 0.0016 mm/a. Although we recorded corrosion rates during 1st measurement period, they are very low (up to -0.0007 mm/a or originally -0.0003 mm/147 days). Although original values of corrosion are within maximum error of measurement (±0.0004 mm), corrosion was detected during autumn and winter months, which corresponds to findings of Gams (1966b, 35).

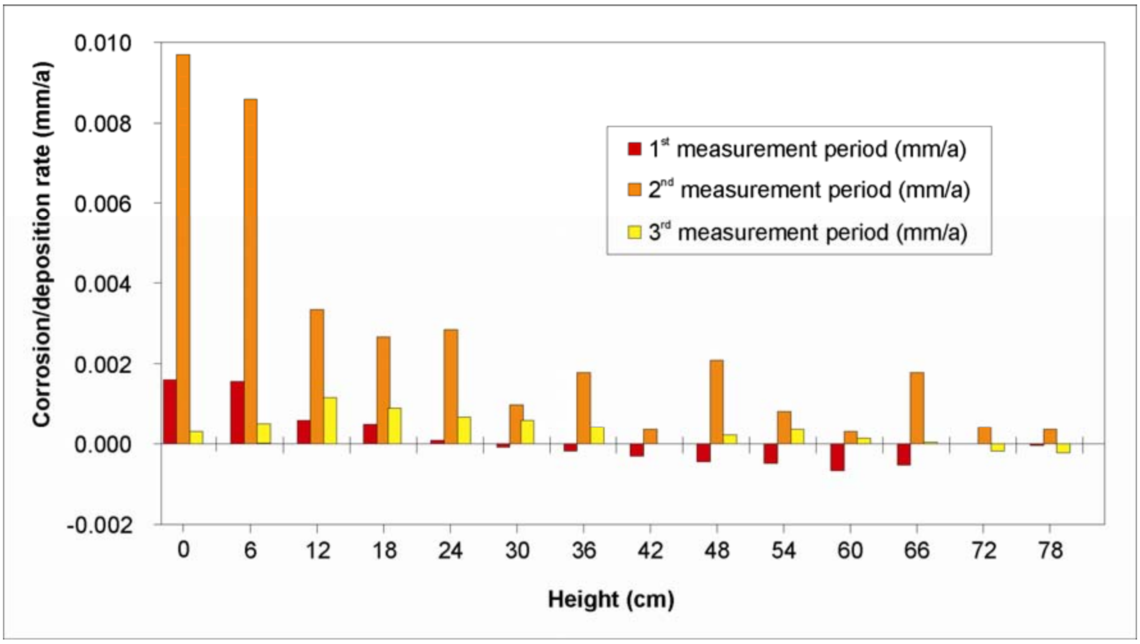


Figure 4.4.1.3: *Corrosion and deposition rates in 3 measurement periods between 26th September 2007 and 26th March 2009 at measurement point P-1.*

During the beginning of the 2nd measurement period, water level was for about 50 days constantly higher than $H_{\text{Veliki dom}} = +70$ cm without significant flood events (Fig. 4.4.1.4). Later, it was all the time relatively low. Therefore, all limestone tablets indicate deposition. The highest values were recorded on the two lowest places

(0.0091 mm/a or originally 0.0053 mm/211 days). Upward, deposition rates are lower. Differences in deposition rates are higher than maximum error of measurement, most probably due to different thickness of organics deposited on limestone tablets.

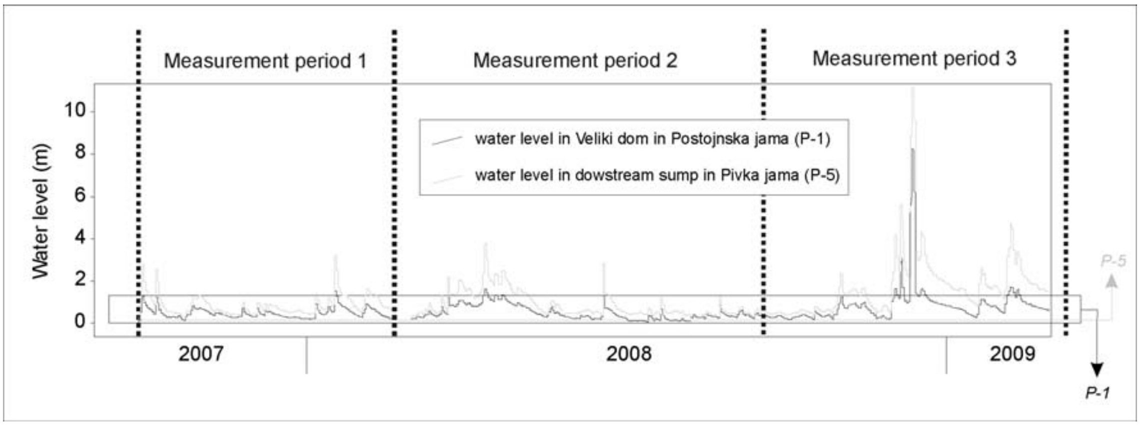


Figure 4.4.1.4: *Water height during 3 measurement periods between 26th September 2007 and 26th March 2009 at measurement points P-1 and at P-5 (data courtesy of Janez Turk).*

The highest discharges were characteristic for the 3rd measurement period, when water flooded all limestone tablets for 8 m (Fig. 4.4.1.5). Nevertheless, the expected higher corrosion rates are absent. Moreover, all limestone tablets below $H_{Veliki\ dom}$ = +69 cm indicate deposition and only the upper two show corrosion close to the average measurement error (-0.0002 mm/a or originally -0.0001 mm/189 days). The latter values are even lower than corrosion rates observed during the 1st measurement period. This means that the most important factor for corrosion seems to be hydrological situation in catchment area – during the time of low discharges with several small flood events, the majority of water comes from Nanoščica river, which has catchment area mostly on flysch rocks. At that time, the contribution of Pivka river is negligible (GAMS, 1966B, 35). At high water level, the discharge of Pivka river strongly prevails over Nanoščica river – therefore, corrosion rates are absent. During that time, the limiting factor for corrosion rates seems to be diffuse autogenic recharge of Pivka river, which is rich with CO_2, solution load and close to saturation. Along superficial flow, the saturation index most probably even increases due to outgassing of CO_2. During the 3rd measurement period, the lowest two results at measurement point P-1 could indicate corrasion from the side of bed load material. Nevertheless, corrasion was only strong enough to remove part of relatively soft organic material, while the limestone tablets remained uncorraded.

Figure 4.4.1.5: *Flood in Veliki dom (entrance chamber of Postojnska jama) on 12th December 2008. Measurement point P-1 is located at the arrow 8 m below the water level (photo: Mitja Prelovšek).*

4.4.2 Measurement points P-1, P-2, P-3, P-4, P-5, P-6, P-7 and P-8 – temporal and longitudinal changes of processes along underground water flow in Postojnska jama-Planinska jama cave system

Underground water flow of Pivka river and Unica river (downstream of confluence with Rak river) is more than 10 km long. Since the 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 give us excellent opportunity to measure karst processes all along underground water flow. The latter is crucial for hydrological connection between Pivška kotlina and Planinsko polje and therefore indirectly dictates the geomorphological evolution of both depressions.

Rate of corrosion or deposition was measured at 9 measurement points along underground water course (Fig. 4.4.1). The upstream one (P-1) was located 150 m from the entrance to Postojnska jama and the downstream one 175 m upstream from the entrance to Planinska jama. All measurement points were placed at similar depth and were under the water even during low water level. The most evident difference between them is velocity of water flow, which was the lowest at measurement points P-1 and P-5 and the fastest at P-3, P-2 and P-6. At all measurement points, measurements were done using 3 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 and P-8, measurement started on 26th September 2007 while at P-6 and P-7, measurement started on 19th February 2008. In Pivka jama (measurement points P-3, P-4 and P-5), measurements already started on 29th September 2006. Limestone tablets were replaced several times – nevertheless data for almost complete longitudinal cross-section are available from 26th September 2007 to 26th March 2009. This time-span was divided in 3 measurement periods. Limestone tablets were replaced at low water level almost simultaneously at all measurement points.

Average rates of processes between 26th September 2007 and 26th March 2009 (547 days) are represented in Fig. 4.4.2.1. At all measurement points, the net process is deposition. The lowest rates (0.0005 mm/a) are characteristic for the middle part of the underground water flow, that is for Pivka jama. The highest deposition rate appears at the ponor to Postojnska jama (0.0019-0.0043 mm/a) and at the spring in Planinska jama (0.0019 mm/a). Deposition in the entrance part of Postojnska jama could be related to deposition of organic material, which can be seen as black coating on limestone tablets. Organic material is carried into Postojnska jama by Pivka river and significantly decayed in the underground passage to Pivka jama (SKET & VELKAVRH, 1980, 42). Therefore, decreased deposition rates between entrance to Postojnska jama (P-1) and Pivka jama (P-5) can be attributed to decreased deposition of organic material. Downstream of Pivka jama, concentration of ammonium nitrogen and nitrite reduces due to dilution but the biological oxygen demand usually slightly increases toward Planinska jama (SKET & VELKAVRH, 1980, 42). In the latter, lower pollution can be recognized also from the absence of blackish coating. Therefore, increase of deposition rate between Pivka jama (P-5) and entrance part of Planinska jama (P-8) cannot be assigned to deposition of organic material but rather to the slight flowstone deposition.

Nevertheless, values are too small that the flowstone deposition could be observed even under magnification.

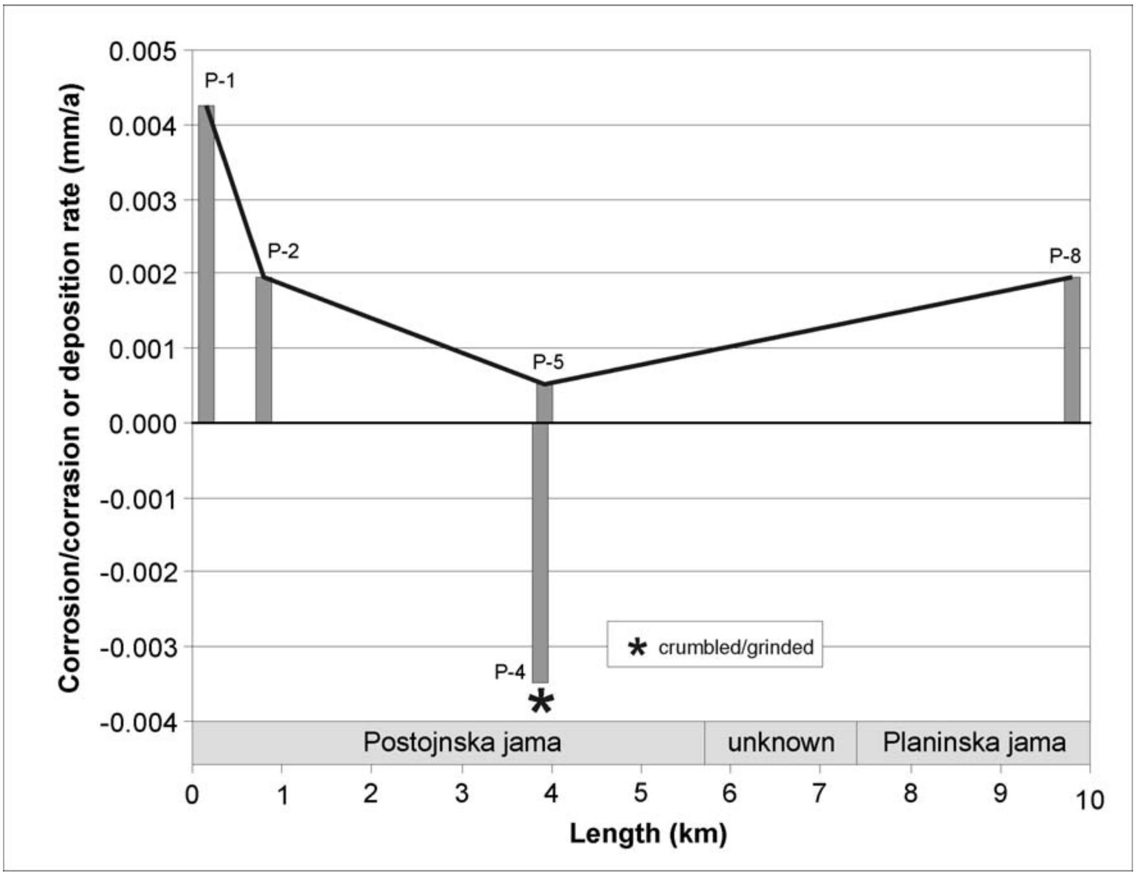


Figure 4.4.2.1: *Average corrosion/corrasion or (organics/flowstone) deposition rates in Postojnska jama-Planinska jama cave system between 26th September 2007 and 26th March 2009.*

Fig. 4.4.2.2 offers much better insight into the temporal and longitudinal variability of processes. The highest deviation was noticed in the entrance part of Postojnska jama mainly due to result obtained during the 2nd measurement period. The latter period started in the middle of February 2008 and ended in the middle of September 2008, while the other two measurement periods reflect processes from September 2007/2008 to February 2008/March 2009. Since the Pivka river is highly polluted especially during summer months characterized by low water level and high temperatures (and resulting reduced decomposition of organics because of too high biological oxygen demand and consequential even anoxic conditions in the water), high rates of organic deposition is expected. Much lower values of deposition are characteristic for autumn and winter months. Flood that was characteristic for the middle of December 2008 was not detected with net corrosion rates, even further downstream. Nevertheless, deposition is lower especially close to the ponor of Pivka. Much lower deviation is characteristic for other measurement points (from P-3 to P-8), which indicate similar rates of deposition irrespective of season or discharge.

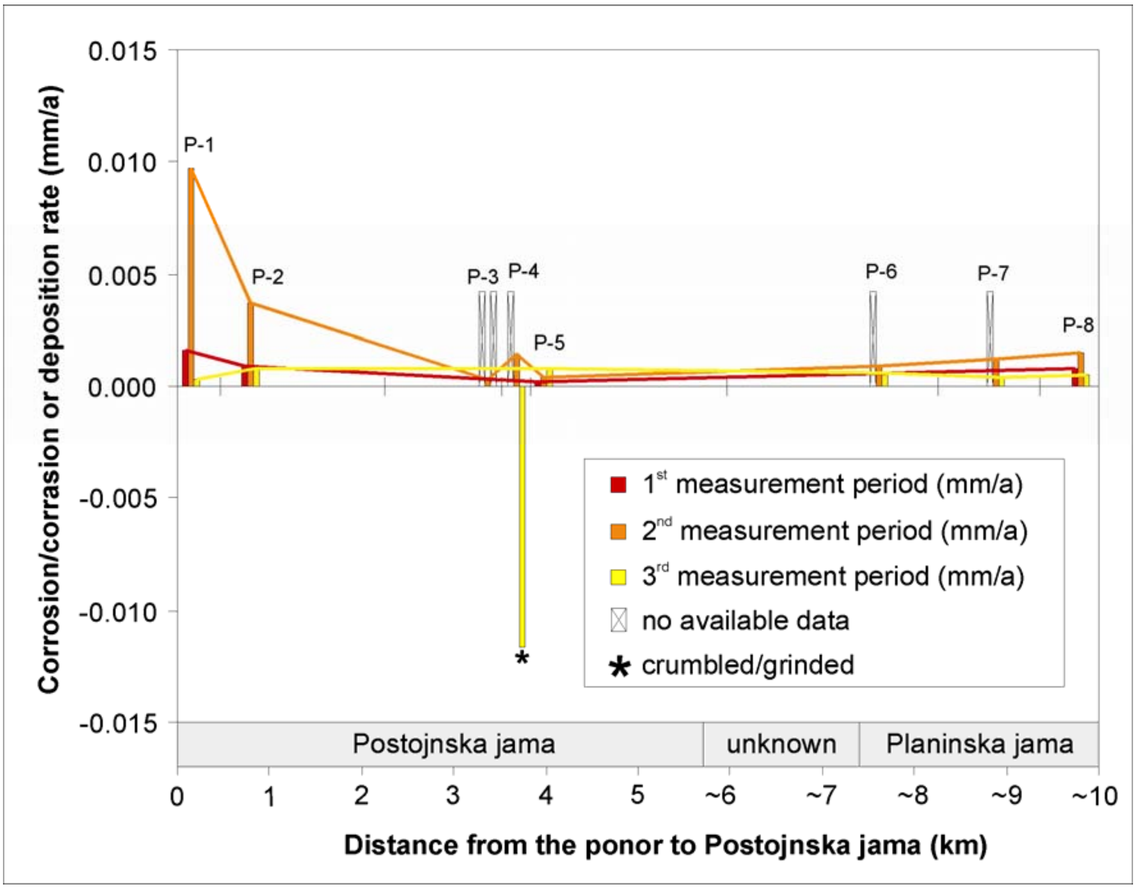


Figure 4.4.2.2: *Corrosion/corrasion and deposition rates during 3 measurement periods between 26th September 2007 and 26th March 2009 along underground water course through Postojnska jama-Planinska jama cave system.*

A pattern of decreased deposition from the ponor to Postojnska jama to Pivka jama and increased deposition from Pivka jama to the outflow from Planinska jama can be observed during 1st and 3rd measurement period. Differences in Planinska jama are rather small but constant and unequivocal, which shows a stable phenomenon. The most probable explanation for increasing (flowstone) deposition rates seems to be outgassing of CO_2 from the water, which was recognized on superficial Unica river downstream of Planinska jama. In Planinska jama, one measurement of physicochemical properties of water at low discharge (19th February 2008) showed almost constant pH value (8.07-8.09) from the upstream sump in Planinska jama to the confluence of Pivka river with Rak river, which does not show high outgassing of CO_2 from the water. Nevertheless, if we take into account slight flowstone deposition, which lowers pH value, and slight outgassing of CO_2, which increases pH value, pH value can be constant along the watercourse. Increased CO_2 concentration in the water of underground Pivka river can be expected at least due to tributary from Javorniki mountains, which was most probably observed by divers downstream of Pivka jama and confirmed by several tracing tests.

At high water level, bed load transport was observed only in Pivka jama, where mechanical weathering is common due to the big entrance. The latter allows frost shattering especially during winter months and supplies the water course with limestone blocks. Bed load transport was observed at measurement places P-3 and P-4, where the water flow is the fastest. A power of corrasion was observed especially during the 3rd measurement period, when limestone tablets at P-3 were washed away together with their screw. At P-4, all limestone tablets were strongly modified by corrasion (crumbling and grinding; Fig. 4.4.2.2). During very high discharge, bed load transport has to be reduced or absent due to backflooding from the downstream sump in Pivka jama (from P-5 upstream).

Along underground Pivka river and Unica river, breakdown morphology strongly prevails since the water passages formed along faults and tectonically deformed bedding planes (ŠEBELA, 1998, 78). At some places, corrosional morphology is developed but it is relatively rare. The most evident corrosional features along underground water course of Pivka river are scallops, which form during fast water flow, corrosionally widened cracks and poorly developed boxwork, where the water flow that formed them was relatively slow. Nevertheless, present-day formation of scallops seems to be questionable due to smoothened transition between them at many places (Fig. 4.4.2.3). In Planinska jama, absence or at least very weak corrosion is proved also with many thin and fragile carbonate cave snail shells that are deposited on the banks and cannot be dissolved by Pivka river or Unica river. Since the present-day net process shows deposition, scallops were most probably formed under different physicochemical properties of water in the past. In the present-day situation, corrosional features are preserved but slightly modified by corrasion and maybe by poorly known processes at the contact between carbonate rock and organic blackish coating. Flowstone coating along the underground Pivka river and Unica river downstream of confluence with Rak was not noticed anywhere. This is a result of low rates of chemical processes, since only 5 to 20 mm of flowstone coating could develop during the last 10,000 years at equal rates of processes.

Figure 4.4.2.3: *Corrosional morphology, limestone tablets, TD Diver for measuring height and temperature of water (used by Janez Turk) and Proteus anguinus at measurement point P-5 (downstream sump in Pivka jama).*

4.4.3 Measurement points P-7, P-8 and P-9 – spatial changes of processes at underground confluence of Pivka river and Rak river

The confluence of Pivka river and Rak river is one of the biggest underground confluences in the world. At specific hydrological situation (middle-low discharges), courses that join at Sotočje (=Confluence) have very different catchment areas; Pivka river drains mostly northern Pivška kotlina while Rak river drains autogenically recharged water of Javorniki mountains. Therefore, measurements upstream and downstream of the confluence can give us important data about geomorphic activity upstream and downstream from mixing. At high discharge, hydrological situation is much more complex – both rivers are fed by diffuse autogenic, concentrated autogenic and allogenic recharge.

To observe geomorphic influence of mixing, three measurement points were used. Measurement point P-7 was located in underground Pivka river, P-9 in Rak river and P-8 downstream of the confluence in the underground Unica river. At each measurement point 3 limestone tablets were used at the same time to get more precise data. All limestone tablets were placed in very similar hydrological conditions; they were flooded at low and high water level and dry only at very low water level. Water flow can be characterized as turbulent and subcritical, only at P-9 can be due to higher velocity of flow characterized as supercritical. Limestone tablets were fixed with stainless steel screw, nuts and felted washers.
Measurement at P-8 began on 26th September 2007, on P-7 and P-9 on 19th February 2008. Therefore, only data from 19th February 2008 till 26th March 2009 (end of measurements) were used for evaluation. Since the limestone tablets were changed on 12th October 2008, two measurement periods (146 and 235 days) are available.

Results of measurements near underground confluence of Pivka river and Rak river are represented in Tab. 4.4.3.1. On average, all measurement points indicate net deposition, which, due to the absence of black organic coating, are supposed to be flowstone deposition. The lower rates were observed in the Rak river (P-9), where the average rate corresponds to rates at Malni springs (Chapter 4.6) and in Tkalca jama (Chapter 4.5). Net deposition is slightly higher at P-7 (Pivka river) and the highest downstream of confluence in the Unica river. It is worthy of note that the same succession was observed during the 2nd and 3rd measurement periods. During the 3rd measurement period, slight corrosion in the range of average error was observed in Rak river. During the 2nd measurement period, which was characterized by low discharges especially in the second part of measurement period (Fig. 4.4.1.4), the rates in Pivka river were similar to Rak river although catchment areas were characterized by various types of recharge.

Table 4.4.3.1: *Corrosion or deposition rates at the underground confluence of Pivka river and Rak river between 19th February 2008 and 26th March 2009.*

	P-7 (Pivka river)	P-9 (Rak river)	P-8 (Unica river)
1st measurement period (mm/a)	/	/	0.0008
2nd measurement period (mm/a)	0.0012	0.0011	0.0015
3rd measurement period (mm/a)	0.0004	-0.0001	0.0005
AVERAGE	**0.0009**	**0.0006**	**0.0011**

The higher flowstone deposition rates were observed downstream of confluence at P-8. Mixing corrosion is therefore not expressed downstream of confluence although the rivers have quite different catchment areas especially during middle-low discharge. It seems that the highest influence is from outgassing of CO_2 from the water, which is the highest downstream of confluence due to the nearness of the well ventilated entrance to Planinska jama. If mixing corrosion (or lower flowstone deposition) exist, it is limited to several decades of meters downstream of confluence. Further downstream, outgassing of CO_2 from the water strongly prevails over mixing.

Conclusion

Postojnska jama-Planinska jama cave system represents the most extensive mostly horizontally developed cave system in Slovenia. Almost all passages were developed in epiphreatic conditions, where present-day water oscillation occupies slightly more than 10 m of the lower parts. Nowadays, the lower passages are developed along the underground course of the Pivka river, while the upper horizontal passages belong to the now fossil epiphreatic zone.

Measurements with limestone tablets along Pivka river underground water course indicate prevailing net deposition process, although results obtained during 8-month-long measurement (Chapter 3) indicate corrosion rates (-0.0045 mm/a; Appendix I). The latter was most probably caused by iron oxide, which can result in such high misleading corrosion (Chapter 2.1.3). Net deposition is especially characteristic for lower parts of entrance passages in Postojnska jama (from 0.0016 to 0.0043 mm/a; due to deposition of organic material) and with lower rates for lower parts of Pivkin rokav (=Pivka branch; up to 0.0019 mm/a; most probably due to flowstone deposition). The middle part of a system (Pivka jama) indicates lower rates of deposition (0.0005 mm/a). Corrosion is most probably related to the special events (the beginning of moderate flood events following low water levels), when the superficial runoff from Nanoščica river catchment area prevails. Corrosion is not related to severe flood events, since the majority of water is contributed by non-aggressive Pivka river. The latter is mainly fed by diffuse autogenic recharge, which seems to be (over)saturated during its superficial water course to the entrance of Postojnska jama – even during very high discharge. Due to short-time measurements, any long-term influence of the organic layer deposited on limestone tablets is not known. In Rak river near the underground confluence with Pivka river, rates are similar to the one observed in Pivka river upstream of confluence and to net deposition rates at Malni springs (4.6) and in Tkalca jama (4.5). Nevertheless, insignificantly low corrosion rates can be expected during high discharge along the underground Rak river. Downstream of the confluence (at underground Unica river), measurements indicate net flowstone deposition during all 3 measurement periods.

Although the prevailing morphology of hydrologically active passages indicates strong influence of collapsing, some parts of passages show (epi)phreatic corrosional morphology. Present-day factors and processes do not support formation of such morphology due to net deposition rates. Therefore, corrosional features found along underground Pivka river seem to be of older age, when hydrologic, climatologic or geomorphic situation was different. Colder climate with higher percentage of superficial runoff and lower CO_2 concentration in diffuse autogenic recharged water would certainly support higher aggressiveness of water that sinks into Postojnska jama.

4.5 Tkalca jama

Tkalca jama (=Weaver's cave; Reg. No. 857) is situated between Cerknica and Planina polje at the downstream end of Rakov Škocjan. It drains the water arriving from Cerknica polje toward Planina polje. It is a typical ponor cave with 2,885 m of wide almost horizontal passages. Entrance part (~200 m) looks like a roofed continuation of superficial flow of Rak river with riverbed formed in bed load material (sand, gravel, cobbles) and breakdown blocks. On average, the passage is 8 m wide and 8 m high. This part is accessible only at low water level. Continuation of the cave leads through a narrow passage, which acts as a hydrological barrier due to massive accumulation of trunks. The downstream passage is accessible only at very low water level, when the Rak riverbed dries out. Continuation of the passage leads through phreatic tubes, which are also partly choked with tree trunks and branches. About 350 m from the entrance, a sump 24 m deep and 147 m long is located. Diameter of the sump is in some places quite small (1×2 m; Krivic & Praprotnik, 1975, 128). Together with a lot of wooden debris it can therefore function as a restriction for water flow. The majority of cave (passages downstream of 1st sump) was discovered in 1974, when the rescue diving team searched for drowned young diver Janko Petkovšek in the 1st sump. Downstream of the 1st sump (also known as Sifon J. Petkovška (=sump of J. Petkovšek), Tkalca jama continues with 5-10 m wide passage with many rapids between several lakes (KRIVIC & PRAPROTNIK, 1975, 128-129). The stream bed is covered with bed load material. At the known end of passages, the terminal sump is located. At high water level, almost all known passages are flooded to the roof.

Geological and geomorphological characteristics

Tkalca jama is developed in Lower Cretaceous fine-grained micritic limestone, which covers all the karst valley of Rakov Škocjan. Limestone has a low amount of impurities and usually a low amount of dolomite. Especially in Tkalca jama, the entrance part is formed also in sedimentary and tectonic breccia with layers and lenses of dolomite, but the extension of such rocks is limited to the entrance part of the cave (GOSPODARIČ ET AL., 1982). Well developed stratigraphic layers are inclined for ~30 º toward W, NW or SW direction (GOSPODARIČ ET AL., 1982, 25; HABIČ & GOSPODARIČ, 1989, 46). Tectonic structures in the cave usually cross actual passages in NW-SE and NE-SW directions. The biggest distinctive tectonical deformation runs along the central and the lower part of Rakov Škocjan and is thought to be a perpendicular hydrological barrier for waters between Cerknica and Planina polje. Because of this tectonic zone, springs are located at the eastern side and the ponors on the western side (the only exception are Kotliči springs; HABIČ & GOSPODARIČ, 1989, 48).

Rakov Škocjan is a typical karst valley since it is incised in an extensive levelled area and has a spring cave (Zelške jame) at the upstream and a ponor cave (Tkalca jama) on the downstream side. At up- and downstream side of karst valley, the gradient of Rak river is very steep (3-5 %) in comparison with long middle part with gradient about 0.3 %. According to Habič & Gospodarič (1989, 46) this can be a consequence of differential uplift and subsidence of some smaller tectonic blocks. Another explanation for the gentle gradient is deep accumulation of Pleistocene sediments which can be deeper than 10 m in the centre and partly eroded at the up- and downstream end of a karst valley (HABIČ & GOSPODARIČ, 1989, 46). According to our observations, the greatest mechanical weathering takes place near the caves, which are due to many rockfalls gradually transformed into karst valley. If the corrosion, mechanical erosion or transport ability of river is low in the water channel, deeper accumulation of such material would result in steeper slopes. Therefore, higher gradients can be just a result of disability of water flow to remove rockfalls. This explanation is supported by the presence of long lake in Zelške jame due to mechanical breakdown at the upstream part of Rakov Škocjan. According to our observations, biocorrosion can play a significant role in lighted environments while in the darker (i.e. near the cave entrances) biocorrosion can be much weaker due to lack of light (Chapter 3).

Hydrological characteristics

Tkalca jama is a part of a major cave system that hydrologically connects Cerknica and Planina polje. This connection was proved with several tracing tests (ŠERKO, 1946, 126; GAMS, 1966a; GAMS, 1970). According to Gospodarič & Habič (1976, 52) about 42 % of water from Cerknica polje flows directly to springs of Ljubljanica, while the rest (58 %) of water flows into the ponors at the NW side of Cerknica polje. The latter water with average discharge of 10.28 m^3/s mostly appears at the surface in Rakov Škocjan from Zelške jame as the Rak river, from Kotliči springs and at Prunkovec spring at higher water level (GOSPODARIČ & HABIČ, 1979). The great majority of this water sinks in Tkalca jama and reappears again in the Rak branch of Planinska jama and in Malni springs (Chapter 4.6).

Along the more than 6.5 km long cave system between Cerknica polje and Rakov Škocjan, the watercourse from Cerknica polje gets also some diffusely recharged autogenic water, which percolates vertically through the vadose zone and joins the main water course in the (epi)phreatic zone. The biggest area of such recharge is the Javorniki mountains, which starts to rise above the levelled surface 1 km SW from the main water course. In spite of proved water connection from Javorniki mountains (KOGOVŠEK, 1999) the contribution of this recharge to the water flow through Rakov Škocjan is still not known very well. I seems that the majority of autogenic recharge at Javorniki mountains flow directly to Rak branch in Planinska jama and to Malni springs and therefore avoids Rakov Škocjan, since the water course from Cerknica polje pushes away the water course from Javorniki mountains to the northwest, that is toward Malni springs (ČADEŽ, 1955/1956 after GAMS, 1966a).

Hydrological conditions at the Cerknica polje and in the karst aquifer SW from Tkalca jama strongly define the origin of water that flows into Tkalca jama. When the water level is very low at Cerknica polje, the main source of water is the Cerkniščica river, which sinks in Velika Karlovica (GAMS, 1966a, 15). The latter gets water from many karst springs north from Slivnica mountain and from some superficial streams in the same area. The water is very rich in Mg^{2+} since the catchment area lies mainly on Upper Triassic dolomite. At higher water level, Cerkniščica in sinking together with Stržen river. The latter is a part of eastern Ljubljanica branch and, on the way toward Cerknica polje, sinks and reappears on the surface twice before it appears at Cerknica polje. Contribution of autogenic recharge, that feeds the main water course between Cerknica polje and Tkalca jama, seems to be very small at low and middle discharges but can increase at high water level (KOGOVŠEK, 2004, 149). Autogenic recharge in Rakov Škocjan can be detected also at some less important springs with very stable yearly temperature and some other different physicochemical characteristics (GOSPODARIČ ET AL., 1982) and can therefore slightly change physicochemical properties of water along the main water course. The exact portion of each contribution is hard to obtain, since it changes according to discharge and actual hydro-meteorological conditions. Some springs in Rakov Škocjan drain mainly autogenic water at low water level and combined autogenic-alogenic water at high water level.

Although caves have usually huge diameters, some restrictions at the main water course cause relatively high oscillations of water level. At very low water level, only a few l/s flow through Rakov Škocjan and disappear into some small ponors 200 m upstream from Tkalca jama. Tkalca jama is therefore without water course all the way to the 1st

sump. At middle water level, 10.28 m^3/s is flowing into the cave without significant damming. Backfloding from the side of Tkalca jama occurs at much higher discharge. If high discharge lasts several days, water can rise to the 515 m a.s.l., which is 36 m above the 1st sump in Tkalca jama (Fig. 4.5.1). At high water level, decrease of SEC is observed (GOSPODARIČ ET AL., 1982). Lower SEC was observed also in spring, while the highest SEC is characteristic for low water level (ususlly in summer) and autumn months (GOSPODARIČ ET AL., 1982).

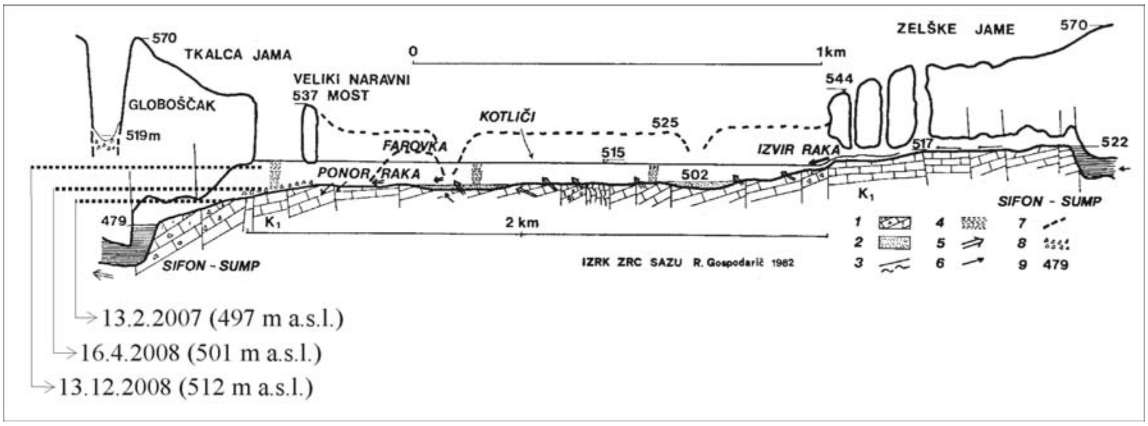


Figure 4.5.1: *Longitudinal cross-section through karst valley Rakov Škocjan with the highest water levels observed from 25th October 2006 to 12th September 2008 (hydrological data courtesy of Janez Turk; morphology modified after GOSPODARIČ ET AL., 1982).*

Meteorological characteristics

Since Tkalca jama has 2 big entrances at the ponor, the entrance chamber is very well ventilated. Completely different is its continuation, which is separated from the entrance chamber by low and usually flooded narrow passage. The passage at the other side of the narrow part rises above the usual water level and is flooded just at the highest water level. Even when the passage on the other side of the narrow is accessible, ventilation is extremely low due to several very tight fractures connected with the surface. Such a situation is characteristic for all dry passages which end in a sump. Due to extremely weak ventilation and decay of organic matter near the sump, oxygen concentration can be very low and a relatively high amount of CO_2 (up to 4,230 ppm) was measured soon after the 1st sump was accessible.

Corrosion rate measurements and their relation to key factors and forms

4.5.1 Measurement place T-1, T-2, T-3 and T-4 – temporal and spatial variability of processes at 1st sump

Although Tkalca jama lies in the middle of Classical Karst where the carbonates are far from the contact with non-karstic rocks we can expect some corrosion rates due to gradual saturation of water when approaching equilibrium (DREYBRODT, 1988) and due to mixing corrosion (BÖGLI, 1964 after GAMS, 1966b). The latter can be expected when the two almost saturated waters with different CO_2 concentration join together in combined stream. Although diversity of discharges plays a significant role in the resulting degree of undersaturation (equal discharge of combining saturated streams leads to the highest undersaturation), weak corrosion can be expected although differences in discharge can be very high. According to SEC oscillation, which can is actually a negative correlation function of discharge, the highest corrosion rates can be expected in spring months and in moments of high discharge.

All measurement points were located a few meters beside the 1st sump. Measurement point T-1 and T-2 were located in the middle of fast water flow before it ends in the 1st sump. Water flow there can be considered as fully turbulent and supercritical and seems to be in strong relation with small scallops at the wall. Measurement points T-3 and T-4 were located at least 10 m from this fast water flow. At middle and high water level, T-3 and T-4 were most probably located in relatively slow flowing water. At low water level, all measurement points were out of reach of watercourse (when the 1st sump was accessible, limestone tablets were 2 m above water level – $H_{level\ logger}$ = +2 m; see Fig. 4.5.1.1). At each measurement point, 3 limestone tablets were installed to get better insight into the ending results. Since the 1st sump is accessible only at very low water level (usually for just several days per year), limestone tablets were replaced after 4 months, if they were accessible. Limestone tablets were fixed with stainless steel screws, nuts and felted washers like the limestone tablets in Lekinka (Chapter 4.2).

Water levels at the 1st sump, which were used for comparison with corrosion or flowstone deposition rates, were measured by Janez Turk, young researcher at the Karst Research Institute ZRC SAZU.

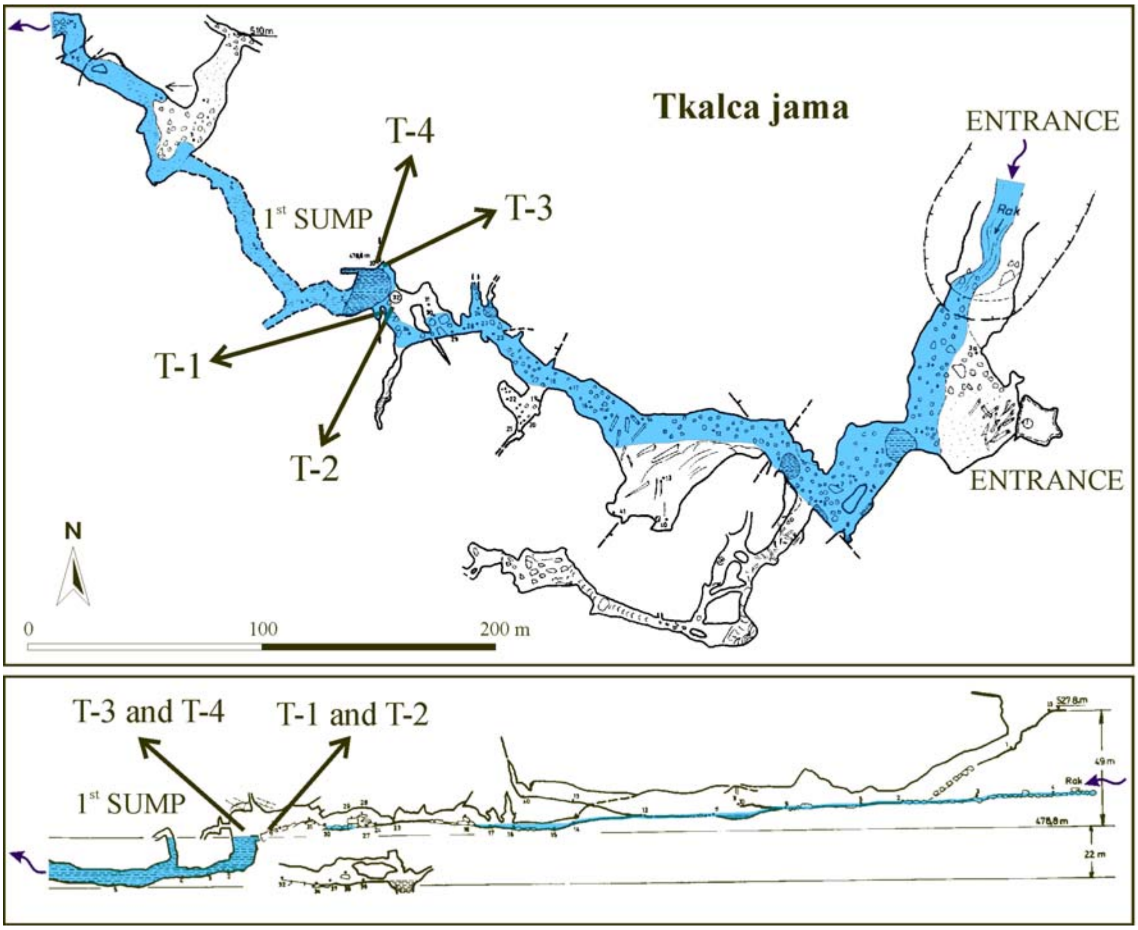


Figure 4.5.1.1: *Location of measurement points in Tkalca jama (modified after* G*OSPODARIČ ET AL., 1982).*

Results from measurement points T-1, T-2, T-3 and T-4 are represented in Fig. 4.5.1.2. Measurement period 1 (from 17th November 2006 to 26th April 2007) was relatively short (130 days) but several increased discharges flooded limestone tablets for about 117 days. Low increase of weight/thickness (on average 0.0011 mm/a) indicates that corrosion can be very low or even absent at high water level. This was confirmed in the second measurement period (from 26th April 2007 to 12th September 2008), which was much longer (505 days) with one very high discharge, when the water level rose for about 22 m. We have to stress that such high discharges are quite rare and have recurrence interval longer than 1 year. The duration of water level $H_{level\ logger} > +2$ m was also much longer (about 239 days) in comparison with measurement period 1. Although discharge was exceptionally high, we did not detect any corrosion. Even more, at all limestone tablets we detected slight (flowstone) deposition (on average 0.0006 mm/a). Since this value extends over the interval of maximum methodological error (±0.0004 mm; Chapter 2.1.3), we can be sure that corrosion was definitely under the limit of detection, even the maximum discharge had a recurrence period more than one year. Finally, we were not able to prove any corrosion in Tkalca jama within almost two years of measurements. It is interesting that little known Örtly (1953 after GAMS, 1966b, 34) already proved inactivity of waters in Ljubljanica catchment area on the basis of difference of carbonate hardness between ponors and springs. Gams (1966b, 13) uncritically rejected his finding due to plenty of corrosional forms in caves but without thought on activity of such corrosional features.

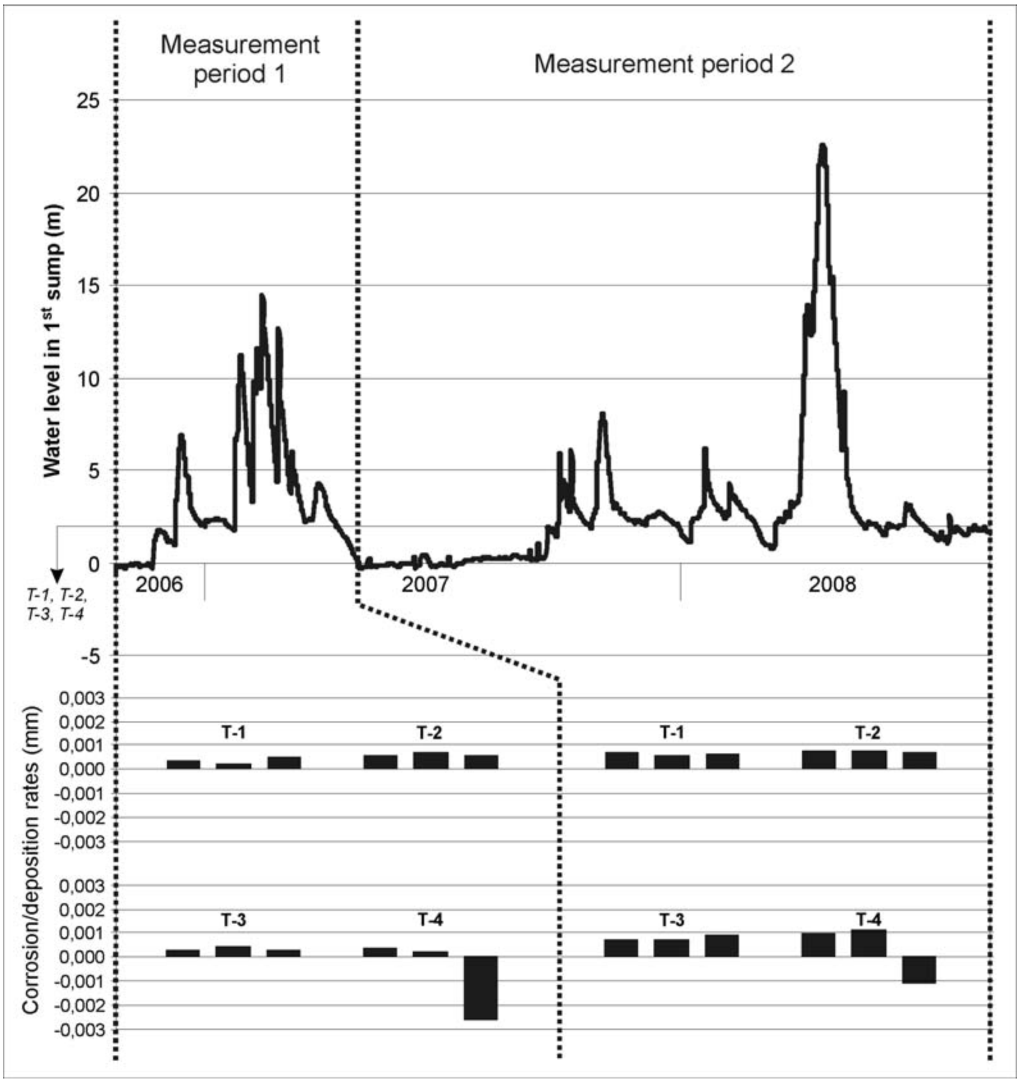


Figure 4.5.1.2: *Water level at 1st sump (*$H_{level\ logger}$*; data courtesy of Janez Turk) and corrosion/deposition rates from measurement points T-1, T-2, T-3 and T-4 in measurement period 1 (17th November 2006 – 26th April 2007) and measurement period 2 (26th April 2007 – 12th September 2008).*

Although measurement points T-1 and T-2 were exposed to much faster water flow in comparison with measurement point T-3 and T-4, differences in rates are very small and insignificant. Therefore, water seems to act equally at fast and at slow water flows.

Results represented in Fig. 4.5.1.2 shows that water that sinks into Tkalca jama does not corrode in the cave even at high water level. At the latter, exposure time does not seem to be problematic since the exceptionally high water level in the second measurement period lasted 11 days. Responsibility for absent corrosion is therefore hidden in the absent (or very low) aggressiveness of water. Quite low corrosion rates, as a result of low aggressiveness of water and low corrosion due to iron oxide, were already detected during 8-month measurements at Velika Karlovica (ponor cave at the NW edge of Cerknica polje; measurement point 34 in Appendix I), under the Veliki naravni most (=Great Natural Bridge) in Rakov Škocjan (measurement point 22 in Appendix I) and at Kotliči (measurement point 27 in Appendix I). Therefore, water that sinks at Cerknica polje is already (almost) saturated even at high water level. During underground water flow, some tributaries of percolation water with definitely higher CO_2 concentration in the water can increase aggressiveness due to mixing corrosion, but such an increase seems to be relatively small. Additional measurements in Zelške jame are necessary to confirm this supposition. None the less, along the underground water flow water absorbs CO_2 from the cave air of from tributaries. This can be nicely observed in pH when the water appears in Rakov Škocjan with open atmosphere CO_2 concentration. Longitudinal measurements of pH and SEP were done on 24th September 2007 at middle-low water level ($H_{level\ logger}$ = +1.67 m) from Zelške jame all the way to Tkalca jama (Fig. 4.5.1.3). Immediately when the water course exited Zelške jame, a high rise of pH and decline in SEC was detected. The latter changes indicated outgassing of CO_2 from the water and, surprisingly, even low calcite precipitation. The same changes along superficial water course were detected also below Prunkovec spring and Kotliči spring, although the changes were much smaller at the latter due to very low water gradient. Decrease in pH of river Rak at confluences is a result of confluence with tributaries, which have much smaller pH value. Below confluences, outgassing of CO_2 from the water and calcite precipitation continues all the way to the Tkalca jama. Increase of pH was not detected in the entrance part of Tkalca jama. Although further measurements in Tkalca jama were not possible due to a sump at the narrow passage it seems, that outgassing of CO_2 from the water stops when the water starts to flow through the cave. As a result, measurement revealed increase of SI_{Ca} due to lowering of CO_2 concentration in the water. At higher water level, initial SEC is certainly higher (GOSPODARIČ ET AL., 1982) and longitudinal changes of pH definitely smaller. None the less, results of measurements with limestone tablets show that fall of SEC and at least equal values of pH are not enough to cause any corrosion rates in Tkalca jama. Absence of corrosion also proves that substantially higher CO_2 concentrations in Tkalca jama are not sufficient enough to turn the water toward aggressiveness. This can be a result of short underground flow, too low gradient, too low cave air CO_2 concentrations or too slow transition from CO_2 to H^+ ions.

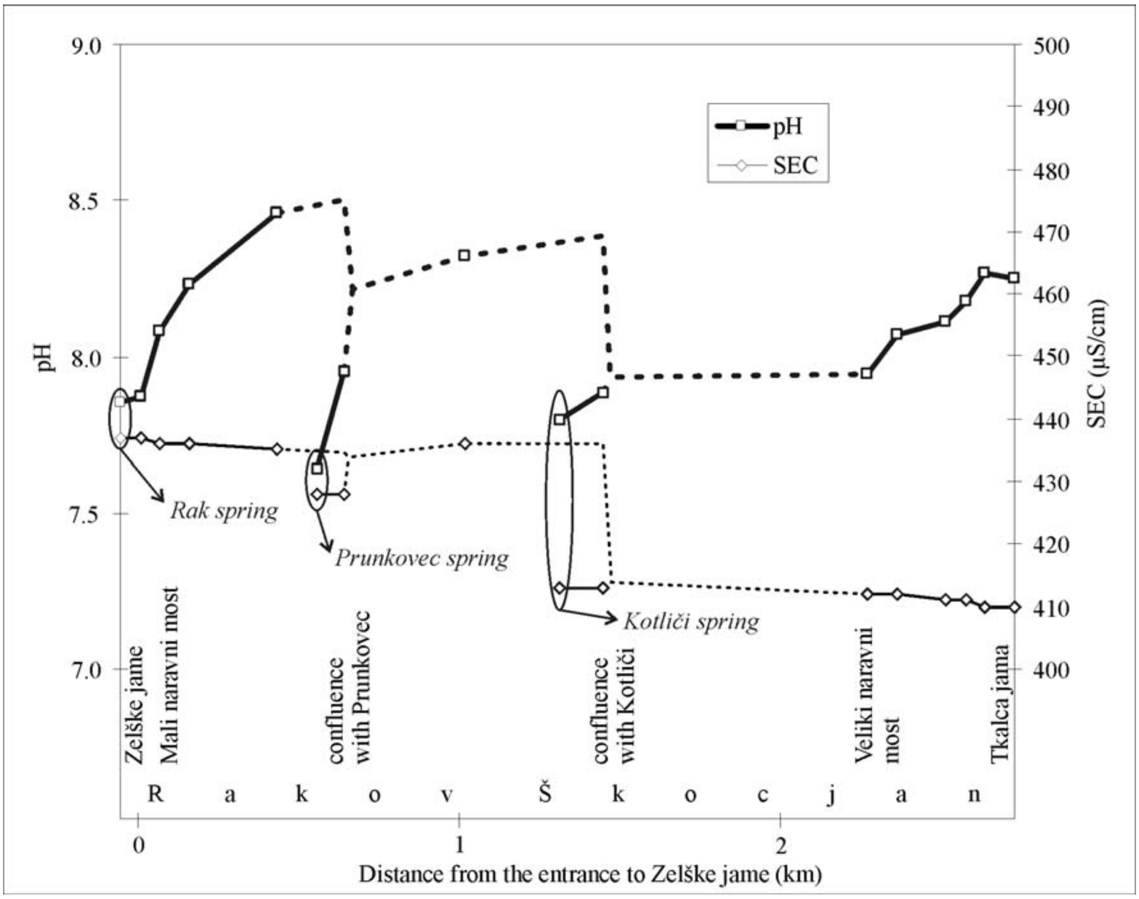


Figure 4.5.1.3: *Longitudinal changes of pH and SEC of river Rak and Kotliči in Rakov Škocjan between Zelške jame/Kotliči spring and Tkalca jama.*

Morphological characteristics near measurement points T-1, T-2, T-3 and T-4 are represented in Fig. 4.5.1.4. At this place, Tkalca jama has rectangular morphology, which is a result of several breakdowns along cracks and bedding planes in the past.

Therefore, the actual bottom of a passage lies several metres below breakdown blocks. Accumulation of breakdown material shows that the watercourse was not able to eliminate it with corrosion, corrasion or simply remove it into the steep-dipping sump with force of water flow. In spite of this, small corrosional and corrasional features are developed, especially on the NW part of the wall at A-A' cross-section (Fig. 4.5.1.4).

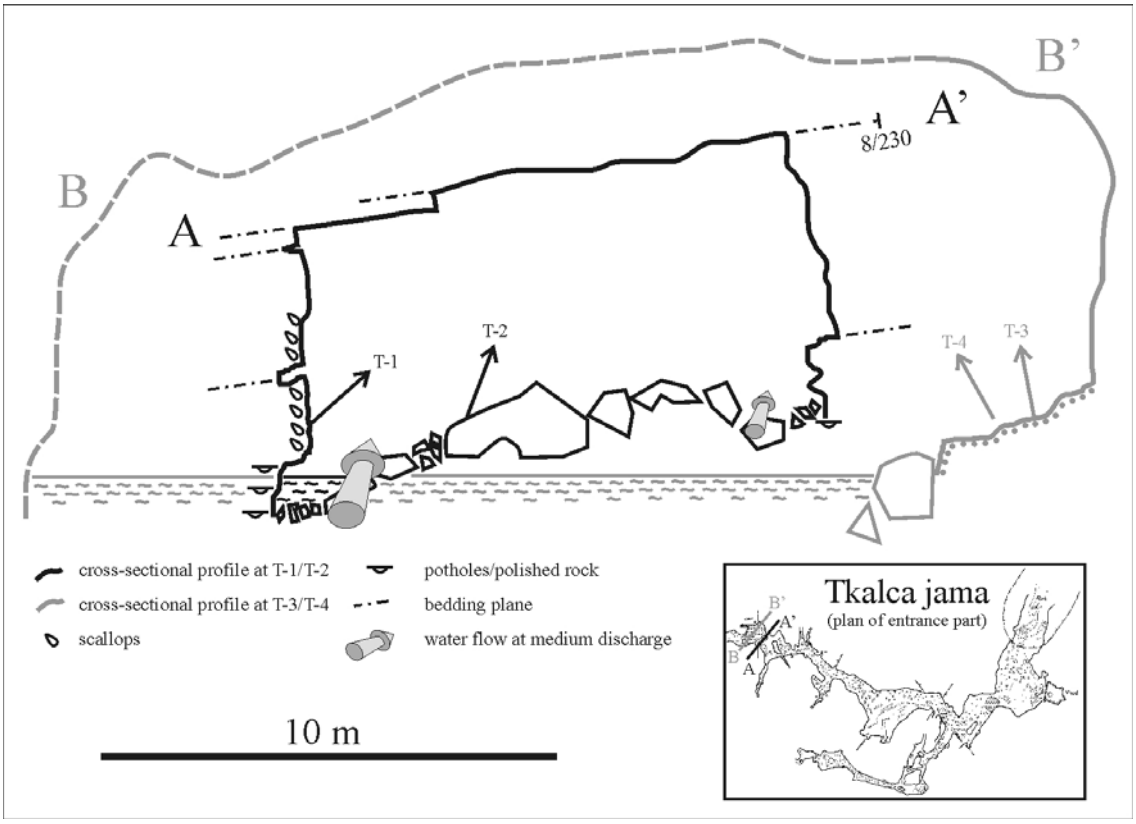


Figure 4.5.1.4: *Cross-sectional profile at measurement points T-1, T-2, T-3 and T-4 with basic corrosional and corrasional features on the cave wall.*

At first sight, present-day morphology seems to be equilibrated with hydraulic conditions in the cave – 2-3 cm long scallops are developed at the place with the strongest water flow at middle water level and corrasional potholes are developed between the breakdown blocks below scallops. However, smoothened (but not polished due to corrasion) edges of scallops (Fig. 4.5.1.5) point out that they are not active any more and that they were formed in the past when the water was corrosively active. Very peculiar also is the location of scallops – since they are located only in the lower part of a channel and not on the ceiling, they had to be formed at low and middle water levels, which is not possible under present-day conditions. At high water level, the cross-sectional area of the water course is definitely bigger and therefore water flow is slower, which obstructs formation of small scallops. Therefore, even the present-day hydrological conditions correspond to location of scallops, and their relation with low-middle waters indicates their development in some past conditions which supported aggressiveness of water even at middle water level.

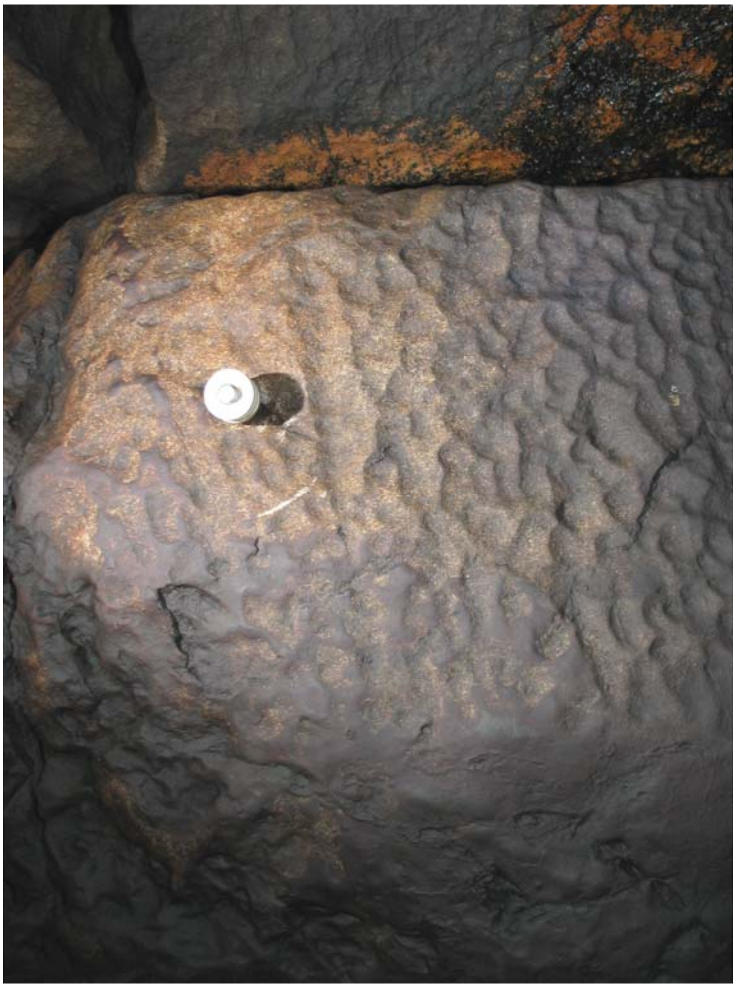


Figure 4.5.1.5: *Measurement place T-1 at the scalloped wall 2 m from the 1st sump. The lower part of a wall is smoothned due to the corrasional activity in the water flow. Water flow is directed from left to right.*

Conclusion

Tkalca jama is a textbook example of epiphreatic cave within a long underground cave system that connects two karst poljes. Along this underground water flow, the superficial watercourse in Rakov Škocjan supports outgassing of CO_2 from the water, which can be evidently observed especially in water channel with high gradient at low water levels. Together with high saturation of waters, which sinks at the upstream polje, these two factors seems to be the biggest disadvantage for any corrosion rates at middle and low discharge in Tkalca jama. At high water level, the situation is not much different – corrosion is very low or even absent. Therefore, at present we can observe slight net flowstone deposition (0.0006 mm/a) which leads to stagnation in cave enlargement.

Micro-features on cave walls were sometimes uncritically used to determine present-day hydraulic conditions and physicochemical characteristics of water. For example, Gams (1966a, 15) used orientation of scallops in Mala Karlovica as a proof for present-day water flow direction (even at low and middle water level!) although he was not sure, if the scallops are forming at present-day conditions. In Tkalca jama, present-day morphology beside 1st sump corresponds to present-day hydraulic conditions of water flow but does not correspond to some important present-day physicochemical characteristics of river Rak. At least, water is not aggressive any more even at high water level. In the past, water was aggressive even at middle water level. Present-day underground karst processes are therefore to some extend unbalanced with present-day morphology but since the water is inactive, past morphology remains at least mainly unchanged.

4.6 Malni springs

Malni springs are located in the SW part of Planinsko polje (=Planina polje) and represent one of the most important group of springs at the edge of Planinsko polje. At low water level, the biggest portion of inflow to Planinsko polje comes from Malni springs while at high water level, their discharge is about 10 times lower than the Unica that springs from Planinska jama. Therefore, fluctuation of Malni's discharge is very small. Since there is no bigger cave behind the springs, Malni has not get any speleological attention in the past. But since they drain also an important part of Javorniki mountains, they represent an important insight into the hydrogeological characteristics of vast area, for which diffuse autogenic recharge is characteristic. Nevertheless, mixing with waters that come from Rakov Škocjan is common for the major part of a year.

Schmidl (1854 after HABIČ, 1987, 8) listed 33 springs, among which the lower is of the greatest significance since it is captured for the water supply of Postojna and its surroundings from the end of the 1960s. On average, the captured quantity amounts 50-100 l/s (RAVBAR, 2007, 34) and is still small if compared with the lowest measured discharge of 1.25 m^3/s.

Geological and geomorphological characteristics

The maximum catchment area of Malni springs is very complicated since it is estimated to be about 800 km^2 of mainly carbonate rocks (HABIČ, 1987, 5). Due to this vast catchment area, the lithological structure of watershed is expectedly varied: from Lower Triassic semi-permeable dolomites with clayish layers at Bloke plateau, Upper Triassic dolomites and Jurassic dolomites with layers of limestones along Notranjsko podolje (=Notranjska lowland) to Creatceous limestones at Javorniki mountains. Malni springs are formed in Lower Cretaceous mycritic limestones (ČAR & GOSPODARIČ, 1984), which are crushed, especially along the main fault in SE-NW direction. This strong tectonic deformation crosses SW part of Planinsko polje and continues through Rakov Škocjan toward the SW edge of Cerkniško polje (=Cerknica polje) and is therefore parallel to (or part of) Idrija fault zone.

According to Habič (1987), collapse of a big cave along the mentioned tectonic deformation led to formation of a pocket valley, nowadays surrounded with collapse material. The latter is thickest and least permeable at the formers cave's entrance. Since the underground water is coming from the southwest and the permeability of karst conduits is limited, Malni springs are located all along the 1 km long NW edge of this pocket valley. Water appears on the surface at many places through collapse material, behind which the less karstified limestone massif is situated. Since the thinnest collapse material lies in the NW part of the pocket valley and the latter is inclined toward the NW, the majority of spring water discharges at the NW side. At the latter location, the springs are permanent while the springs southeast from them can be active only at high water level. The permanent springs, which have also the highest discharge, are captured for water supply. None of the springs is accessible for more than several metres – they are blocked with collapse material or too narrow for divers (HABIČ ET AL., 1987, 10). Passages between the upstream sump in Rakov rokav (=Rak branch) in Planinska jama and Malni are probably very narrow, with was proved by the side of Malni, by the side of Planinska jama (MOREL, 2000) and with relatively high gradient of underground water flow (16-22 ‰; HABIČ ET AL., 1987, 12).

Hydrological characteristics

From a hydrogeological point of view, the watershed of Malni springs is very complicated due to the high extent of watershed (Fig. 4.6.1), different types and arrangement of carbonate rocks, different type of recharge and especially because of extensive areas of bifurcation, where the directions of flow are defined with momentary hydrological and meteorological conditions. In the watershed of Malni springs, bifurcation is characteristic for all upper Pivka valley upstream of contact between limestone and flisch rocks, Javorniki mountains and all the area above Cerkniško polje. Even at the hinterland of Malni springs, about 1 km SW from the springs, bifurcation was noticed. At the latter location (Planinska jama), at low water level all the water flows directly toward Malni springs while at the high water level, the majority of water flows into Planinska jama.

Tracing tests, which were done here already before 2nd world war (Boegan and Perko in 1928 after MICHLER, 1955, 75; ŠERKO, 1946), are of the greatest importance to understand complicated characteristics of water connections in the watershed of Malni springs, especially since they were carried out at different water levels. At low water level, Malni springs are fed by a small amount of water, that sinks at Cerkniško polje in Velika Karlovica and reappears on the surface again in Rakov Škocjan (GAMS, 1966a; GAMS, 1970). This is mainly the water that originates in the dolomitic catchment area of Cerkniščica river. Another, probably much higher portion of water comes from

Javorniki mountains, where a portion of water also flows toward the Adriatic sea (to Vipava spring; KOGOVŠEK, 1999). Water flow from Javorniki mountains can be visible at the upstream end of Rakov rokav (=Rak branch) in Planinska jama and was also proved with tracer test from Planinska jama to Malni spring (MICHLER, 1955, 84). At low water level, lower piezometric level also attracts waters from upper Pivka valley, which joins the water flow below Javorniki mountains toward Malni springs (JENKO, 1959 after HABIČ, 1987, 19; HABIČ, 1989, 248-249). Therefore, at low water levels Malni springs are fed by diffuse autogenic recharge at Javorniki mountains and from the area in the upper Pivka valley on one side and by alogenic recharge from Cerkniško polje on the other side.

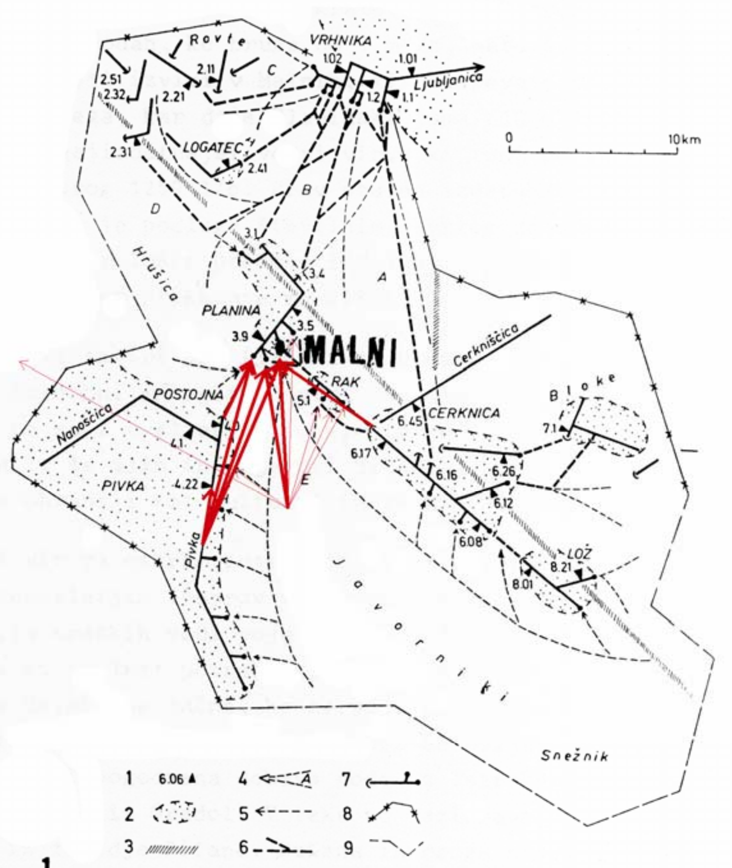


Fig. 1. *Schematic review of superficial and underground waters in Ljubljanica karst river basin.* 1 — important gauging stations, 2 — karst polje with sediment, 3 — central hydrogeologic relative barrier, 4 — intake area of permanent karst springs, 5 — periodic high water discharges of karst water, 6 — underground water connections, 7 — superficial stream with springs and ponors, 8 — superficial watershed, 9 — supposed karst watershed.

***Figure 4.6.1:** Catchment area of Malni springs with the most important tracing tests (thick red line-main connection, thin red line-weak connection; modified after HABIČ ET AL., 1987, 26; GAMS, 1966a; KOGOVŠEK, 1999; KOGOVŠEK, 2004).*

At high water level, discharge from Cerkniško polje increases and piezometric level below Javorniki mountains rises. This results in disintegration of diffusely recharged autogenic water below Javorniki mountains: on the western side underground water flow is directed toward upper Pivka valley while the eastern water flow remains directed toward Malni. However, since the water flow from Cerkniško polje redirects water flow from Javorniki mountains toward the NW, water flow from Javorniki mountains is more or less directed into the Rakov rokav in Planinska jama (HABIČ, 1987, 13-14, 24). Therefore, at high water level Malni springs are mainly fed by water flow from Cerkniško polje, while the water from Javorniki mountains leaves the aquifer through Rakov rokav in Planinska jama. Connection between Pivka in Postojnska jama and Malni was never proved with tracing tests (HABIČ, 1987, 33; HABIČ, 1989, 240).

Different catchment area of Malni springs is well recorded with observation of physicochemical properties of water (temperature, Ca^{2+}/Mg^{2+} ratio, concentration of SO_4^{2-}, NO^{3-}, PO_4^{3+}, Cl^-; KOGOVŠEK, 2004). Prevailing **diffusely recharged autogenic water** at low water levels was recognized from high Ca^{2+}/Mg^{2+} ratio, stable annual temperature and slightly polluted water. Since the **concentrated autogenic recharge** derives from area of Cerkniško polje, which is populated and agriculturally used, there is more polluted water with higher annual amplitudes of temperature and lower Ca^{2+}/Mg^{2+} ratio. Since the latter characteristics are common at high water level and the first one at low water level at Malni springs, water seems to derive from Cerknica lake at high water level and from Javorniki mountains at low water level. Most of the time, we can expect a mixture of water from Javorniki mountains and Cerkniško polje.

Due to the weakly karstified zone behind Malni springs and a lot of accumulated collapse material, changes in hydrological conditions within an aquifer are not so well reflected in changes of discharge. The lowest recorded discharge amounts 1.25 m^3/s while the highest amounts to “only” 9.5 m^3/s (HABIČ, 1987, 9). The ratio between the lowest and the highest discharge is therefore much lower in the case of Malni (1:7.6) if compared with Unica downstream of confluence with Malni springs (~1:100; HABIČ, 1987, 9).

Regarding the small ratio between the lowest and the highest discharges at Malni springs, important geomorphological question arise: which factor is the most responsible for low permeability of karstic aquifer behind Malni springs? Can it be low corrosion rates or youthfulness of water channels? Although some important information cannot be attained due to inaccessibility of passages (i.e. reaction surface, differentiation between corrosion of diffusely and concentrated recharged autogenic waters), corrosion rates can give us a gentle hint to answer this question. At least we can get an insight into the increased or decreased aggressiveness of water downstream Tkalca jama and some information on aggressivity of water from Javorniki mountains, at low and at high water level. Moreover, since the Malni springs are a very nice example of mixing of two waters with very different origin, the location is interesting also from the viewpoint of mixing corrosion.

Meteorological characteristics

Meteorological characteristics in the hinterland of Malni springs are poorly known due to the lack of access behind Malni springs. The only location where the meteorological conditions could be studied, is Rakov rokav in Planinska jama at low water level. In spite of this, meteorological data are sparse even for this location. Air temperature was measured by Michler (1955) and amounts from 8.6 to 13.6 ºC in summer time. It seems that the air temperature strongly corresponds to water temperature, since the passage is weakly or non-ventilated but the temperature amplitude quite high. The latter characteristic equals to the weakly or non-ventilated Pivkin rokav (=Pivka branch) in Planinska jama. If the conditions are really very similar, then we can expect similar increasing concentration of CO_2 toward the terminal sump as was recorded in Pivkin rokav in Planinska jama (with peak at ~1900 ppm at the inlet sump in October 2008).

Corrosion rate measurements and their relation to key factors and forms

4.6.1 Measurement place M-1 – temporal and spatial variability of processes

Malni springs give us an excellent opportunity to study geomorphic activity of two mixing karst waters that drain an extensive part of karst area. In Tkalca jama (Chapter 4.5) we were able to observe mainly water which changes its physicochemical characteristics along superficial flow at several poljes (Babno, Loško, Bloško, Cerkniško) and along Rakov Škocjan, while in Malni, another genetically different tributary joins this water course – water course from Javorniki mountains. The latter water flow is characterized by almost completely autogenic recharge and represents an important portion of water at Malni springs, especially at low water level.

During measurement of corrosion rates in an 8-month-long period (Chapter 3) we found out that biocorrosion represents a high portion of total corrosion, while the "pure" chemical corrosion is not known. Therefore, further measurements with limestone tablets were taken inside a reservoir at the pumping station in complete darkness. For measurements at measurement point M-1 we used 13 limestone tablets, which were located vertically with distance 20 cm. They were fixed with stainless steel screws, nuts and felted washers. Water flow at measurement point M-1 can be characterized as subcritical and turbulent. Oscillation of water is supposed to be within 1.5 m and corresponds to the inflow and to the degree of pumping (water demand). At high water level, all the limestone tablets were under the water level while at low water level, only the lower 2 or 3 were below the water level. Measurements were taken between 3rd October 2007 and 3rd March 2009. In this time, limestone tablets were replaced 4 times and therefore the whole period of measurement can be divided into 4 measurement periods. At the end of the 2nd measurement period, we forgot to weigh limestone tablets and results from 2nd and 4th measurement period are therefore represented together.

Results of measurements in Malni springs are represented in Tab. 4.6.1.1 and in Fig. 4.6.1.1. In the 1st measurement period, which was very short (39 days), values are very small. They are all close to the average error of measurement and within maximum error of measurement. In the vertical set of limestone tablets we were able to observe very low (R^2=0.20) vertical trend in decreasing corrosion rates with depth. Nevertheless, values are so small that conversion from original to one year corrosion rates could show dubiously high corrosion rates. Due to conversion, differences between limestone tablets are abnormally high.

Table 4.6.1.1: *Flowstone deposition and corrosion rates at Malni springs in 4 measurement periods between 3rd October 2007 and 3rd March 2009.*

Depth (cm)	240	220	200	180	160	140	120	100	80	60	40	20	0
1st measurement period (mm)	-0,0001	0,0000	0,0000	-0,0002	-0,0001	-0,0002	-0,0003	0,0000	-0,0001	0,0000	-0,0001	-0,0004	-0,0003
3rd measurement period (mm)	0,0003	0,0009	0,0006	0,0003	0,0009	0,0005	0,0007	0,0008	0,0004	0,0006	0,0005	0,0005	0,0001
2rd in 4th measurement period (mm)	0,0009	0,0008	0,0007	0,0004	0,0004	0,0006	0,0002	0,0003	0,0004	0,0000	0,0000	-0,0001	-0,0002
1st measurement period (mm/a)	-0,0008	-0,0003	-0,0001	-0,0021	-0,0008	-0,0016	-0,0032	-0,0001	-0,0010	0,0000	-0,0013	-0,0034	-0,0029
3rd measurement period (mm/a)	0,0005	0,0013	0,0009	0,0004	0,0014	0,0007	0,0011	0,0012	0,0006	0,0009	0,0008	0,0007	0,0002
2rd in 4th measurement period (mm/a)	0,0014	0,0012	0,0010	0,0006	0,0006	0,0009	0,0003	0,0005	0,0006	-0,0001	0,0000	-0,0001	-0,0004

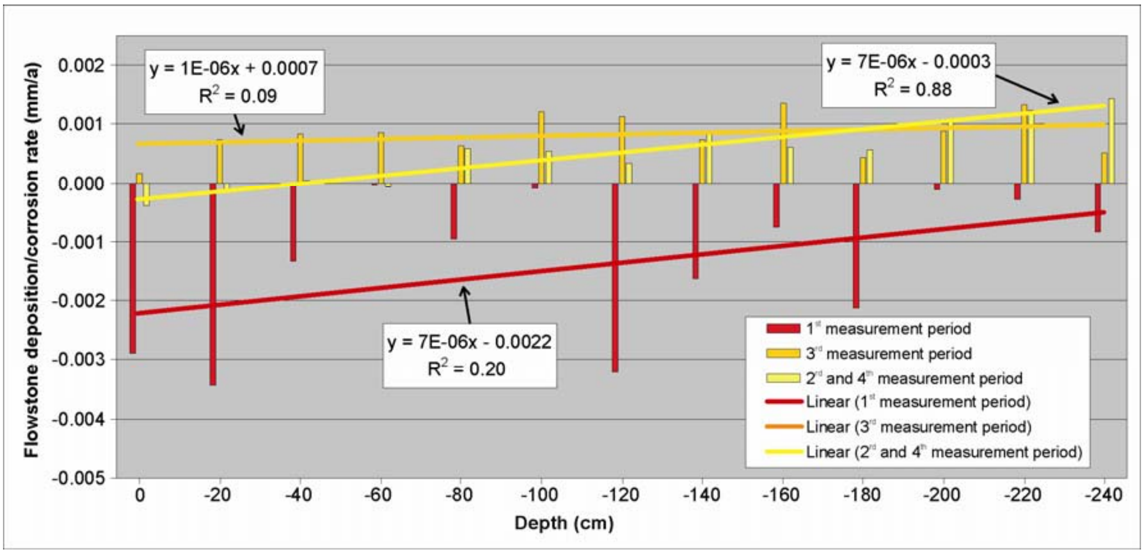


Figure 4.6.1.1: *Flowstone deposition and corrosion rates at Malni springs in 4 measurement periods between 3rd October 2007 and 3rd March 2009.*

The much longer, 236 days, 3rd measurement period shows values that are higher than average error of measurement and often also higher than maximum error of measurement (therefore, results of 3rd measurement period are more certain that results from 1st measurement period). All limestone tablets show flowstone deposition. The smallest flowstone deposition rate (0.0002 mm/a) is observed at the highest limestone tablet, which was mostly above the water level. Trend of falling flowstone reposition rate with height is statistically not important, since the R^2 amounts 0.09. Therefore, flowstone deposition rate of 0.0009 mm/a is more or less characteristic for all limestone tablets below the highest one.

The best results were got in united 2nd and 4th measurement period. For this 231-days-long measurement period high discharges were characteristic for December 2008 and for January 2009. Limestone tablets below H = -70 cm show flowstone deposition while the limestone tablets above H = -70 cm show slight corrosion. Transition between flowstone deposition and corrosion is gradual. Very high Pearson product moment correlation coefficient (0.94) and R^2 (0.88) shows very good dependency of flowstone deposition or corrosion rates with depth. Differences between predicted and real value are close to standard error of measurement and within maximum error of measurement. This means that, beside depth, error of measurement could be the only factor for difference between predicted and real data. This statement is supported also with results from the 1st measurement period, which, although with low values, shows the same slope of trend line. The slope of trend line is the same also for 3rd measurement period.

Although results from vertical set of limestone tablets at M-1 show high dependency of water level, the influence of seasonal effect that was noticed in Križna jama with autogenic recharge (Chapter 4.1) can not be excluded at Malni springs. The 1st, 2nd and 4th measurement periods were carried out also during the late autumn and winter months, while the 3rd measurement period was carried out during late winter, spring, summer and early autumn months. Corrosion rates that were observed at least at the highest two limestone tablets should be related also to combined influence of high water level and season of the year. Unfortunately, this supposition cannot be confirmed due to very low corrosion rates, which forced us to take measurements at longer intervals before the influence of season was recognized in Križna jama (Chapter 4.1.1).

It is evident that all trend lines point to the same phenomenon – increasing flowstone deposition rates with depth or decreasing corrosion rates with depth. This can be observed also if we summarize all results from the beginning to the end of measurement and convert them to one year (Fig. 4.6.1.2). In these summarized results, corrosion can be observed only at the highest limestone tablet, which is under the water just at very high water level. The limestone tablet at H = -20 cm seems to be situated in equilibrium conditions, which is a result of similar corrosion rates at high water level and flowstone deposition at low water level. Deeper, net flowstone deposition increases to the H ≈ -100 cm, where remains almost equal to the deepest zone at net flowstone deposition rate 0.0007 mm/a. Such a distribution could be a result of corrosion, which takes place at all limestone tablets, and flowstone deposition rates, which affects especially limestone tablets below H ≈ -100 cm. Limestone tablets between H ≈ -100 cm and H ≈ -20 cm are exposed to flowstone deposition, which increases with declining water level/discharge and to corrosion, which most affects the lowest limestone tablets. Nevertheless, corrosion rate is the highest at the highest limestone table since there flowstone deposition rates are the smallest. The relationship between intensity of processes and depth can be quite successfully explained with polynomial function valid for values above H > -240 cm (Fig. 4.6.1.2) or with two linear functions – one from H > -100 cm and another one H < -100 cm. In the latter case, R^2 is even higher for the upper limestone tablets (0.95) but very low for deeper limestone tablets (0.18).

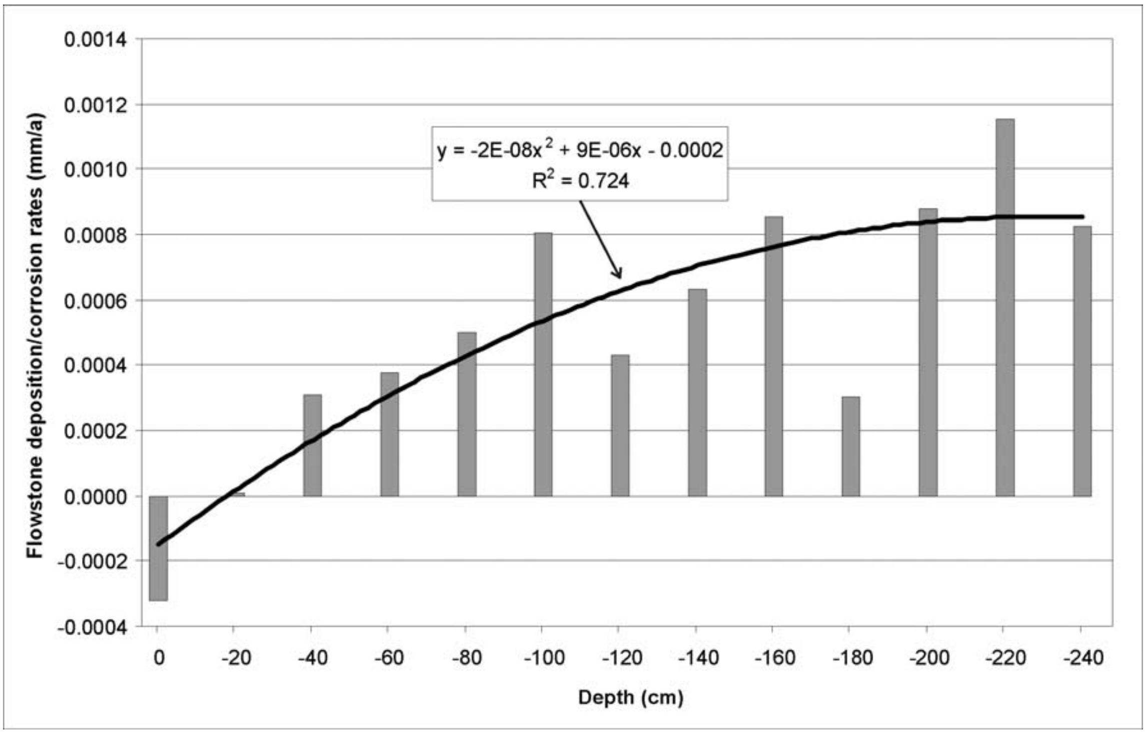


Figure 4.6.1.2: *Summarized flowstone deposition and corrosion rates between 3rd October 2007 and 3rd March 2009.*

Average net flowstone deposition rate below H ≈ -100 cm (0.0007 mm/a) is almost equal to net flowstone deposition rate observed in Tkalca jama (0.0006 mm/a), where the limestone tablets were located in similar hydrological conditions. Therefore we can say that the watercourse from Javorniki mountains, which is especially important at low water level and was confirmed by many hydrogeological studies (Boegan and Perko in 1928 after MICHLER, 1955, 75; ŠERKO, 1946; JENKO, 1959; GAMS, 1970; GAMS, 1966a;

HABIČ, 1987; HABIČ, 1986; KOGOVŠEK, 1999; KOGOVŠEK, 2004), does not importantly change the geomorphic activity of the combined stream at Malni springs, if the water from Tkalca jama does not significantly change during underground water course toward Malni springs. If the saturation of water remains the same, saturation state of water from Javorniki mountains is not so different to saturation state of water from Tkalca jama or the portion of water from Javorniki mountains is not so high. If the water from Tkalca jama becomes less oversaturated or even corrosive along underground water course toward Malni springs, water from Javorniki mountains has to be more oversaturated. Increase of oversaturation of waters from Tkalca jama and higher corrosiveness of water from Javorniki mountains is less probable, since the passages of Tkalca jama downstream of 1st sump are weakly or non-ventilated, which does not support outgassing of CO_2 and consequential increase of saturation. Nevertheless, the most reliable explanation for similar flowstone deposition rates in Tkalca jama and Malni is similar saturation state of water and negligible consequence of mixing, although origin of waters is very different.

At high water levels (in autumn/winter time) slight corrosion (-0.0003 mm/a) can be observed in Malni but since we do not have comparative results from Tkalca jama or a watercourse below Javorniki mountains, the origin of water that causes corrosion cannot be defined with certainty. Since Malni springs get the majority of water from Tkalca jama especially at high water level when slight corrosion can be observed, we can expect aggressive water from the side of Tkalca jama. Such corrosion can be measured just in occasionally flooded passages, which are out of reach of flowstone deposition. Nevertheless, corrosion rates are so low that they cannot result in vast enlargement of occasionally flooded underground passage at present-day rates even during the whole Holocene. Moreover, corrosion is characteristic just for the upper part of the epiphreatic zone, which is rarely flooded with water, while the phreatic and lower epiphreatic passages are still characterized by slight flowstone deposition. Net flowstone deposition occupies channels that are active during low and middle water levels and therefore is not able to decrease water gradient behind Malni springs.

Conclusion

Measurements of processes at Malni spring during a 506 days period confirmed high biocorrosion rate during 8-month-long measurements (-0.0149 mm/a; Chapter 3), which was responsible for almost all corrosion detected at Malni springs. Chemical corrosion is much weaker since it amounts to -0.0003 mm/a. The latter difference (50:1) shows very interesting geomorphic development of pocket valley and nearby aquifer – when the valley deepens relatively fast due to biocorrosion, water passages behind the valley keep almost the same dimensions.

Net corrosion rate is characteristic only for occasionally flooded passages in epiphreatic zone. In the lower epiphreatic and at least shallow phreatic zone, the prevailing process is net flowstone deposition. The rates of the latter are rather small (0.0007 mm/a) and very similar to net flowstone deposition rates registered in Tkalca jama (0.0006 mm/a). This suggests that saturation state of the water, which flows from Tkalca jama toward Malni springs, is not significantly changed due to underground mixing with waters from Javorniki mountains. Although waters are of very different origin, they seem to be very similar in Ca^{2+} and CO_2 concentration. Otherwise, net flowstone deposition rates should be at least lower.

Present-day processes at Malni springs show that during Holocene, enlargement of passages amounts to several millimeters, but some lower epiphreatic and shallow phreatic passages are stagnating or are becoming even smaller due to flowstone deposition. Therefore, permeability of passages behind Malni springs is not increasing but rather decreasing. Most probably before Holocene, higher corrosion rates or at least much lower flowstone deposition rates are expected; otherwise development of passages behind Malni springs could not be possible.

4.7 Jelovička jama

Jelovička jama (Reg. No. 727) is a 184 m long and up to 25 m high cave on the left bank of Kolpa river. The latter appears on the surface from over 86 m deep sump (GASPARI, 1999, 102) in Croatia about 4 km from the Slovenia-Croatia border. Along its superficial water course, Kolpa river gets several tributaries – superficial and from karst springs. The latter combination is a result of very complicated and diverse lithologic structure, which is composed of impermeable rocks (mainly of Permian, Carboniferous and Lower Triassic age) and permeable rocks (mainly of Upper Triassic, Jurassic and Cretaceous age). In the upper Kolpa valley, superficial tributaries prevail from southern (Croatian) side, whereas tributaries originating from karst springs are much more characteristic for northern (Slovenian) side of Kolpa river. One of such the most important tributaries is Kotnica stream, which appears on the surface from Jelovička jama.

Kotnica is about 350 m long left tributary of Kolpa river. At low water level, the majority of water flows under the superficial water channel and the latter remains dry. Water from Jelovička jama appears about 100 m beside Kolpa river. At high water level, superficial water channel drains several m^3/s of water flow and hydrologically connects Kolpa river with Jelovička jama. In the latter, water flow is permanent and even at low water level some tens of l/s flows through the cave. Underground water flow appears from the upstream sump and disappears in usually flooded narrow passages (downstream sump). Since the water originates most probably from superficial stream of Reški potok, which has catchment area on siliceous rocks, and from the autogenic recharge through karst area above underground connection between Reški potok and Kotnica, Jelovička jama can be characterized as a typical cave with steep permanent underground water flow, which transfers allogenic and autogenic water from the northern part of Kolpa river catchment area.

Investigation of Jelovička jama and its catchment area was always in the shadow of other speleological and hydrological investigations in the neighborhood. The only important investigation about Jelovička jama and its supposed catchment area was done by Novak (1969), who measured physicochemical characteristics of Kotnica stream.

Geological and geomorphological characteristics

Jelovička jama is located about 100 m northeast from a very important fault, which is oriented in NW-SE direction and tectonically separates Permian/Carboniferous rocks at SW from Upper Jurassic rocks at NE (Fig. 4.7.1). Jelovička jama is therefore developed in Upper Jurassic rocks that are formed mainly as limestones. Tectonic deformations in the cave are well expressed and cause extensive collapsing. Nearly "Dinaric" direction (60/60) of the main cave's fault, which is parallel to the fault dividing Permian/Carboniferous and Upper Jurassic rocks, strongly prevails and is especially noticeable in Velika dvorana (=Big chamber).

Since the trunk cave passage, which is composed of Vhodna dvorana (=Entrance chamber) and Velika dvorana (Fig. 4.7.1.2), has the same direction as the main fault, primary cave development is supposed to be related to this fault and collapsing along it. Collapsing is a result of 20-30 m wide lateral extension of passages, which reduced the stability of an already faulted (60/60) roof. Partial removal of collapse material with mechanical and chemical erosion formed vast breakdown chambers at highly tectonically deformated zone (e.g. 70 m long, 40 m wide and over 55 m high Velika dvorana). None the less, collapse material was not completely removed and is still preserved in Velika dvorana. Since it has fallen also into the underground water channel, water flow is partially dammed and water has to flow over it. Therefore we suppose that the cave was primarily developed at the same elevation as the downstream sump. Later, breakdown in Velika dvorana forced the water to rise for about 9 m (depth of an upstream sump) and to increase underground water gradient.

Present-day morphology reveals some sedimentary, corrasional and corrosional features. Allogenic sediments are deposited all through the cave, they cannot remain just in the water channel defined by medium discharge since the water flow there is the fastest. At all other places, breakdown is covered by flood material (mainly fine sand and silt) which originates from impervious area on Permian/Carboniferous rocks located SW of the main fault. In the water channel defined by medium discharge, which is usually covered with 0.5 mm thick black coating (manganese oxide?), scallops and small potholes are developed. Both disappear outside from the water channel defined by medium discharge, since the velocity of flow strongly reduces at high discharge due to backflooding. In the zone of flooding, decantation flutes can be observed. At first sight, spatial arrangement of features seems to correspond to present-day hydraulic conditions. Nonetheless, we have no proof that present-day processes correspond to present-day morphology.

Hydrological characteristics

At middle water level, discharge of Kotnica in Jelovička jama amounts about 2 m^3/s. At low water level, the stream in the cave never dries up but discharge can be reduced to 0.35 m^3/s (our measurements) or to even 0.29 m^3/s (NOVAK, 1969, 33). At high water level, inflow to the cave is higher than the capacity of ponors in the cave. This characteristic leads to spilling over into the usually dry water channel of the superficial Kotnica stream. At such water level, discharge in the cave amounts to several m^3/s.

Open water water flow in Jelovička jama is accessible for 80 m. Downstream it disappears in very narrow passages (sump), while in the upstream direction, water emerges from an up to 9 m deep and more than 50 m long sump. Between the spring and ponor in the cave, typical width of water channel is 3.5 m at middle water level. Water flow is extremely fast since the water flows over several metres big collapse blocks and descends for almost 10 m between upstream sump and ponor within the cave. At high water level, water flow is slower due to increased cross-sectional profile. The latter depends on the degree of backflooding from ponors toward upstream sump but usually amounts several tens of m^2.

At low and middle water level, water flow can be observed in Jelovička jama and at several springs 100 m beside Kolpa river. Physicochemical characteristics of these springs are equal, at least at low and middle water levels. Hydrological connection between water flow in Jelovička jama and Kotnica was never questionable since the distance is short and physicochemical characteristics of water and discharge are nearly the same. Nonetheless, it seems that total discharge of Kotnica springs is slightly higher than discharge in Jelovička jama. This is not surprising and means that we can expect underground water flows that are parallel to water flow through Jelovička jama.

Catchment area of water that flows through Jelovička jama is more questionable, since tracing tests nearby are almost absent. It was proved that hydrological connection between the southern edge of Kočevje polje and Kotnica exist but it is very weak (KOGOVŠEK & PETRIČ, 2007; Fig. 4.7.1). The connection is so weak that older tracing tests from the ponors of Rinža river (SE from Kočevje) could not prove this connection (HABIČ ET AL., 1990). Therefore it seems that the catchment area of Kotnica is located west of straight line from Rinža ponor to Bilpa spring – toward area of impervious rocks NE from the main tectonic fault that separates Permian/Carboniferous rocks from Upper Jurassic rocks. Therefore we can expect that water of Kotnica spring originates from allogenic recharge SW of the main fault and from autogenic recharge between main fault and strait line Rinža ponor - Bilpa spring (Fig. 4.7.1).

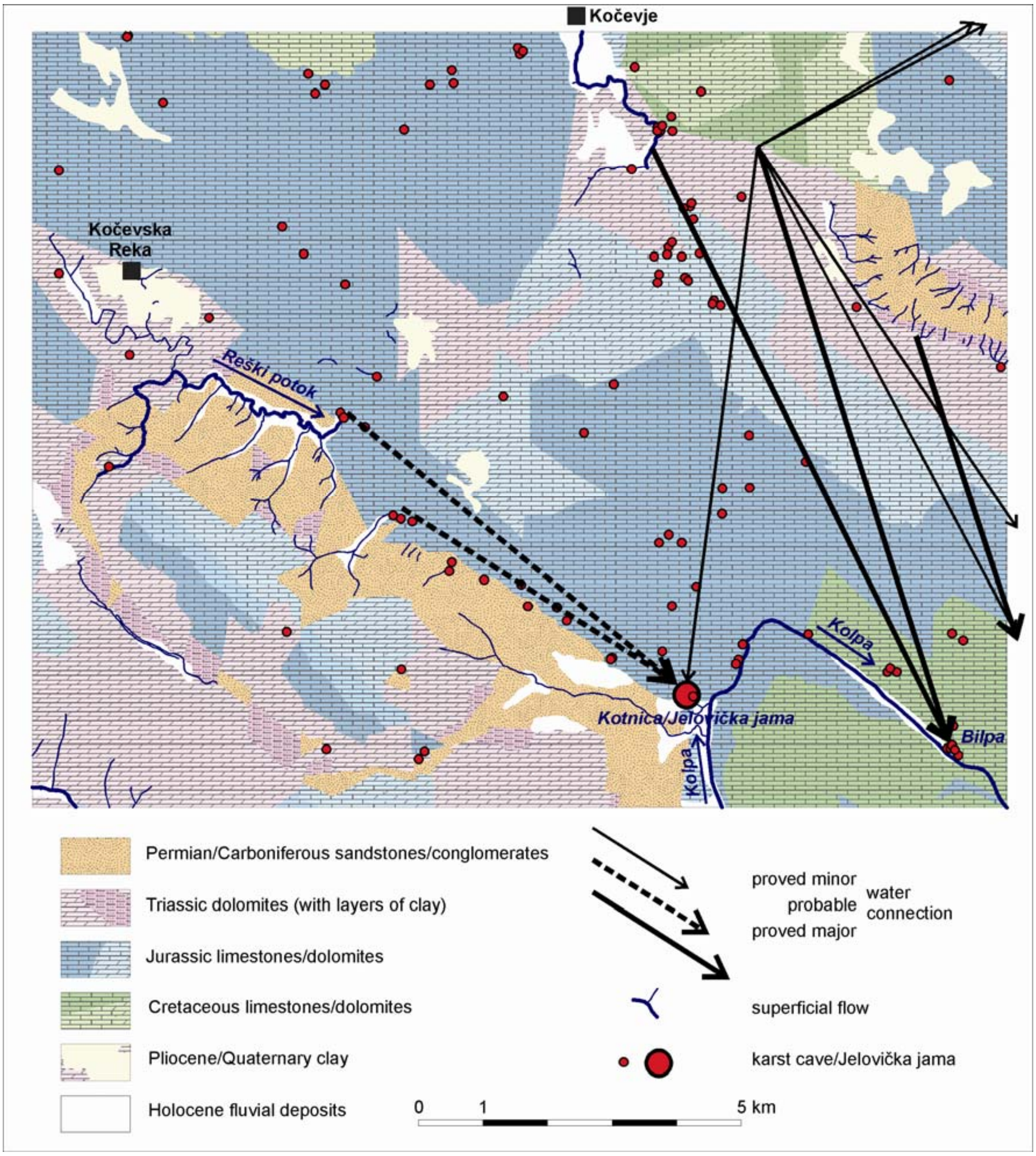


Figure 4.7.1: *Geological structure with proved and probable underground water connection on and near the supposed catchment area of Kotnica stream (source of geological data: SAVIĆ & DOZET, 1985; source of water connections: KOGOVŠEK & PETRIČ, 2007; source of karst caves: CAVE CADASTRE IZRK & JZS, 2008).*

Water connection between ponors of allogenic water, which are located along the main fault in NW-SE direction, is very probable since we are able to observe pure siliceous and siliceous siltstone pebbles, sand and silt in Jelovička jama (NOVAK, 1969). Transport of this allogenous material through Jelovička jama is obvious since we

detected relatively high corrasion at the limestone tablets during 8-month measurements (Chapter 3; Appendix I). During our measurements with limestone tablets, we found up to 4 cm long branches, up to 1 cm^2 parts of leaves and charcoal in Jelovička jama, which can be connected with ponors of allogenic water along the fault or with combined short superficial-underground drainage from levelled karst plateau northern of Jelovička jama. Underground connection between ponor of Reški potok and Jelovička jama was never proved with tracing test but it seems very probable. Nonetheless, very stable temperature during the year (7.5-9.0 ºC; Fig. 4.7.2; NOVAK, 1969, 35) indicates autogenic recharge through the karst plateau, which lies between main fault and straight line from Rinža ponor to Bilpa spring. This suggests autogenic recharge although the lack of annual temperature oscillation could be a result of high diminution of annual temperature differences since the distance between the farthest ponor of allogenic water (Reški potok) and Jelovička jama is at least 6.9 km. Because of less probable connection of ponors along main fault and with other springs, we suppose that Kotnica is fed by combination of allogenically and autogenically recharged water.
Regarding to Novak (1969), water hardness of Kotnica fluctuates between 7.2 and 13.2 dHº, which corresponds to 128-235 mg $CaCO_3$/l. Such high hardness is not able to corrode under superficial conditions but during its underground course it suggests that the water can be aggressive due to higher CO_2 concentration under the surface. Surprisingly, the highest hardness was detected at the end of autumn and in spring, while the lowest hardness corresponds to late winter months and beginning of summer, irrespective of discharge (NOVAK, 1969, 35). This oscillation is very close to that one observed in Križna jama (Fig. 4.1.5.2 in Chapter 4.1.5) for which autogenic recharge is characteristic. In Jelovička jama, pH value is relatively constant during the year and during variable discharges – on average it amounts about 8±0.3 (NOVAK, 1969, 35).

Meteorological characteristics

Especially in winter time, the entrance part (Vhodna dvorana) of a cave is well ventilated due to 10 m wide and 8 m high entrance. At the latter, cold air enters the cave in the lower part and leaves the cave under the roof. More distant part of a cave is less ventilated since it is separated from the entrance part by low roof. Exchange of air there is very limited. Morphology of a cave has influence also on poor ventilation in summer months, since the entrance and separated distant part of a cave acts as a trap for colder cave air and does not allow outside warmer air to enter the cave. Therefore, CO_2 concentration can be quite high (~2,250 ppm) in the cave during summer months.

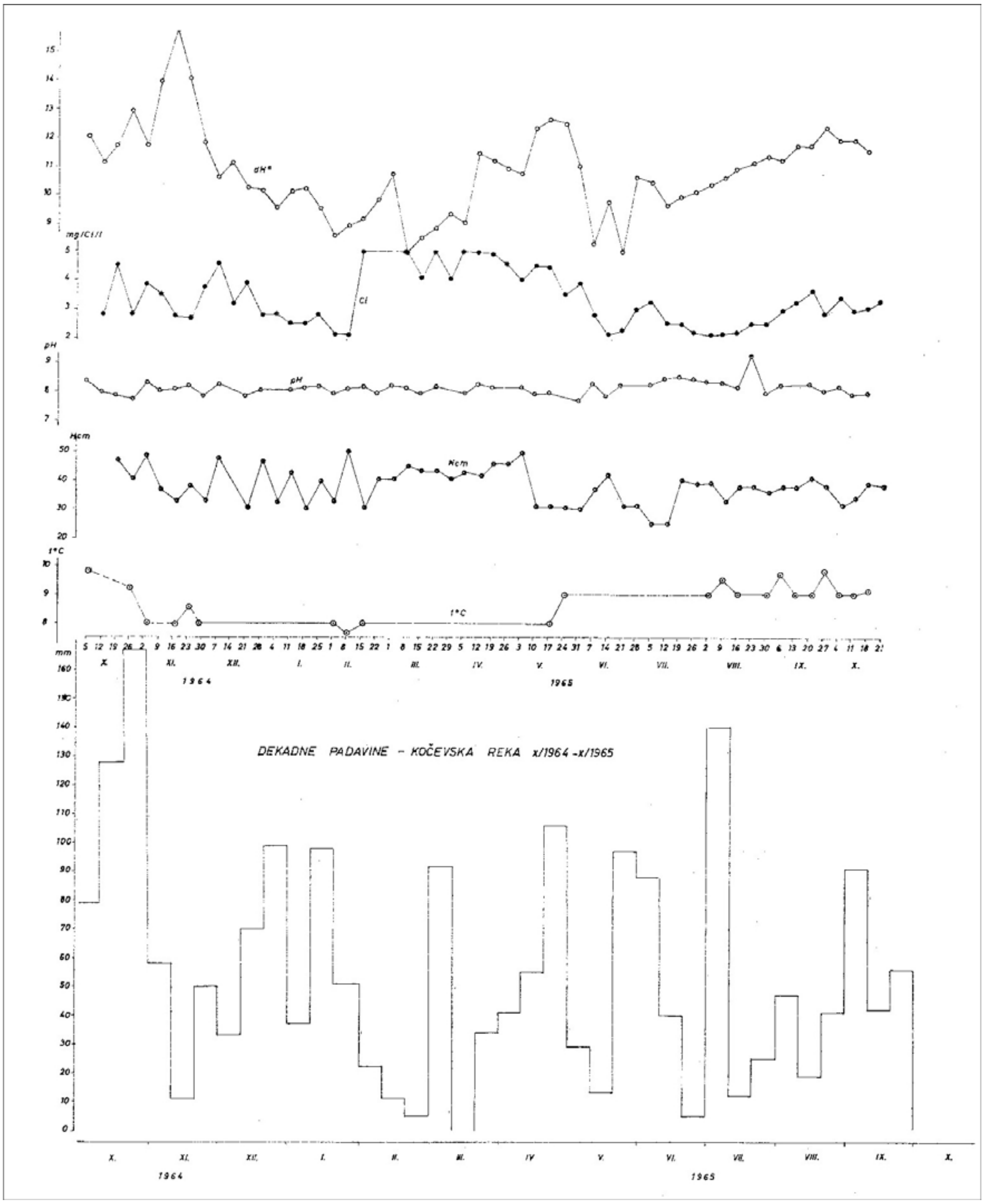


Figure 4.7.2: *Physicochemical characteristics of Kotnica spring(s) as were measured by Novak (1969, 35) between autumn 1964 and autumn 1965.*

Corrosion rate measurements and their relation to key factors and features

4.7.1 Measurement places J-1, J-2, J-3, J-4 – spatial and temporal variability of processes

Water flow in Jelovička jama is relatively short (~160 m) but very heterogeneous with respect to hydrodynamic characteristics. In the upstream sump, water flow is extremely slow due to the big cross-sectional profile (~20 m^2). Downstream, velocity of flow strongly increases due to many cascades several metres high. Such a situation and quite high corrosion/corrasion rates gathered during 8-month-long measurements (measurement point 10 in Appendix I) give us excellent opportunity to get insight in corrosion/corrasion rates along a short watercourse. Moreover, along water flow scallops are developed but strongly polished by siliceous pebbles, sand and silt transported by underground water flow. The main questions that arise here are connected with relation between corrosion and corrasion and their influence during feature development.

Measurement points J-1, J-2, J-3 and J-4 were located in a hydrodynamically very heterogeneous environment (Fig. 4.7.1.2). Measurement point J-1 was situated in mostly calm water in the upstream sump, where deposition of silty and clayish material is common. J-2 was situated in much faster water flow at the outflow from the upstream sump. J-3 was placed into the strongest water flow at cascades (Fig. 4.7.1.1), where the velocity of flow reaches several m/s. The latter location is 1 m from measurement point 10 during 8-month-long measurements (Chapter 3). Measurement J-4 was located outside the cave 100 m beside Kolpa river at the major spring of Kotnica, where the measurement point was exposed to sunlight but to more or less the same water that is characteristic for measurement points in Jelovička jama. At high water level, all measurement points except J-4 lie in relatively calm water due to backflooding from the side of downstream sump in Jelovička jama. Measurement points are above water level only at very low water level, when discharge falls below ~0.4 m^3/s. At each measurement point, three limestone tablets were fixed to get better insight into micro-local changes in karst processes and for easier recognition of possible corrasion. All limestone tablets were fixed with stainless steel screws, nuts and felted washers. Since they were replaced several times, we have insight into 4 measurement periods (between 6th December 2006 and 20th April 2007, between 20th April 2007 and 14th September 2007, between 14th September 2007 and 3rd July 2008 and between 3rd July 2008 and 24th March 2009). Measurements therefore started on 6th December 2006 and ended on 24th March 2009 (837 days).

Figure 4.7.1.1: *Measurement point J-3 at medium discharge (photo: Saša Minihofer).*

Average values during all four measurement points are represented in Fig. 4.7.1.3. The smallest standard deviation was characteristic for measurement point J-3, where it reaches from 0.0001 to 0.0002 mm/a. At this location, results are the most trustworthy due to absence of corrasion, no deposition of loam and absence of misleading corrosion due to iron oxide. The latter was a problem at limestone tablet at J-1 due to low quality of stainless steel. Misleading corrosion was not a problem during 1st measurement period but later, which can be seen from Fig. 4.7.1.5. At J-2 we detected the highest corrosion rates in the cave but also the highest differences between limestone tablets at one measurement point in the cave (see Fig. 4.7.1.5). Differences, which are especially during 1st and 3rd measurement period out of maximum error of measurement, are not a consequence of corrasion, since the differences lack any spatial pattern that would indicate corrasion (e.g. increased/decreased corrasion from rock surface – for comparison see Fig. 4.3.2.1 in Chapter 4.3.2). The most probable explanation is deposition of a thin film of clay, which was usually the thickest at the middle limestone tablets due to the slowest water flow and the thinnest at the farthest limestone tablet from the rock (left limestone tablet at measurement point J-2 in Fig. 4.7.1.3). Such a film of clay could increase corrosion rates, which was already presumed by Gams (1966b, 35) in Postojnska jama.

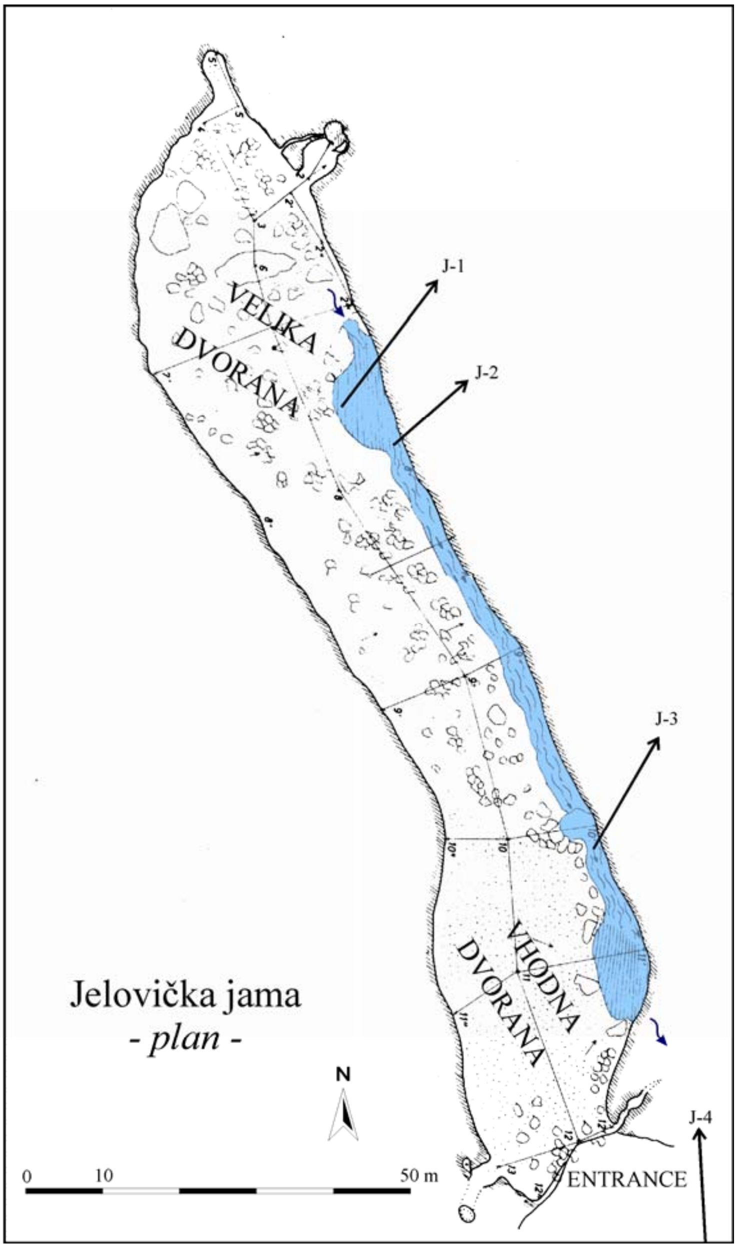


Figure 4.7.1.2: *Location of measurement points in Jelovička jama (modified after* K*RANJC, 1965).*

Average values at J-1, J-2 and J-3 show no differences which could be interpreted as a consequence of different hydrodynamic characteristics of water flow. Nevertheless, differences within a measurement point are usually smaller in comparison with differences between measurement points, which have to be a result of some other factors. Average value of rates (-0.0004 mm/a) shows slight corrosion, which is much lower in comparison with measurement point 10 during 8-month-long measurement (-0.0146 mm/a; Chapter 3). Difference is a result of corrasion, which was much more intense on measurement point 10 in comparison with measurement point J-3. This was visually observed also on the limestone tablet's edges. Low corrosion rates are proved also with sawing traces, which were observed at both sides of the limestone tablet exposed during 8-month-long measurements (see results of measurement point 10 in Appendix 1)

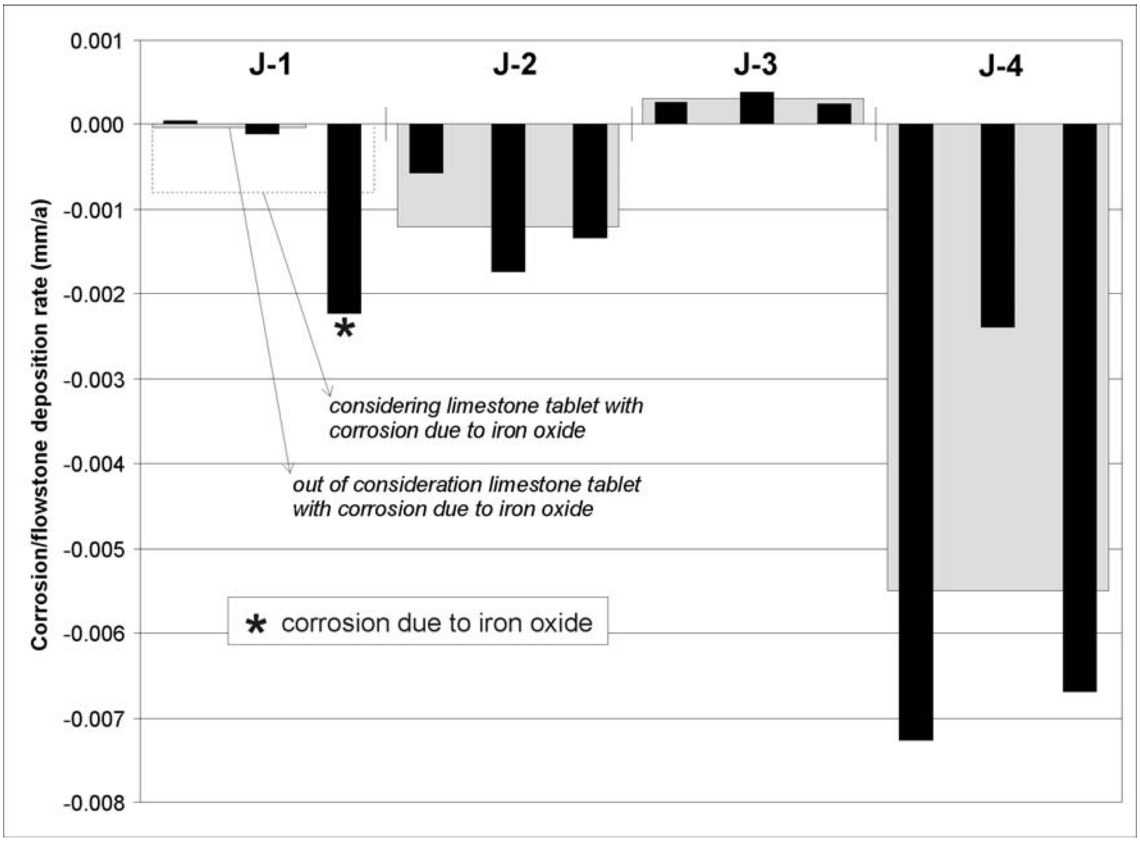


Figure 4.7.1.3: *Average corrosion/flowstone deposition rate between 6th December 2006 and 24th March 2009 at measurement places J-1, J-2, J-3 and J-4.*

The highest standard deviation and corrosion rate was observed at measurement point J-4. Such differences were expected due to differences in amount of sunlight between the cave's and outside measurement points, which influences rates of biocorrosion. Since the middle limestone tablet at J-4 gets the smallest amount of sunlight, the biocorrosion rate there is the lowest. The latter phenomenon points out that biocorrosion rates strongly depend on availability of light and that biocorrosion occurs only on the limestone blocks which are exposed to sunlight. Corrosion rate at J-4 due to sunlight is at least 15 times higher in comparison with measurement points located in the cave (J-1, J-2 and J-3). Out of consideration the middle limestone tablet at J-4, difference is 22 times higher and is even higher if we take into account just a half of limestone tablet's surface, which was fully exposed to sunlight. The latter differences are not a consequence of different physicochemical properties of water, since the differences in temperature, pH and SEC are often within the range of measurement error.

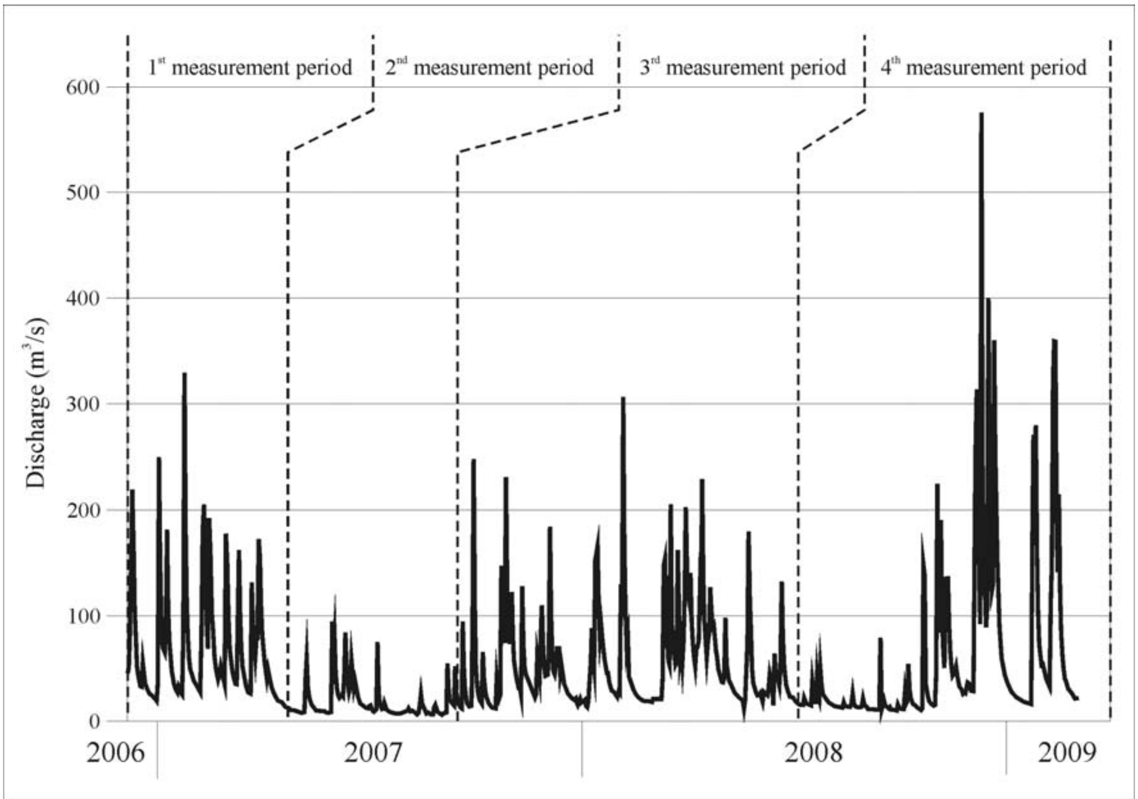


Figure 4.7.1.4: *Hydrological conditions during measurement periods based on average daily discharge at measurement station Radenci (Kolpa river; source of data: DISCHARGE DATA FOR PERIOD 2006-2009).*

Fig. 4.7.1.5 represents more detailed insight into corrosion rates during the measurement periods. Since we were not able to observe the hydrological situation in the cave, data from measurement station Radenci (Kolpa river; ~20 km downstream of Jelovička jama) are represented in Fig. 4.7.1.4. Data from the latter hydrological station reflects the hydrological situation in the whole catchment area of Kolpa river (therefore also in the catchment area of Kotnica), but they are partly valid for catchment area of Kotnica, since the latter is small and only a part of the whole catchment area covered by hydrological station Radenci. At the latter, the highest discharge was recorded during the 4th measurement period, when it reached 564 m^3/s. Nonetheless, corrosion rates at J-1, J-2, J-3 and J-4 were not the highest during the 4th measurement period but during the 3rd measurement period, which had several events with high discharges but only one which exceeded 300 m^3/s. The lowest discharges were observed during the 2nd measurement period, when average process at J-1, J-2 and J-3 shows slight deposition (0.0001 mm/a), but is not the highest (the highest average deposition rates were observed during 1st measurement period). Since the highest deposition was recorded in the 1st measurement period, which was according to discharges similar to the 3rd measurement period, relation between discharges and processes at J-1, J-2 and J-3 seems to be weak. Only results on measurement J-3 could correspond to maximum and average discharges recorded at hydrological station Radenci.

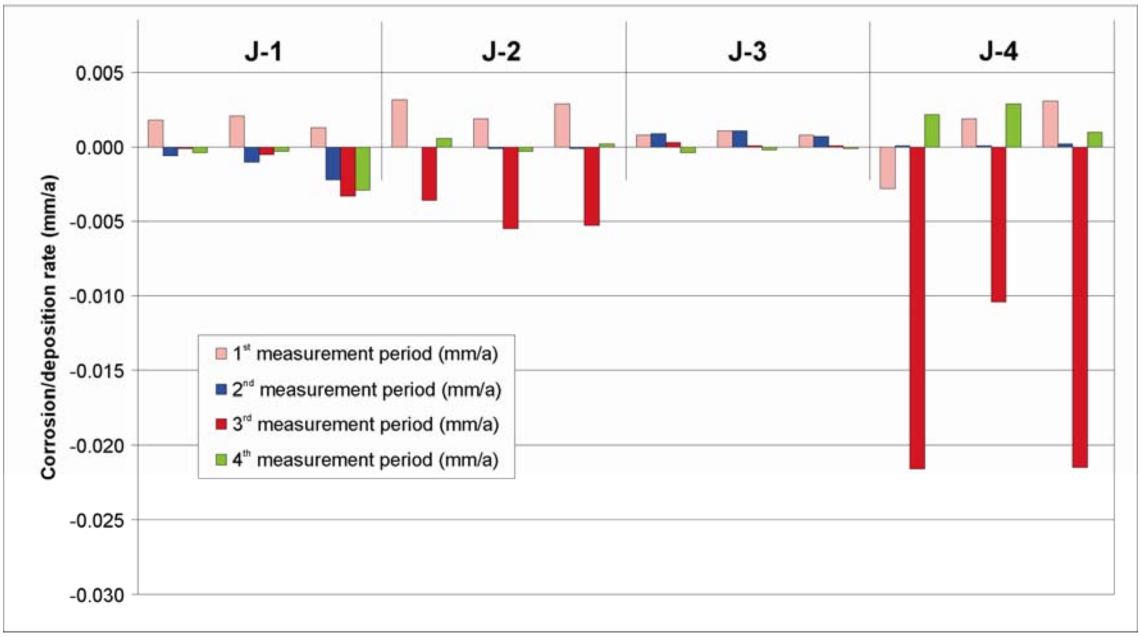


Figure 4.7.1.5: *Corrosion and flowstone deposition during 4 measurement periods at measurement points J-1, J-2, J-3 and J-4.*

Very indicative are results on measurement point J-4 (Fig. 4.7.1.5) that is under the influence of biocorrosion. The latter is absent on limestone tablets, which were exposed only during summer, autumn and winter. Therefore we detected (slight) deposition during the 2nd and 4th measurement periods. Biocorrosion was the most characteristic for the 3rd measurement period, when the measurement started at the end of summer (14th September 2007) but lasted to the beginning of summer (3rd July 2008). During the autumn and winter, organisms had enough time to spread and colonize limestone tablets at J-4, but the majority of biocorrosion occurred during spring time, which can be slightly noticed also during 1st measurement period. During the latter, deposition seems to be the prevailing process during winter time (when the limestone tablets were also colonized), but in the spring time, biocorrosion reduced the thickness of the deposited layer especially at the highest limestone tablet (this is on left and right limestone tablet of J-4 in Fig. 4.7.1.5), which is exposed to the strongest sunlight. Here, the net process turned toward corrosion.

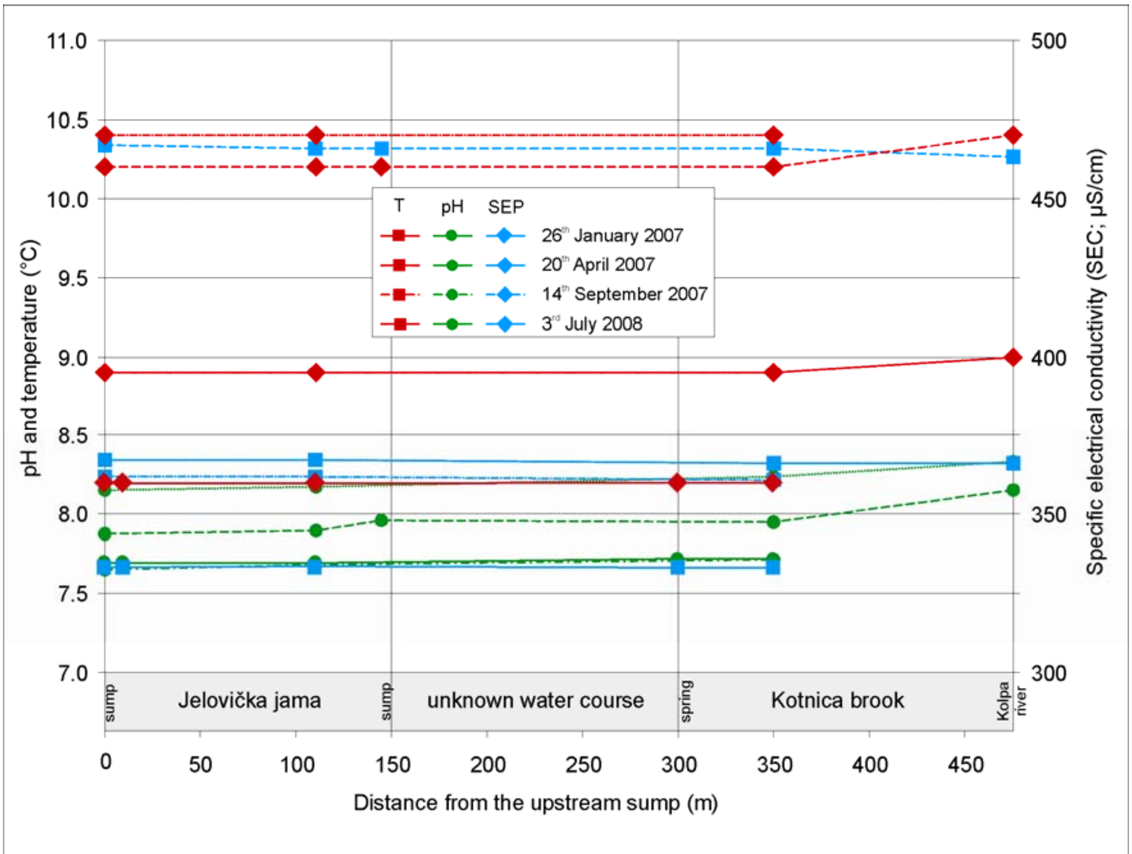


Figure 4.7.1.6: *Temperature, specific electrical conductivity (SEC) and pH changes at low water level between upstream sump in Jelovička jama and Kolpa river.*

During low and middle water level, outgassing of CO_2 from the water was recorded between sumps in Jelovička jama. The process of degassing was observed with slight increase of pH (Fig. 4.7.1.6 and Tab. 4.7.1.1), which usually changes for only 0.03 along ~150 m long water course (0.02/100 m). Although this change is within the range of error, growing of pH was observed several times, while decreasing of pH was never detected. Much bigger changes of pH are characteristic for superficial flow of Kotnica stream, where pH changed on average for about 0.14 during 175 m (0.08/100 m) along watercourse. Higher degree of outgassing along superficial flow is related to lower CO_2 concentration in the atmosphere outside the cave. Changes of SEC are relatively small (~1 μS/cm) although always negative, which indicates deposition. The latter is possible also because of slightly positive saturation index (SI_{Ca}=+0.13), which was characteristic for low discharge in Jelovička jama on 6th December 2006. At middle-high discharge (26th January 2007), changes of SEC were not recorded due to lower saturation index (SI_{Ca}=+0.03). Positive SI_{Ca} and downstream decrease of SEC shows that increased weight of limestone tablets is most probably related to flowstone deposition along underground water course in Jelovička jama.

Table 4.7.1.1: *Temperature, specific electrical conductivity (SEC) and pH changes at low water level between upstream sump in Jelovička jama (0 m) and Kolpa river (475 m). Middle-high discharge was characteristic just for 26th January 2007, while during other measurements, low discharge is characteristic.*

Distance from the upstream sump (m)	26.1.2007			20.4.2007			14.9.2007			3.7.2008		
	T	SEP	pH	T	SEP	pH	T	SEP	pH	T	SEP	pH
0	8,2	333	7,69	8,9	367	8,15	10,2	467	7,89	10,4	362	7,65
10	8,2	333	7,69									
110	8,2	333	7,69	8,9	367	8,17	10,2	466	7,90	10,4	362	7,68
145							10,2	466	7,96			
300	8,2	333	7,72									
350	8,2	333	7,71	8,9	366	8,24	10,2	466	7,95	10,4	361	7,71
475				9,0	366	8,33	10,4	463	8,15			

Breakdown morphology is a prevailing morphology in Jelovička jama. Collapse blocks cover the entire cave floor. Only at Vhodna dvorana, collapse blocks are covered by several metres thick deposits of silt and clay, which creeps toward the downstream part of water flow. Creeping proves that deposition and removal of allochtonous material is a lively and very active process in the present-day situation. In Velika dvorana, the thickness of allochtonous sediments is smaller due to higher elevation (several metres above the entrance) and water flow, which is entering the cave also through collapse blocks in Velika dvorana. Due to dimensions of blocks (several decimetres to metres), collapse material can leave the cave only by dissolution or as small fragments as a result of corrasion and grinding. Lack of rocky floors points out that rate of collapsing generally prevails over rate of corrosion and corrasion and that the latter two processes are not strong enough to remove collapse material completely. Therefore, high water gradient, formed between upstream and downstream sump due to breakdown, is more or less sustained by low geomorphic activity of water. In contrast, presence of corrosional and corrasional features in the water channel indicates corrosion and corrasion.

The prevailing microfeatures along the watercourse in Jelovička jama are scallops. They are developed all along the watercourse characteristic for low and middle water flow. In the zone of flooding, scallops are absent due to much slower water flow. From a hydrological point of view, location of scallops therefore corresponds to present-day location of fast water flow in the cave.

More detailed observation showed that scallops are not developing any more and that they are decaying by corrasion. After formation, scallops were covered with about 0.5 mm thick black coating (most likely manganese oxide; FORD & WILLIAMS, 2007, 294), which is most probably deposited even now in the zone of flooding – away from the areas of high corrasion. At a majority of exposed surfaces in the water channel, black coating has been removed with corrasion but it is still preserved at places where corrasion is less effective. This most often occurs at the upstream part of scallops (Fig. 4.7.1.7), where a corrasion rates are almost absent due to lack of bed load and suspended material in upstream parts of scallops. The most effective corrasion takes place at exposed surfaces, this is at the downstream parts of a scallops. Therefore, transition between scallops is very sharp especially at places where the edges of scallops are perpendicular to water flow. At places where direction of edges is parallel to water flow or where direction of water flow was changed, transitions between scallops can be smoothened to almost flat surface. Potholes are quite rare and if they exist, their diameter does not exceed 5 cm. The absence of potholes is most probably related to the small dimension of bed load material, which has a very low chance of being caught into the circular depressions.

Very low or even absent corrosion rates were confirmed also with measurements with limestone tablets at J-1, J-2 and J-3. At the latter location, the prevailing process seems to be even slight flowstone deposition. Nevertheless, at present-day rates, we can expect from 0 to 15 mm of corrosion or about 4 mm of flowstone deposition during Holocene, while the corrasion rates seems to be much higher if we take into account rates gathered during 8-month-long measurements at point 10. Small corrosion rates, slight net flowstone deposition rate at J-3 and presence of black coating on scallops suggest that even small corrosional features are result of much longer evolution and are most probably inherited from Pleistocene. At that time, concentration of CO_2 in the water was certainly lower, which led to higher aggressiveness of water even during middle discharge. Nowadays, the prevailing process along water channel defined by medium discharge is corrasion. The latter is also generally quite low since some scallops are still preserved.

Figure 4.7.1.7: *Corrasionally deformed scallops with black coating in Jelovička jama. Water flow is directed from left to right.*

Conclusion

Jelovička jama is a cave in a epiphreatic zone, which most probably drains allogenic water from impermeable Permian rocks and autogenic water from the karst plateau north of the cave. The main passage developed along a NW-SE oriented fault and was later modified by collapses. The latter partially dammed underground water flow and raised the water gradient between the upstream and the downstream sump.

Collapse material can be removed only by corrosion, corrasion or as small fragments due to corrasion, since the downstream sump is too narrow and since the entrance lies several metres above collapse material. Measurements of rates of present-day karst processes point out that present-day removal of collapse material with corrosion is very low (up to -0.0012 mm/a). At another location, even slight flowstone deposition was recorded (0.0003 mm/a). Both rates show that water is close to equilibrium with respect to Ca^{2+} even at high water level, when discharge amounts to several m^3/s. At lower discharge, slight flowstone deposition was confirmed also with positive SI_{Ca} and downstream decrease of SEC. Downstream of upstream sump, SI_{Ca} rises due to outgassing of CO_2 from the water. Corrosion and flowstone deposition rates are generally lower than that of corrasion, which is decaying corrosional (and depositional) features.

Morphology in the cave corresponds to the present-day hydrological situation but only partly to present-day geomorphic processes. Corrasionally modified scallops show that corrosion was higher in the past especially at medium discharge. During such discharge, the scallops were formed in the water channel. Later, black coating was deposited over the scallops and is now removed by corrasion. Nevertheless, corrosion was not strong enough to eliminate all black coating and scallops and even not long enough for formation of bigger corrosional features (i.e. wall notches). Present-day corrasion is a process that prevails over corrosion and flowstone deposition and modifies corrosional features. It would be interesting to get actual corrasion rates, from which it would be possible to estimate roughly the age of scallops by comparison of corrosion and corrasion rates. The biggest problem can be low rate of corrasion, which seems to be too low for measurements with micrometer, even within tens of years.

5 General conclusions and potential for further research

Methodology

Measurements of karst processes require use of special techniques, among which are use of micrometer, hydrochemical method, direct observation of corrosion in known periods of time and use of limestone tablets. Since the rate of geomorphic processes on karst is low, the biggest advantage of measurements with limestone tablets is their high precision (up to ±0.00005 mm) and accuracy (on average ±0.0002 mm; maximum error ±0.0004 mm). Nevertheless, use of limestone tablets brings some problems, which are related to different types of host rock where speleogenesis takes place (corrosion rates on dolomites can be 10-times lower in comparison with corrosion rates on limestones), and unnatural surface of limestone tablets due to freshly cut surface. Moreover, shorter intervals of measurements also reduces influence of cave microorganisms, which can play a significant role at low corrosion rates but they require stable living conditions, which are significantly changed with short interval of measurements. Limestone tablets have to be fixed with stainless steel, plastic (or brass) to prevent misleading corrosion due to rusting of iron.

Comparisons with micrometer measurements show the rates of processes are of the same order of magnitude, but deviation can detected on some occasions (beginning of measurement, differences in surface roughness during high rates of processes) still high (on average 25 % lower corrosion/flowstone deposition rates can be expected with use of limestone tablets). Significant errors can appear with either methodology. Use of appropriate methodology for measurements depends on rates of processes (micrometer measurements are more appropriate in environment with high corrosion rates and useless in environment with very low corrosion rates), corrasion rates (limestone tablets were useless in environment with moderate-high corrasion rates) and accessibility (limestone tablets are easier for transport).

At least in the Slovene epiphreatic zone, rates of chemical processes are usually so low that use of limestone tablets is necessary to obtain rates of processes within several years. Some more study is needed to find out the reasons for differences between micrometer measurements and measurements with limestone tablets. Further care is advised in using of limestone tablets, since some deviations from real corrosion/flowstone deposition rates are still possible to be observed.

Rates of corrosion/flowstone deposition

Generally, corrosion or flowstone deposition rates in epiphreatic zone are low, which corresponds to long-term evolution of caves. Along main underground water courses in the epiphreatic zone, rates of several µm/a are common. Such rates are characteristic for caves influenced by concentrated autogenic recharge, diffuse autogenic recharge, even allogenic recharge, where the catchment area is composed of carbonate rocks, and for composed diffuse/concentrated autogenic-allogenic recharge. The highest corrosion or flowstone deposition rates (and their spatial changes) are observed at places of the highest differences with respect to CO_2 concentration (i.e. in Križna jama) or of the highest difference in actual and potential concentration of Ca^{2+} (i.e. in Lekinka), where we can expect less than -0.1 mm/a of corrosion rates and more than 0.1 mm/a of flowstone deposition rates. Along underground rivers which connect poljes, low changes of corrosion rates were observed, most probably due to the high amount of water that is flowing underground and consequentional weak contact with CO_2 in the air. Such rivers are usually (over)saturated already at the ponor – therefore, flowstone deposition about 0.0006 mm/a can be observed all along underground water flow. Inactivity of main karst water courses was already proved by Oertly and questionable for Melik but, interestingly, never accepted by Gams. Low rates of corrosion or even flowstone deposition in epiphreatic zone show that by far the highest corrosion occurs in the epikarstic and vadose zones, which is a well known phenomenon but very rarely quantified. Ventilation in the epiphreatic zone usually even increases flowstone deposition rates or decreases corrosion rates due to outgassing of CO_2.

Rates of processes at springs/superficial rivers/ponors can be much higher due to high biocorrosion rates (even -0.15 mm/a). Therefore, rates at superficial locations do not correspond to the rates in the underground due to different degree of illumination. If such high rates are characteristic for a long time, at least once higher biocorrosion rates than chemical denudation of surface could develop some gorges and even valleys. This is supported also with (present-day) lack of corrasional material in Obrh gorge at Lož

polje, upstream end of Krka and Kolpa valley, with illuminated location of upstream end Unica river, bowl-shaped spring lakes etc. A lot of measurements should be done in the future to confirm these presumptions.
A little is known about the long-term role of microorganisms, which can be studied with different measurement intervals with limestone tablets at the same place. If we are right, higher biocorrosion rates in caves are expected during uniform several years of measurements in comparison with sum of values obtained in shorter intervals.

Relation between present-day processes, factors and features

One of the biggest surprise was detection of prevailing low flowstone deposition rates in some important caves (Postojnska jama, Planinska jama, Škocjanske jame, Tkalca jama, Jelovička jama, Križna jama 2, but high flowstone deposition rates in Križna jama), which does not agree with corrosional formation of passages and some basic corrosional features (i.e. scallops). This proves that corrosional features in these caves are more or less fossil since they cannot be formed by present-day processes, sometimes even not during the very high discharges observed during 2005-2009. Widespread prevailing flowstone deposition rate and thickness of flowstone in Križna jama and Škocjanske jame show important changes in rates and rates's direction at the transition between Pleistocene and Holocene. During cold climate periods (e.g. MIS 2, MIS 4, MIS 5a-d), lower (or absent) flowstone deposition rates and higher corrosion rates are expected. The most obvious change was change in temperature, which influenced vegetation cover and supply of soil CO_2. Lower CO_2 concentration in the soil causes lower total hardness of vadose water and lowers the possibility and rates of outgassing of CO_2 from diffusely recharged water. This phenomenon was already observed in growth of stalagmites and tufa dams but it was rarely attributed to speleogenesis in epiphreatic (or shallow phreatic) zone. Consequently, higher corrosion rates in the epiphreatic zone can be expected during colder climate and lower corrosion rates during warmer climate. This can be tested with a similar procedure to ours in colder and warmer climates. Nevertheless, some caves that are fed by allogenic recharge can show no or inversed dependence on climate change.

In Križna jama-Križna jama 2 cave system, which is fed by diffusely recharged water, the course of flowstone and corrosion rates does not depend on discharge or vegetation season due to an average relatively high residence time of water in the soil, epikarst and vadose zone. It is interesting that the seasonal course of processes corresponds to ventilation of the cave, which was up to now very rarely observed due to absence of similar measurements or lack of accuracy of methodology used. The connection between rates of processes and ventilation can be found in cave air CO_2 concentration – higher CO_2 concentration during summer and autumn months sustains aggressiveness of the stream, while the low CO_2 concentration during winter and spring increases flowstone deposition rates. It would be interesting to get such a course of geomorphic processes also in other caves that are fed by the same type of recharge.

6 Povzetek

6.1 Predstavitev problematike, namen, cilj in pristop

Sedanje poznavanje oblik, dejavnikov in procesov na krasu temelji na več stoletnem proučevanju kraških pojavov. Osnovne ideje so bile izdelane že v 19. stoletju, ko so bile poznane osnove raztapljanja na krasu, 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. Ta doktorska disertacija ni torej nič več kot dodaten delček v mozaiku znanja o krasu, ki ga vse bolj kvantificiramo, obenem relativiziramo, predvsem pa objektivno spoznavamo. Zaradi bližine in tradicije je bilo delo v okviru doktorske disertacije izvedeno večinoma na slovenskem dinarskem krasu.

Naslov doktorske disertacije omejuje njeno razsežnost v času (današnji pojavi), predmetu (procesi, dejavniki in oblike) ter prostoru (epifreatična cona). Recentna dinamika je bila v slovenski geomorfologiji in speleologiji vedno v senci drugih raziskav, ki so bile osredotočene na pretekli in precej daljši razvoj jam (speleogenezo). To je povezano z željo po časovno čim celovitejšem pregledu razvoja jam, ki v krasu običajno poteka več 10.000 ali 100.000 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 60-ta leta 20. stoletja (POROČILO O..., 1959), vendar ni bil načrt nikoli realiziran. Precej bolje je na področju poznavanja dejavnikov, s katerimi pa se večinoma ukvarjajo negeomorfologi (analize voda opravljajo kemiki in hidrologi, litološke značilnosti kamnin geologi, z biološkimi procesi mikrobiologi ipd.). Pri tem se primanjkljaj kaže v geomorfološkem vrednotenju hidroloških in litoloških podatkov. Precej bolj pesto in široko je znanje o speleomorfologiji, ki je najbolj očiten in najlažje prepoznaven rezultat učinkovanja procesov pod vplivom dejavnikov. Jamska morfologija je zaradi tega najbolj proučen pojav v trojici procesi-dejavniki-oblike. Njeno poznavanje je bolj ali manj omejeno na suhe in pa obdobno poplavljene rove (vadozna in epifreatična cona), medtem ko je freatična cona zaradi tehnično precej zahtevnejšega pristopa precej slabše proučena. S tega vidika smo se tudi v tej doktorski disertaciji omejili na proučevanje pojavov v epifreatični coni, ki nam s svojo veliko horizontalno dimenzijo, lahkim dostopom do/vzdolž podzemnih tokov in hidrološko-geomorfološko pomembnostjo (večina najdaljših slovenskih jam je razvita ravno v epifreatični coni) nudi dober vpogled v sedanjo morfodinamiko.

Cilji doktorske disertacije so potemtakem:

- Testiranje na videz zelo natančne metode merjenja procesov z apnenčastimi ploščicami, uvesti izboljšave in jo primerjati z drugimi razpoložljivimi metodami za ugotavljanje recentne korozije,
- Ugotoviti intenziteto recentnih speleogenetskih procesov v epifreatični coni slovenskega krasa,
  - Določitev vodilnih dejavnikov, ki na procese vplivajo, in oblik, ki pri tem nastajajo,
- Meriti recentno morfodinamiko v izbranih jamskih sistemih,
  - Določitev vodilnih dejavnikov, ki na procese vplivajo, in oblik, ki pri tem nastajajo,
  - Določitev vodilnih oblik, ki z recentnimi procesi nastajajo (potencialne oblike),
  - Določiti povezanost med recentnimi procesi, recentnimi in potencialnimi oblikami ter recentnimi dejavniki.

Običajno se je na recentne procese sklepalo iz podzemnih oblik, ki jih občasno dosega podzemna voda (Slika 1.3.1-a). 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). Majhna intenziteta je še toliko bolj značilna za kraške procese, ki so običajno počasni in vizualno težko prepoznavni. Zaradi tega smo za proučevanje recentne in pretekle morfodinamike uporabili drug pristop (Slika 1.3.1-b). Zanj je značilna ločenost med recentno morfodinamiko in obstoječo morfologijo. Ločenost analize nam omogoča navzkrižno primerjavo med dejansko in potencialno morfologijo ter določitev preteklih dejavnikov, v kolikor je odstopanje preveliko.

6.2 Uporabljena metodologija

Za meritev procesov smo uporabili mikrometrske meritve, apnenčaste ploščice, v omejeni obliki pa tudi hidrokemično metodo. Mikrometrske meritve so najbolj uporabljena metodologija za ugotavljanje 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 relativno enostavna, meri se dejansko odmikanje (ali približevanje) jamske stene, metoda omogoča več meritev na istem mestu in izračun povprečne vrednosti. Slabost so napake meritev, ki se znatno večajo pri višji resoluciji (SPATE ET AL., 1985). Hidrokemične meritve so se večinoma izvajale na izvirih z meritvami prevodnosti (informacija o celokupni trdoti) in pretoka. Čeprav omogoča metoda tudi ugotavljanje raztapljanja oz. odlaganja sige med dvema točkama vzdolž toka brez vmesnih pritokov, je slabost zlasti težko določljiva reakcijska površina. Rezultati prostorskih meritev vzdolž toka nam torej bolj ponujajo ugotavljanje prevladujočega procesa kakor dejansko intenziteto le-tega.

V želji po čim bolj natančnih meritvah smo največ meritev opravili z metodo apnenčastih ploščic, ki smo jo tekom meritev vseskozi preizkušali, primerjali pa tudi z mikrometrskimi meritvami. S strani raziskovalcev procesov na krasu je bila običajno uporabljena za meritve intenzitete korozije 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 mikrometrskih meritev, saj izračunavamo tanjšanje ploščic iz dosti lažje določljive razlike v teži, vendar tudi njo spremlja več potencialnih napak. Ker smo isto ploščico v jami izpostavili večkrat, sočasno pa smo uporabljali več kot 30 apnenčastih ploščic, smo se izognili prepogostemu sušenju pri temperaturi nad 100 ºC, ki odstrani vlago iz apnenčaste ploščice (GAMS, 1985; Slika 2.1.3.1). Zaradi tega smo uvedli korekcijski faktor, ki izniči spremembo relativne vlage v kemijskem laboratoriju Inštituta za raziskovanje krasa ZRS CAZU, kjer so bile meritve opravljene (Enačba 2.1.3.2). Kljub temu smo na podlagi ploščic, ki so bile v jamo postavljene, ne pa izpostavljene tekoči vodi, ugotovili povprečno ±0,0002 mm največ pa ±0,0004 mm napake (velja za 20-25 g težke apnenčaste ploščice; Slika 2.1.3.4). Le-to se da v veliki meri odpraviti z apnenčastimi ploščicami, 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 večjim številom apnenčastih ploščic na istem mestu (Slika 2.1.3.6; Slika 2.1.3.7). S tem se povprečna napaka zmanjša na ±0,00005 mm, maksimalna pa na ±0,0002 mm. Dodatno napako lahko predstavlja oksidacija železa, ki ga uporabljamo za pritrditev. Intenziteta zavajajoče korozije, ki se pri tem pojavlja, je odvisna od lokacije in znaša od 0,0000 do -0,0024 mm v 30 dneh. Zavajajoči koroziji s strani železovega oksida se lahko izognemo s pritrditvijo na nerjaveči, plastični (ali medeninasti) 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 nekoliko višjo intenziteto korozije (za okoli 0,0020 mm na 15 dni). Razlika izgine, ko je odstranjena okoli 0,025 mm debela plast na apnenčasti ploščici (Slika 2.1.3.9). Podobna razlika se pojavlja tudi pri odlaganju sige, pri čemer so začetne vrednosti odlaganja nekoliko manjše (Slika 2.1.3.10). Del napake običajno izhaja tudi zaradi heterogenosti med apnenčastimi ploščicami in znaša v povprečju ±0,0005 mm na 15 dni (maksimalno -0,0013 ter 0,0007 mm na 15 dni), vendar so razlike v daljšem časovnem obdobju povprečene, zato je končna topnost praktično enaka (Slika 2.1.3.9). Največja napaka lahko izhaja iz različnosti litologije. V kolikor merimo z apnenčastimi ploščicami, napaka v rovih iz apnenca ni velika (do 20 %). Če pa so jamski rovi izoblikovani 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 (Slika 2.1.3.11). Precejšen del napake lahko izhaja tudi iz poškodb pri transportu. Poškodbam apnenčastih ploščic pri transportu smo se izognili s prenašanjem ploščic v posebej za ta namen izdelanem transporterju (Slika 2.1.3.8). Primerjava med metodo apnenčastih ploščic in mikrometrom tudi pokaže, da sta korozija in odlaganje sige izmerjeni z mikrometrom običajno intenzivnejši v primerjavi s korozijo in odlaganjem sige izmerjeni z apnenčastimi ploščicami (Slika 2.1.3.12 in Slika 2.1.3.13). Čeprav obe meritvi izkazujeta enako magnitudo procesov, so lahko odstopanja precejšnja in terjajo nadaljnje proučevanje.

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^+ (H_3O^+) ionov in temperatura so bili izmerjeni z merilcem WTW Multiline P4 in ustreznimi sondami na terenu. Indeks nasičenosti glede na kalcij (SI_{Ca}) je bil ob pridobljenih koncentracijah Ca^{2+}, Mg^{2+}, HCO_3^+, T, SEP in pH izračunan s programom WATEQ4F (BALL & NORDSTROM, 1991). Pretok vode smo merili z injektiranjem vodne raztopine NaCl v vodo ter dolvodnim merjenjem SEP v znanem časovnem intervalu (KÄSS, 1998). Višino 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. Pretok v Križni jami in Lekinki smo izračunavali s pomočjo izdelanih pretočnih krivulj.

Karakteristike zraka smo ugotavljali predvsem z vidika gibanja (intenziteta, smer) ter koncentracije CO_2. Prostorske meritve ter meritve v 20-12 dni dolgem časovnem razponu smo izvajali s prenosnim merilcem CO2 Vaisala GM70 z pripadajočo sondo GMP222 z maksimalno koncentracijo 3.000 ppm.

Zaradi relativno kratkega merilnega obdobja procesov in dejavnikov smo se morfološko omejili predvsem na proučevanje mikroreliefnih oblik. Večino spoznanj smo povzeli iz literature, del pa obsega tudi vizualno opazovanje in tematsko kartiranje pomembnejših oblik. Za podlago smo uporabljali izdelane načrte jam, ki so bili zaradi zgodovinske pomembnosti proučevanih jam zelo natančno izdelani.

6.3 8-mesečne meritve korozije in odlaganja sige

8-mesečne meritve korozije so sploh prve zaokrožene meritve korozije na podzemskih vodotokih. Z njimi smo poskušali:

- Testirati uporabnost in točnost metodologije merjenja z apnenčastimi ploščicami,
- Dobiti okvirne vrednosti korozije na slovenskem (dinarskem) krasu,

- Ugotoviti prostorsko variabilnost korozije v epifreatični coni,
- Izluščiti najbolj poglavitne faktorje, ki vplivajo na intenziteto in prostorsko razporeditev korozije ter
- Določiti mesta za podrobnejše meritve intenzitete ter časovno in prostorsko razporeditev korozije.

Meritve smo med oktobrom/novembrom 2005 in julijem 2006 opravljali na 85 lokacijah po jamah, izvirih, ponorih in kraških rekah (Slika 3.2). Osnovna predpostavka je bila, da je površinska intenziteta korozije enaka koroziji v jamah. Ploščice smo na steno pritrdili s pomočjo železnega vijaka, s filcem podloženih železnih podložk in železne matice (Slika 3.1). Zaradi železovega oksida smo ponekod opazili pojav zavajajoče (intenzitete) korozije. Povprečne hidrološke razmere v času meritev so ustrezale dolgoletnemu povprečju 1971-2000 (Slika 3.3). Izpostaviti velja le razmeroma nizke maksimalne pretoke Reke, nadpovprečno visoke maksimalne pretoke v jugovzhodni Sloveniji (porečje Krke, Kolpe in Temenice/Prečne) v novembru/decembru 2005 ter velike mesečne pretoke na istem območju marcu 2006. To pomeni, da je lahko intenziteta korozije v jugovzhodni Sloveniji precenjena, v jugozahodni pa podcenjena.

Rezultati prikazani v histogramu kažejo, da se večina merilnih mest uvršča v razred med -0,001 do -0,01 mm na leto (Slika 3.4). Krivulja porazdelitve je podobna log-normalni, opazen je le odklon krivulje v smeri korozije in močna koničavost. To pomeni, da je imamo nadpovprečno število merilnih mest v najbolj zastopanem razredu, medtem ko so višje ali nižje vrednosti razmeroma redke (Slika 3.6). Najvišja korozija znaša manj kot -0,1 mm na leto, največje zabeleženo odlaganje sige pa več kot 0,1 mm na leto. Zaradi železovega oksida na pritrdilnih elementih, ki je povzročal zavajujočo korozijo, je dejanska korozija verjetno še nekoliko šibkejša od izmerjene.

Največja korozija (-0,1664 mm na leto) je bila zabeležena v jami Lekinka v stalno zalitem delu rova. Visoka korozija je povezana z nizko celokupno trdoto vode (nizko koncentracijo Ca^{2+} ionov; GOSPODARIČ & HABIČ, 1966) ter morda z veliko organskimi kislinami v vodi, saj priteka voda iz močvirne pleistocenske terase Nanoščice in Pivke. Poudariti je potrebno, da se na vseh mestih z alogenim dotokom ne pojavljajo visoke vrednosti korozije, saj lahko (del) vodozbirnega območja leži na deloma karbonatnih kamninah (npr. cement med kremenovimi zrni eocenskega fliša). Taki vodotoki imajo višjo karbonatno trdoto.

Primerjava ugotovljenih celokupnih trdot (GAMS, 1962; GAMS, 1966) z intenziteto korozije/odlaganja sige kaže slabo linearno korelacijsko povezanost (R^2 = 0,03; Slika 3.5). Precej boljšo povezanost (R^2 = 0,39) dosežemo brez upoštevanja merilnih mest, ki kljub visoki trdoti vode kažejo visoko intenziteto korozije. To so mesta z ugotovljeno biokorozijo, ki so najbolj očitno razvrščena vzdolž desnega brega Krke, kjer smo korozijo merili na izvirih (Slika 3.7). Opazovanja pod lupo so pokazala globoke vdolbinice na pozelenjeni površini apnenčastih ploščic, vendar le na prisojni strani. To je rezultat biokorozije. Njena intenziteta je bila na pritokih Krke ocenjena na -0,15 mm na leto (Tabela 3.1). Pojavlja se tudi drugod, vendar je intenziteta manjša. Na nekaterih površinskih merilnih mestih je njen vpliv zanemarljiv. Če izločimo merilna mesta s pojavom biokorozije in velikim neravnotežjem s koncentracijo CO2 v vodi, lahko povezavo med celokupno trdoto in opišemo z Enačbo 3.1. Kemično »neaktivna voda« se pojavlja pri celokupni trdoti ~205 mg $CaCO_3$/L, kar je precej več od topnosti $CaCO_3$/L v padavinski vodi (80-90 mg $CaCO_3$/L – GAMS, 1966b, 56; 50-60 mg $CaCO_3$/L; 2007, 40 – FORD & WILLIAMS, 2007, 40). To lahko pripišemo bodisi višji koncentraciji CO_2 v vodi bodisi vsebnosti ostalih snovi, ki vplivajo na ravnotežno koncentracijo $CaCO_3$.

Nekatera merilna mesta kažejo tudi na prevladujoče odlaganje sige. Najbolj intenzivno se ta proces odvija v Križni jami, kjer opažamo visoko celokupno trdoto vode, nekoliko manj intenzivno pa v zgornjem delu vzhodnega kraka kraške Ljubljanice, kjer se voda razpršeno infiltrira skozi dolomit. Počasna infiltracija ob visoki koncentraciji CO2 v prsti (in podzemlju) očitno determinira (pre)nasičenost vode na izvirih ter tudi v kraških jamah, ko iz vode izhaja CO_2.

Prostorska razporeditev korozije oz. odlaganja sige/lehnjaka (Slika 3.7) kaže na homogenost, pa tudi na heterogenost intenzitete korozije. Homogenost se kaže vzdolž podzemeljske Pivke, v Rakovem Škocjanu, zgornjemu delu vzhodnega kraka kraške Ljubljanice in vzdolž desnih spodnjih pritokov Krke. Prostorska heterogenost se kaže bodisi zaradi različnega vodozbirnega zaledja (npr. Lekinka in Postojnska jama), zaradi razpoložljivost svetlobe (npr. Bruhalnik za Javornikov Žago in desni pritoki Krke) ali različne vsebnosti karbonatov v flišnem vodozbirnem območju (npr. Ponikve v Odolini in Račiške ponikve).

Čeprav so bile vrednosti intenzitete korozije vplivane s strani zavajajoče korozije s strani železovega oksida, nam intenziteta korozije v danem časovnem intervalu vendarle poda določeno magnitudo korozije, ki jo lahko pričakujemo. V holocenu (10.000 do 11.000 let pred sedanjostjo), ko so bile klimatsko-vegetacijsko-hidrološko-geomorfne razmere relativno stabilne, lahko tako v povprečju pričakujemo 135 mm korozije, kar je dovolj za ustvarjanje mikroreliefnih oblik (npr. fasete, rebra, majhne konkavne oblike). Višje vrednosti (npr. V Lekinki, Ponikvah v Odolini, mesta z opazno biokorozijo) so se lahko odrazile v nastanku nekaterih mezoreliefnih oblik (stenske zajede, deli vadoznih meandrov, stropne kupole). Tudi ob najhitrejših kemičnih procesih je za oblikovanje celotne jame potrebno obdobje, ki sega preko več klimatskih obdobij. Enako je v primeru odlaganja sige/lehnjaka, kjer se je lahko tekom holocena razvila največ 1,1 m debela plast sige/lehnjaka, običajno še znatno manj. Meritve na nekaterih mestih (pr. Podpeška jama, Markov spodmol, Golobina, Račiške ponikve) kažejo na neaktivno vodo, medtem ko so nekatere oblike na stenah sedanjega vodnega rova povsem korozijske. To kaže, da imamo opraviti s fosilnimi kraškimi oblikami, ki so nastajale v drugačnih klimatskih, vegetacijskih, hidroloških ali geomorfoloških pogojih.

6.4 Izbrani primeri podrobnejših meritev

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 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 je bogata s 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 se zunanje temperature oddaljujejo od 8 °C (jamska temperatura). Pozimi je prepih usmerjen skozi glavni vhod v jamo, pozimi pa iz glavnega vhoda prihaja relativno mrzel jamski zrak na površje. Križna jama 2 je prevetrena v znatno manjši meri, predvsem zaradi majhnega in edinega vhoda. Glede na meritve Mihevca

(1997) je prevladujoč geomorfni proces v Križni jami odlaganje sige s hitrostjo 0,128 mm na leto. Podobne vrednosti smo dobili tudi v 8-mesečnih meritvah kraških procesov (Poglavje 6.3).

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. 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 zraka pa prenosni merilec koncentracije CO_2. Specifične jamske oblike smo kartirali, na njih pa smo izvajali tudi osnovna morfometrična merjenja.

15-dnevna merjenja kraških procesov 10 m dolvodno od 1. jezera (merilno mesto KJ-1 na Sliki 4.1.2; Križna jama) v večinoma stalno zaliti coni so pokazala, da odlaganje sige prvenstveno ni odvisno od vodostaja, temveč od intenzitete in dolgotrajnosti zimskega prepiha v jamo. Največje odlaganje sige smo zabeležili ob dolgotrajnem prepihu v jamo, ko se zunanja temperatura ne dvigne nad -2 °C. V taki meteorološki situaciji koncentracija CO_2 v jamskem zraku pade iz ~1.500 ppm na zunanjih ~360 ppm, s tem pa so pogoji za izhajanje CO_2 iz vode dovolj ustrezni za znatno zvišanje SI_{Ca} oz. za znatno odlaganje sige. Tako se v nekaj dneh odloži praktično vsa siga v celem letu. Količina letno odložene sige je prvenstveno odvisna od intenzitete in trajanja zimskega prepiha v jamo – relativno šibkemu in kratkotrajnemu prepihu ustreza manjša količina sige in obratno. V preostalem delu leta je intenziteta kraških procesov nizka (manj kot ±0,0005 mm na 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 korozije, saj smo 21 apnenčastih ploščic razvrstili navpično v cono najpogostejšega nihanja vodne gladine v 1. jezeru. Zgornje ploščice, ki so bile izpostavljene zgolj visoki vodi, v skoraj 3 letih niso nedvoumno pokazale na korozijo. Spodnje ploščice, ki so bile izpostavljene tako odlaganju sige kakor tudi potencialni koroziji, so kazale daleč prevladujoč proces odlaganja sige, vendar precej manj kot na brzicah pod 1. jezerom. Glavne razlike so nastale v času zimskega odlaganja sige, ki je pogojeno 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 obstajala. 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 4.1.4.2). To je povezano z naraščajočim SI_{Ca} pod sotočjem potoka iz Pisanega rova s potokom iz rova Blata. Pri mešanju voda sicer ne prihaja do korozije mešanice, vseeno pa se odlaganje sige v enem mesecu (=interval merjenja) pod sotočjem približa povprečni napaki merjenja z apnenčastimi ploščicami (±0,0001 mm). V kolikor je zimski prepih premalo intenziven, na gorvodnih sigovih pregradah sploh ne prihaja do odlaganja sige. Morfološki učinek tega procesa je viden v tanjšanju sigove prevleke na stenah jezer od 1. jezera do Kalvarije in pa predvsem v upočasnjeni rasti gorvodnih sigovih pregrad z dolvodnimi. Le-to pripelje do poplavljanja gorvodno ležečih pregrad s strani dolvodnih ter daljšanje jezer od 1. jezera proti Kalvariji (Slika 4.1.4.6).

Meritve kraških procesov v Pisanem rovu v grobem ustrezajo razmeram v rovu med 1. jezerom in Kalvarijo. Tudi tu prihaja zaradi močnega zimskega prepiha do odlaganja sige izključno v zimskem in zgodnje spomladanskem času. Odlaganje sige se gorvodno zmanjšuje (Slika 4.1.6.1).

V rovu Blata so geomorfne razmere precej bolj komplicirane, saj se srečujemo z več dotoki, ki popolnoma ustavijo odlaganje sige (Slika 4.1.7.2), vendar se le-ta po nekaj 100 m toka znova okrepi. Odlaganje sige je v rovu Blata precej manjše v primerjavi z odlaganjem v Pisanem rovu in med 1. jezerom in Kalvarijo, vendar precej bolj sezonsko in zvezno (Slika 4.1.5.4 – merilno mesto KJ-7). Glavnina odlaganja sige se zgodi v spomladanskih mesecih, nato sledimo do jeseni upadanje odlaganja sige ter celo prehod v korozijo, v zimskem času pa skromna korozija 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 korozije 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 korozijo nad največjo napako merjenja (±0,0004 mm).

V Križni jami 2 sledimo podoben potek odlaganja sige in korozije kot v rovu Blata (Slika 4.1.8.1). Ta sezonski impulz se torej prenaša preko celotnega jamskega sistema. Tudi količina letno odložene sige je v Križni jami 2 (0,0006 mm na leto) enaka tudi v rovu Blata zaradi visokih koncentracij CO_2 preko zime (Slika 4.1.9.4), kar se pozna tudi pri konstantnem pH preko celotne jame (Slika 4.1.9.3). Dolvodno se količina odložene sige sicer poveča (na 0.0020 mm na leto), 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 (11.000 B.P.). Odstopanja med ugotovljenim, a morfološko neizraženim odlaganjem sige sledimo v Križni jami 2 ter v dolvodnih delih rova Blata. Zaradi majhnih debelin odložene sige je možno, da plasti sproti odstranjuje korazija ali pa mikroorganizmi. Podoben razkorak sledimo tudi pri izredno majhni koroziji, ki pa je morfološko izredno dobro izražena v fasetah. Ker velikost faset marsikje ne ustreza današnjih hidrodinamičnim razmeram v jamskem sistemu smatramo, da so fosilne in se danes ne oblikujejo več. Dosti boljše razmere za njihovo rast so bile v hladnejših obdobjih pleistocena, ko je nižja trdota vode in nižja koncentracija CO_2 zlasti ob visokem vodostaju ugodneje vplivala na njihovo rast.

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 4.2.1). Zaradi nizkih reliefnih amplitud v porečju Črni potok ne prenaša dosti talnega transporta, 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 do stropa (za 8 m) poplavi Lekinko (Slika 4.2.3). 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 (verjetne) povezave z Otoško jamo je Lekinka dobro prevetrena.

Meritve korozije v 8-mesečnem obdobju so pokazale na razmeroma visoko intenziteto korozije, ki je lahko intenzivnejša od -0,1 mm na leto. Nadaljnje meritve na merilnem mesti L-1 med septembrom 2006 in aprilom 2009 so visoke vrednosti potrdile, vendar kljub temu niso segle pod -0,08 mm na leto (Slika 4.2.1.6). Meritve na L-1, ki so bile opravljene z 15 dnevnim intervalom, so pokazale na razmeroma močno odvisnost intenzitete korozije od količine padavin v 15 dnevnem obdobju (R^2 = 0,61). Korelacija z maksimalno višino vode v 15 dnevnem obdobju je nižja (R^2 = 0,31). V opazovanem obdobju nismo zasledili nobenega sezonskega vpliva (Slika 4.2.1.4), ki bi bil povezan s temperaturo vode, koncentracijo 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 tudi višinsko spremenljivost korozije (Slika 4.2.1.1). V skladu s pričakovanji je bila največja intenziteta zabeležena v spodnjem delu jamskega rova, sledil pa je izjemno hiter upad korozije navzgor (Slika 4.2.2.1). To pomeni, da je voda korozivna tudi ob nizkem, najbolj efektivno korozivna pa ob srednjem vodostaju. Največjo agresivnost seveda doseže voda ob najvišjem vodostaju, vendar so ti tako redki, da je efektivna korozija v višjih delih jamskega rova precej manjša, jamski rov pa se tam najmanj spreminja. Velik vertikalni upad korozije in dokaj nizka variabilnost vodostaja je izjemno ugodna za razvoj stenskih zajed, v kolikor je dno zaščiteno s talnim materialom. V tem primeru se rov širi bočno v dveh smereh, poglabljanje pa le v eni, pa še tod lahko stalni dotok talnega materiala ščiti dno jamskega rova. V kolikor ga ne, sledimo bodisi epifreatično širjenje in poglabljanje osnovno freatičnih rovov bodisi vrezovanje vadoznega meandra. Le-ta lahko ohranja širino le v ravnotežni 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 z stenami tvori topi kot, to je kot večji od 90°. 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 4.2.2.3).

Meritve korozije vzdolž podzemnega toka med ponorom in odtočnim sifonom (Slika 4.2.5) so pokazalo dve coni raztapljanja. V prvih 250 m sledimo izredno hiter eksponenten upad korozije (za 54 %), nato pa se upadanje korozije močno zaustavi in upada linearno. V prvem delu je namreč hitrost raztapljanja povezana z debelino difuzijske plasti na površini kamnine, v drugi coni pa s hitrostjo reakcije na površini kamnine. Ker je debelina difuzijske plasti odvisna od hitrosti toka, se v prvem delu pojavljajo tudi razlike med območji hitrejšega in počasnejšega vodnega toka. Poleg tega na korozijo vplivajo še drugi dejavniki (npr. dotoki avtigene vode, razpad organskih snovi, sedimentacija ilovice), zato upad korozije od ponora do Končnega sifona ni zvezen. Na intenziteto korozije na koncu jame vpliva hitrost vodnega toka – ob višjem vodostaju je hitrost pretoka hitrejša, korozija pa dolvodno tudi počasneje upada. V splošnem sledimo 790 m od ponora še vedno okoli 50 % korozije značilne za ponor.

Ponor Lekinke leži približno 1 m nižje od ponora Pivke v Postojnsko jamo. Hitro poglabljanje Lekinke in praktično nično Pivke bo sčasoma v porečju Črnega potoka ustvarilo dovolj močan gradient, da ga bodo vse pogosteje izkoristile vode Nanoščice, ki se že sedaj ob zelo visokih vodah prelivajo preko razvodnice. Meritve korozije ob takih situacijah kažejo, da Nanoščica zavre korozijo 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 korozijskem preoblikovanju. Predvsem lahko pričakujemo 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.

Škocjanske jame

Škocjanske jame spadajo na UNSECO seznam svetovne dediščine zaradi zgodovine odkrivanja podzemnega toka Reke ter nadpovprečno bogato razvitega kontaktnega krasa. Podzemni tok Reke poteka večinoma v obliki podzemnega vintgarja, povprečno globokega 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 korazija razmeroma močan proces (od -0,16 do -0.04 mm na leto), medtem ko je korozija precej šibkejša (okoli -0,01 mm na leto, kar je v območju napake merjenja). Korazija je povezana z okoli 350 km_2 velikim porečjem, katerega 60-75 % (KRANJC, 1986, 112; HABIČ ET AL., 1989, 10; KRANJC & MIHEVC, 1988 after 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 korozije. Z natančnejšimi meritvami smo hoteli ugotoviti, kakšna je odvisnost korozije od pretoka Reke, višinsko ter dolžinsko spremenljivost korozije.

Rezultati z merilnih mest S-1 in S-2 (Slika 4.3.1.1) kažejo, da ob srednjem in nizkem vodostaju prevlada odlaganje sige, medtem ko meritve korozije ob visokem vodostaju ovira korazija. Le-ta je bila odsotna na merilnih mestih pri Martelovem jezeru. Rezultati tam kažejo, da v spodnjem delu struge (1 m) prevladuje odlaganje sige (0,0005 mm na leto), ki se očitno odlaga ob srednjem in nizkem vodostaju, visoke vode pa je s korozijo ne uspejo povsem odstraniti. To potrjujejo tudi dokaj majhna največja zabeležena intenziteta korozije, ki znaša okoli -0,0004 mm na leto približno 6 m nad dnom podzemne struge (Slika 4.3.2.3). Spodaj je celokupna korozija manjša zaradi odlaganje sige ob srednjem-visokem vodostaju, navzgor pa zaradi krajšega časa izpostavitve ob poplavi. Tudi pretok nad 200 m^3/s decembra 2008 se ni odrazil v večji intenziteti korozije. Sprememba iz odlaganja sige v korozijo se zgodi ob pretoku Reke okoli 20 m^3/s. Ker začne Reka ob nekoliko višjem pretoku že retrogradno poplavljati, je »okno« za korozijske oblike hitrega toka (npr. fasete) izredno ozko. To se odraža tudi v morfologiji, saj se fasete nad 2 m nad dnom struge ne pojavljajo več, odsotne pa so tudi 1,5 m nad strugo (Slika 4.3.2.4). V tem delu namreč prevladuje odlaganje sige. ki jo v najnižjih delih struge lahko opazujemo v debelini okoli 6 mm. Potemtakem bi lahko nastala v holocenu.

Dolžinske meritve intenzitete korozije od prestopa Reke iz silikatnih na karbonatne kamnine pa vse do končnega sifona (Ledeni dihnik; Slika 4.3.1.1) kažejo, da je korozija odstotna že ob prestopu na karbonatne kamnine (Slika 4.3.3.1). To potrjuje ugotovitve Gamsa (1962, 278) o precejšnji karbonatni trdoti Reke, s čemer je zaradi površinskega toka Reke manjša tudi možnost korozije. Razmere se vzdolž površinskega in podzemnega toka ne spreminjajo bistveno – neto odlaganje sige znaša med 0,0006 do 0,0019 mm na leto. Visoko celokupno trdoto Reke lahko pripišemo številnim desnim kraškim pritokom Reke, ki odvajajo razpršeno infiltrirano vodo z območja Snežnika in Zgornje Pivke. Levi pritoki s fliša kljub nizki trdoti začetne visoke ne uspejo znižati do te mere, da bi se voda v Škocjanskih jamah obnašala korozivno.

Jamski sistem Postojnska jama-Planinska jama

Jamski sistem Postojnska jama-Planinska jama je hidrološko in geomorfološko izjemno pomemben splet rovov, saj v višinski razliki ~56 m povezuje Pivško kotlino s Planinskim poljem. Skupaj tvori kar 27.226 m rovov, od katerih je vodnih več kot 10 km. 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 4.4.1). Rezultati kažejo, da so v obdobju september 2007-marec 2009 apnenčaste ploščice pridobile na teži. Čeprav verjetno največji delež prirastka teže odpade na odlaganje organskih snovi iz deloma onesnažene vode, rezultati kažejo na zanemarljivo intenziteto korozije. Na spodnjih apnenčastih ploščicah smo vseskozi zabeležili odlaganje materiala (okoli 0,0041 mm na leto), medtem ko smo korozijo na višjih ploščicah zabeležili le v enem merilnem obdobju, ko so visokim vodam Nanoščice v zimskem obdobju sledile še višje vode Pivke (Slika 4.4.1.3). Korozivno so se obnašale le vode Nanoščice (maksimalno -0,0007 mm na leto), medtem ko so vode Pivke korozijsko intenziteto skupnih voda zmanjšale. V naslednjih obdobjih se je tudi na korodiranih ploščicah odložilo toliko materiala, da je skupni proces prevagal na stran odlaganja materiala (Slika 4.4.1.2). Korozivno se niso obnašale niti izredno visoke vode, ki so 12. decembra 1008 dvignile nivo Pivke v Velikem domu za kar 8 m (Slika 4.4.1.4).

V dolžinskem nizu merilnih mest med ponorom v Postojnsko jamo in izvirom v Planinsko jamo smo vseskozi beležili odlaganje materiala iz vode. Najmanjše vrednosti smo zabeležili v Pivki jami, medtem ko se odlaganje dolvodno in gorvodno povečuje (Slika 4.4.2.2). Razlike med merilnimi mesti so kljub temu majhne, še največje se pojavljajo v vhodnem delu Postojnske jame najverjetneje zaradi največjega upadanja odlaganja organskih snovi iz vode dolvodno. Pritoki bistveno ne vplivajo na intenziteto prevladujočega procesa vzdolž Pivke, tudi Rak v Planinski jami ne, saj tudi pri njem ne opažamo prevladujoče korozije. Na nekaterih merilnih mestih smo zabeležili korazijo, kar kaže na prenos talnega transporta vzdolž podzemeljske Pivke. Čeprav bi se lahko odlaganje odrazilo v sigovi plasti, tega nismo nikjer opazili. Je pa tudi res, da nekatere tipične korozijske oblike (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 Pivka v preteklosti bila korozivna, ni pa korozivnosti zaznati danes – tudi v najvišjih rovih, ki jih je občasno zalije zelo visoka voda, ne.

Tkalca jama

Tkalca jama prevaja del voda s Cerkniškega jezera, del voda pa izhaja tudi iz območja Javornikov. Obe povezavi sta bili dokazani s sledenjem (ŠERKO, 1946, 126; GAMS, 1966a; GAMS, 1970; KOGOVŠEK, 1999). V Tkalci jami torej sledimo vode, ki izvirajo iz pretežno koncentriranega in deloma razpršeno autogenega dotoka. Dolvodno odtekajo vode iz Tkalce jame proti izvirom Malni ter Rakovem rokavu Planinske jame. Del slednjega toka je ob zelo nizkem vodostaju dostopen brez potapljaške opreme, glavni del Tkalce jame pa se v obliki vodoravnega preko 1.500 m dolgega rova nahaja za sifonom J. Petkovška (1. sifon). Prevetrenost rovov do sifona J. Petkovška je majhna, kar se pozna turi pri visokih koncentracijah CO_2 v jamskem zraku (do 4.230 ppm).
Meritve korozije smo izvajali med novembrom 2006 in septembrom 2008 na štirih mestih nekaj metrov od sifona J. Petkovška (Slika 4.5.1.1). Dve merilni mesti sta bili izpostavljeni hitremu vodnemu toku (T-1 in T-2), ostali dve (T-3, T-4) pa počasnemu. Rezultati kažejo, da so med vsemi štirimi merilnimi mesti razlike statistično nepomembne (Slika 4.5.1.2). Vsa merilna mesta kažejo odlaganje (najverjetneje sige) s hitrostjo 0,0011 mm na leto v prvem merilnem obdobju ter 0,0006 mm na leto v drugem merilnem obdobju. Slednje je bilo glede na najvišji pretok izjemno, saj se je voda v sifonu dvignila kar za 22 m, visok vodostaj pa je trajal nekaj tednov. Korozija v tem obdobju v obdobno poplavljenih rovih sicer ni izključena, saj so bila merilna mesta izpostavljena tudi nizkemu in srednjemu vodostaju. Kljub vsemu pa rezultati kažejo, da v stalno poplavljenih delih rovov odlaganje (sige) prevladuje nad korozijo. Znižanje SEP in naraščanje pH smo ugotovili tudi vzdolž površinskega toka Raka skozi Rakov Škocjan (Slika 4.5.1.3), kar kaže na izhajanje CO_2 iz vode ter na skromno odlaganje sige. Visoka koncentracija CO_2 v Tkalci jami torej bistveno ne vpliva na prevladujoč proces vzdolž toka Raka – skromno odlaganje sige.

Temu dejstvu ne ustreza pojav faset pri merilnih mestih T-1 in T-2 (Slika 4.5.1.4), saj so le-te morale nastati v obdobju srednjega pretoka s korozivno vodo. Ker je ta v sedanjosti odstotna sklepamo, da je prišlo od nastanka faset do danes do pomembnih sprememb fizikalno-kemičnih lastnosti vode oz. do povišanja SI_{Ca}. V tem času so se robovi faset tudi zgladili, kar tudi kaže na njihovo stagnacijo v rasti (Slika 4.5.1.5)

Izviri Malni

Izviri, ki se pojavljajo v (zatrepni) dolini Malnov, so zanimivi zaradi mešanja koncentriranega autogenega dotoka voda s Cerkniškega polja ter razpršenega autogenega dotoka voda iz območja Javornikov (KOGOVŠEK, 2004). Pretežno kraško zaledje Malnov je izredno kompleksno, saj se ob visokem vodostaju razteza kar na 800 km^2 (HABIČ ET AL., 1987, 5). Zaradi izredno stabilnega pridušenega pretoka ter izdatnosti je del voda v Malnih zajet za vodooskrbo Postojne z okolico (RAVBAR, 2007, 34).

Tekom 8-mesečnih meritev smo merjenje intenzitete korozije izvajali na prostem, pri čemer je znatni delež korozije (-0,0149 mm na leto) odpadel na biokorozijo. Zato smo v nadaljevanju meritve opravljali v temnem rezervoarju zajetja. Rezultati kažejo, da je praktično vsa korozija na površju dejansko odpadla na biokorozijo, saj je prevladujoč proces v stalno zalitih rovih celo odlaganje sige (0,0007 mm na leto). V mesečno poplavljenih rovih ni prevladujoč noben proces, medtem ko šele v najvišjih delih obdobno poplavljenih rovov korozija prevlada nad odlaganjem sige (Slika 4.6.1.2). Upadanje odlaganja sige z višino so pokazale prav vse meritve v štirih (oz. treh) merilnih obdobjih (Slika 4.6.1.1). Največja zabeležena korozija je kljub majhna (0,0003 mm na leto).

Rezultati kažejo, da bodisi cerkniške bodisi javorniške vode kakor tudi mešanje obeh voda ne spremeni povprečne intenzitete odlaganja sige zabeležene v Tkalci jami (0,0006 mm na leto). Zanimivo je, da je tovrstna intenziteta odlaganja sige značilna tako za Malne, kakor tudi osrednji del Postojnske in Planinske jame.

Jelovička jama

V Jelovički jami sledimo stalni tok potoka Kotnica, ki najverjetneje izhaja iz alohtonega napajanja s strani Reškega potoka ter razpršenega napajanja vodonosnika s kraškega ravnika med Kolpo, Kočevsko Reko in Kočevjem. Manjši delež vode priteka s strani Mozlja (KOGOVŠEK & PETRIČ, 2007). Kotnica se kot pomembnejši kraški izvir na levem bregu Kolpe po nekaj 100 metrih izliva v mejno reko med Slovenijo in Hrvaško. Ob srednjem vodostaju je pretok okoli 2 m^3/s, ob visokem nekaj m^3/s, ob nizkem pa okoli 0,29 m^3/s (NOVAK, 1969, 33). Zaradi površinskega zaledja na silikatnih kamninah Kotnica prenaša droben kremenčev pesek, melj in glino.

Meritve tekom 8-mesečnega obdobja so pokazale na dokaj visoko izgubo teže (0,0146 mm na leto), vendar je domnevno velik delež izgube teže odpadel na korazijo. To so potrdile tudi nadaljnje meritve med decembrom 2006 in marcem 2009 na treh mestih v jami in enem zunaj nje (Slika 4.7.1.2). V jami je eno merilno mesto kazalo na korozijo (-0,0012 mm na leto), drugo na odlaganje sige (0,0003 mm na leto), tretje pa na nobenega izmed prevladujočih procesov (0,0000 mm na leto). Razlike med posameznimi merilnimi obdobji so precej velike (Slika 4.7.1.5), še najmanjše so značilne za hiter vodni tok na merilnem mestu J-3 (Slika 4.7.1.1), kjer je prevladujoč proces odlaganje sige. Zaradi razmeroma kratkega dostopnega dela vodnega toka so dolžinske meritve SEP in pH pokazale majhne spremembe. Kljub temu vedno opazovani rastoč pH kaže, da iz vode v jami zaradi močnega hidravličnega gradienta izhaja CO_2, še bolj pa je ta pojav značilen za dolvodni površinski tok Kotnice (Slika 4.7.1.6 in Tabela 4.7.1.1).

Morfologija jame kaže, da se sedanji hiter tok vode ujema s pojavom faset, v sedanji poplavni coni pa se fasete pričakovano ne pojavljajo več. To kaže na uravnoteženost hidrodinamskih pogojev v jami z morfologijo. Precej bolj si nasprotuje neaktivnost voda s pojavom faset. Slednje so na več mestih obrušene, kar kaže na večjo korazijo kor korozijo. Korazija je odsotna na pritočnem delu fasete, saj se zaradi večje gibalne količine delci v suspenzu težje ujamejo v vrtinec posamezne fasete. Na teh mestih je običajno še ohranjena črna (manganova) prevleka, ki se je razvila po nastanku faset. Manganova prevleka, korazijska obrušenost faset in odsotna oz. izjemno majhna korozija kažejo na fosilni nastanek faset in njihov sedanji razkroj s strani korazije.

6.5 Sklep s predlogi nadaljnjih raziskav

Metodologija

Meritve kraških procesov zahtevajo uporabo posebnih metod merjenja, med katerimi velja izpostaviti predvsem naslednje: mikrometrske meritve, hidrokemična metoda, merjenje morfoloških rezultatov korozije v znanem časovnem obdobju in uporaba apnenčastih ploščic. Intenziteta kraških procesov je običajno izredno nizka, zato je glavna prednost uporabe apnenčastih ploščic v izjemni preciznosti (do ±0,00005 mm) in točnosti metode (v povprečju ±0,0002 mm, največje odstopanje ±0,0004 mm). Ne glede na preciznost in natančnost, uporabo apnenčastih ploščic za meritve korozije 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 pri hitrosti procesov vlogo zlasti takrat, ko je hitrost kraških procesov nizka. S pogosto menjavo apnenčastih ploščic jim zaostrujemo življenjske pogoje, ki so sicer v jamah izredno stabilni. Pri apnenčastih ploščicah, ki so pritrjene z železnim vijakom, lahko pričakujemo tudi znaten vpliv korozije rje, zato v izogib temu problemu svetujemo uporabo nerjavečega jekla, plastike (in medenine).

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) kljub temu precej velika (v povprečju z uporabo apnenčastih ploščic beležimo za 25 % manjšo korozijo ali odlaganje sige). 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 zmerne-močne korazije) in dostopnosti do merilnih mest (apnenčaste ploščice so zaradi teže primernejše za transport).

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

Intenziteta korozije oz. odlaganja sige

Na splošno je intenziteta kraških kemijskih procesov nizka, kar ustreza dolgotrajnemu razvoju kraških jam. Vzdolž naših največjih podzemnih vodnih tokov lahko pričakujemo hitrost širjenja nekaj μm na leto. Take hitrosti so značilne tako za jame, ki jih napaja razpršen ali koncentriran dotok kraške vode, celo za jame, ki odvajajo vodo z nepropustnih kamnin (v kolikor je vodozbirno območje sestavljeno iz deloma karbonatnih kamnin), ter za jame, ki jih napaja kombiniran dotok kraške in nekraške vode. Največja intenziteta korozije in njena prostorska različnost 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 korozija lahko močnejša od -0,1 mm na leto, medtem ko se v jamah z odlaganjem sige iz jamskih potokov odloži več kot 0,1 mm na leto sige. Za podzemne vodne tokove, ki povezujejo kraška polja, je poleg majhne intenzitete kraških procesov značilno majhno spreminjanje procesov vzdolž podzemnega toka – najverjetneje zaradi velikega pretoka, ki ne omogoča intenzivnega kontakta s povečano koncentracijo CO_2, značilno za jamski zrak. Taki podzemni vodni tokovi so običajno (pre)nasičeni že na ponorih, zato je zanje značilna celo majhna intenziteta odlaganja sige (0,0006 mm na leto). Izredno majhna intenziteta korozije je značilna celo za visoke vode. Zato ni presenetljivo, da so nekateri raziskovalci dvomili v koroziven nastanek jam (npr. Melik), nekateri so to celo dokazali (npr. Oertly). Presenetljivo je, da v korozijsko sposobnost ni dvomil Gams, čeprav je velikokrat ni mogel dokazati ali pa je bila izredno šibka. Zato v njegovih člankih sledimo tendenco od trdne prepričanosti v korozijo vzdolž jamskih rek in potokov v 60-ih letih do postopnega nagibanja k neaktivnosti jamskih rek v 90-ih letih 20. stoletja. Majhna intenziteta korozije 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. Zgodi se celo, da prezračevanje v epifreatični coni zmanjšuje koncentracijo CO_2 v jamskem zraku, s tem pa povečuje odlaganje sige celo iz jamskih potokov/rek.

Intenziteta korozije je na izvirih, vzdolž površinskih kraških tokov in ponorov lahko precej višja od tiste, ki je značilna za jamske rove. Ta do sedaj nikoli kvantificiran pojav je biokorozija, ki lahko znaša tudi -0,15 mm na leto. S tem daleč presega intenziteto korozije v podzemlju in je potemtakem odvisna od stopnje osvetljenosti vodnega toka. V kolikor je njena intenziteta značilna za daljše časovno obdobje od holocena, lahko biokorozija, ki je običajno za vsaj enkrat višja od kemične denudacije površja, pripelje do ustvarjanja nekaterih sotesk ali celo kraških dolin. To je potrjeno tudi s strani (današnje) odsotnosti abrazivnega materiala v soteskasti strugi Obrha na Loškem polju, zgornjem delu doline Krke in Kolpe, z lokacijo skrajnega zgornjega toka Unice, skledasto izoblikovanimi kraškimi izviri ipd. V bodoče bi bilo te domneve nujno podpreti z meritvami intenzitete in prostorskih značilnosti biokorozije.

Pri intenziteti kraških procesov je zelo malo je znana tudi vloga podzemskih mikroorganizmov, ki se jo lahko enostavno proučuje z različno intenziteto meritev v jamskih rovih. V kolikor so naša predvidevanja pravilna, je večja biokorozija značilna za nekajletno izpostavitev apnenčastih ploščic v primerjavi z vsoto nekaj tedenskih meritev.

Razmerje med današnjimi procesi, dejavniki in oblikami

Eno izmed največjih presenečenj tekom izdelave tega doktorskega dela je prevladujoče (sicer majhno) odlaganje sige v nekaterih hidrološko pomembnih slovenskih jamah (Postojnski jami, Planinski jami, Škocjanskih jamah, Tkalci jami, Jelovički jami, Križni jami 2 in relativno močno odlaganje sige v Križni jami). To se ne ujema s korozijskim nastankom jam in z nekaterimi značilno korozijskimi oblikami vzdolž podzemnega toka (npr. fasetami). To pomeni, da so korozijske oblike bolj ali manj fosilne, saj jih današnji vodni tok ne oblikuje več – marsikje se celo zelo visoke vode opazovane v obdobju 2005-2009 niso obnašale korozivno. Vsesplošno prevladujoč proces odlaganja sige v epifreatični coni in debelina sigovih prevlek v Križni jami in Škocjanskih jamah kaže na pomembne spremembe v intenziteti kraških procesov in njihovi prevladujoči smeri (korozija-odlaganje sige) na prehodu pleistocena v holocen. V hladnih obdobjih pleistocena (npr. v MIS 2, MIS 4, MIS 5a-d) lahko tako pričakujemo manjše (ali celo odsotnost) odlaganje sige ter večjo intenziteto korozije. 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 korozije. 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, saj je koncentracija CO_2 v vodi manjša. 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. V kolikor imamo prav, so višje vrednosti korozije značilne za glaciale, manjše (oz. odlaganje sige) pa za integlaciale. To domnevo bi bilo lahko testirati v današnjih subpolarnih razmerah. Kljub vsemu je potrebno opozoriti, da nižanje letne temperature ne pripelje vedno do povišane korozije – na ponorih visoko korozivne alogene vode lahko pričakujemo celo manjšo intenziteto korozije.

Presenetljivo je, da v jamskem sistemu Križna jama-Križna jama 2, ki se napaja s preniklo vodo, odločilne vloge pri intenziteti odlaganja sige in korozije ne odigra nihanje vodostaja ali sezonske spremembe v produkciji CO_2 v prsti, saj je zadrževalni čas vode v epikrasu in vadozni coni velik in omogoča popolno nasičenost vode glede na kalcij. Ključno vlogo pri smeri in intenziteti kraških procesov ima prezračevanje jame, ki v zimskem in spomladanskem času niža koncentracijo CO_2 v jamskem zraku (s tem povzroča prenasičenje v vodi 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 izredno nizke korozije. Posledično lahko v jamskem sistemu Križna jama-Križna jama 2 opazujemo sezonskost v kraških procesih. Zanimivo bi bilo preveriti domnevo, da je tovrsten pojav značilen tudi za druge rove v epifreatični coni z razpršenim autogenim napajanjem.

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APPENDICES

Appendix I: Characteristics and results of measurement points taken under consideration during 8-month-long measurements of corrosion/flowstone deposition rates

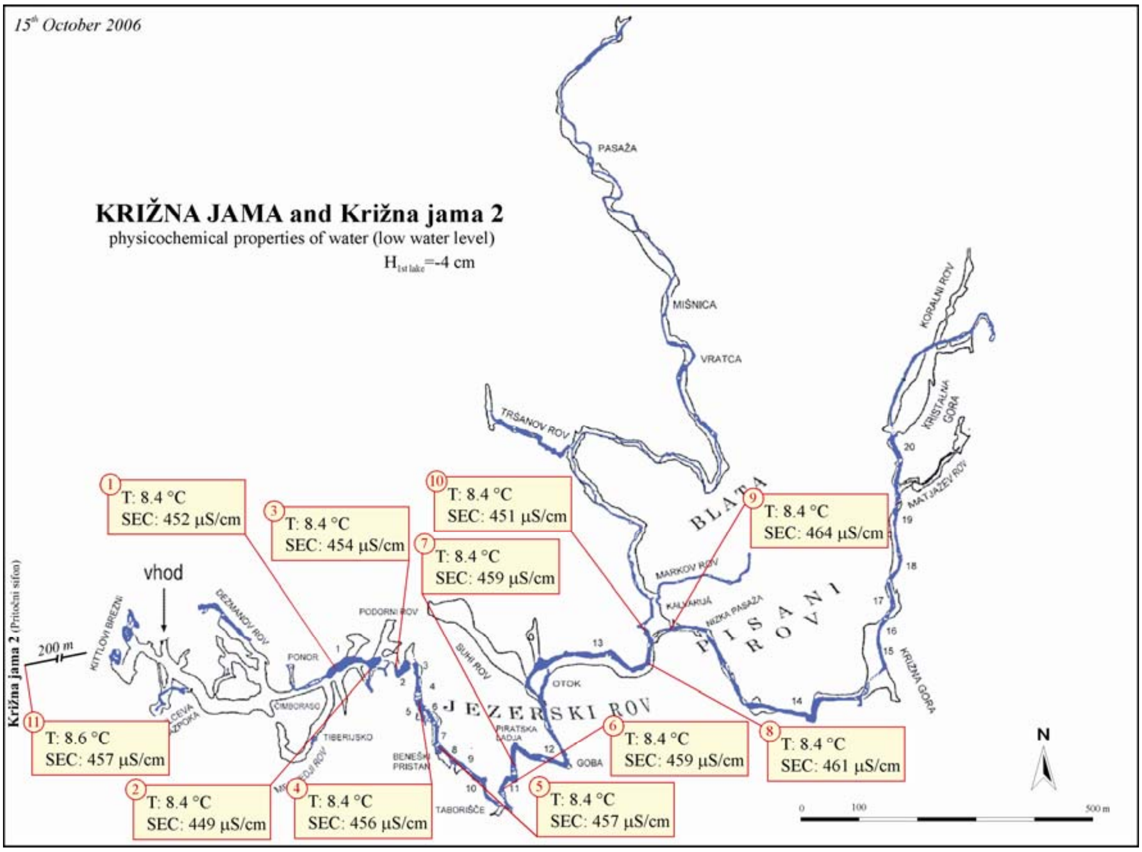
Measurement point	Location								Totala hardnes after Gams (1966, 1962; mg $CaCO_3$/l)
		X	Y	Z	Possition within the local karst massif	Frequancy of flooding (estimation)	Type of recharge	Presence of daylight	
1	Lekinka (entrance part; location 1-lower part of passage)	437650	71910	515	ponor	always	allogenic	dark	/
2	Globočec (spring)	486497	79160	250	spring	always	autogenic (concentrated)+autogenic (diffuse)+allogenic	light	/
3	Radeščica (spring)	503463	66444	180	spring	always	autogenic (diffuse)+allogenic	light	209
4	Tominčev izvir (spring)	497990	72382	175	spring	always	autogenic (concentrated)+autogenic (diffuse)+allogenic	light	209
5	Velika Lebinca (entrance part of a cave)	447800	127200	440	spring	always	autogenic (difuse)	dark	/
6	Ponikve v Odolini (entrance part of a cave)	423400	48900	470	ponor	often	allogenic	dark	104
7	Bistra (Galetovi izviri; spring)	448772	89132	295	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	212
8	Kolpa (few m upstream from confluence with Bilpa)	497363	40846	195	middle	always	autogenic (concentrated)+autogenic (diffuse)+allogenic	light	173
9	Malni (spring)	442545	75591	450	spring	always	autogenic (difuse)+autogenic (concentrated)	light	195
10	Jelovička jama (entrance part of a cave; location 1-lower part of passage)	493275	41800	260	spring	always	allogenic+autogenic (diffuse)	dark	/
11	Predjama (entrance part; location 1-lower part of passage)	432480	74975	462	ponor	always	allogenic	dark	132
12	Planinska jama (entrance part)	441755	75350	453	spring	always	autogenic (difuse)+autogenic (concentrated)	dark	/
13	Poltarica (spring)	482374	82529	275	spring	always	autogenic (diffuse)+autogenic (concentrated)	light	/
14	Temenica (Goriška vas-ponor)	507084	77284	225	ponor	always	autogenic (concentrated)	light	257
15	Bilpa (spring)	497420	40950	200	spring	always	autogenic (concentrated)+autogenic (difuse)	dark	/
16	Lipovka (spring)	483184	81473	265	spring	always	autogenic (diffuse)+autogenic (concentrated)	light	/
17	Postojnska jama (Spodnji Tartar; location 3)	438380	71870	506	middle	always	autogenic (concentrated)+allogenic	dark	/
18	Postojnska jama (Pivka jama; location 4)	438540	73680	540	middle	always	autogenic (concentrated)+allogenic	dark	/
19	Mrzla jama pri Bločicah	457880	68022	610	middle	always	autogenic (concentrated)+autogenic (diffuse)	dark	/
20	Šica (Račna; spring)	476617	83699	325	spring	always	autogenic (diffuse)+autogenic (concentrated)	dark	228
21	Podstenjšek (spring)	440098	51615	520	spring	always	autogenic (diffuse)	light	/
22	Rakov Škocjan (Veliki naravni most)	445030	72590	502	middle	always	autogenic (concentrated)+autogenic (diffuse)	light	198
23	Kozja luknja (location 2)	440145	51710	550	spring	often	autogenic (diffuse)	dark	/
24	Matijeva jama (at the sump; location 1)	443185	60720	547	spring+ponor	always	autogenic (diffuse)	dark	/
25	Matijeva jama (at the sump; location 3-in the ceiling pocket)	443185	60720	547	spring+ponor	always	autogenic (diffuse)	dark	/
26	Bruhalnik za Javornikovo žago (spring; location 1-upper part of passage)	497455	73785	200	spring	rarely	autogenic (concentrated)+autogenic (diffuse)+allogenic	dark	/
27	Kotliči (spring)	445433	72103	502	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	/
28	Bruhalnik za Javornikovo žago (spring; location 2-lower part of passage)	497455	73785	200	spring	often	autogenic (concentrated)+autogenic (diffuse)+allogenic	dark	/
29	Kompoljska jama (entrance part)	479456	72843	425	spring	often	allogenic+autogenic (diffuse)	dark	/
30	Kozja luknja (location 1-the lowest part of passage)	440145	51710	550	spring	always	autogenic (diffuse)	dark	/
31	Matijeva jama (at the sump; location 2)	443185	60720	547	spring+ponor	always	autogenic (diffuse)	dark	/
32	Lekinka (entrance part; location 2-middle part of passage)	437650	71910	515	ponor	often	allogenic	dark	/
33	Prečna/Temenica (spring)	507927	74832	170	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	232
34	Velika Karlovica (entrance part)	447890	70370	548	ponor	often	autogenic (concentrated)	dark	250
35	Škocjanske jame (Swidovo razgledišče; location 1)	420825	58590	233	middle	often	allogenic+autogenic (concentrated)	dark	173
36	Kozja luknja (location 3)	440145	51710	550	spring	often	autogenic (diffuse)	dark	/
37	Šratlova luknja (entrance part)	475640	49800	525	spring	often	autogenic (diffuse)	dark	/
38	Kozja luknja (location 5-near the entrance)	440145	51710	550	spring	rarely	autogenic (diffuse)	dark	/
39	Labodnica (Lindnerjeva dvorana)	409134	60708	329	middle	often	allogenic+autogenic (concentrated)+autogenic (diffuse)	dark	/
40	Škocjanske jame (Swidovo razgledišče; location 2)	420825	58590	233	middle	often	allogenic+autogenic (concentrated)	dark	173
41	Kozja luknja (location 4)	440145	51710	550	spring	often	autogenic (diffuse)	dark	/
42	Viršnica (central part of a cave; location 1-lower part of passage)	477520	84455	349	ponor	always	autogenic (concentrated)	dark	/
43	Lekinka (entrance part; location 3-upper part of passage)	437650	71910	515	ponor	rarely	allogenic	dark	/
44	Predjama (entrance part; location 2-upper part of passage)	432494	74951	455	ponor	rarely	allogenic	dark	132
45	Markov spodmol (entrance part; location 1-at the 1st lake)	430730	65990	555	ponor	often	allogenic	dark	/
46	Krška jama (entrance part)	482619	82890	280	spring	always	autogenic (concentrated)+autogenic (diffuse)	dark	223
47	Temenica (Zijalo/Jama Jezero pod Zijalom; location 2-upper part of passage)	505197	81752	253	spring	rarely	autogenic (concentrated)	dark	271
48	Račiške ponikve (central part)	436640	41450	470	ponor	often	allogenic	dark	155
49	Jelovička jama (entrance part of a cave; location 2-upper part of passage)	493275	41800	260	spring	rarely	allogenic+autogenic (diffuse)	dark	/
50	Podstenska/Finkova jama (entrance part-upper part of passage)	474880	74535	556	ponor	rarely	allogenic	dark	/
51	Viršnica (central part of a cave; location 2-upper part of passage)	477520	84455	349	ponor	often	autogenic (concentrated)	dark	/
52	Postojnska jama (Veliki dom; location 2-upper part of passage)	438490	71330	512	ponor	rarely	autogenic (concentrated)+allogenic	dark	157
53	Mrzla jama pri Ložu	459620	65340	610	spring	often	autogenic (diffuse)	dark	/

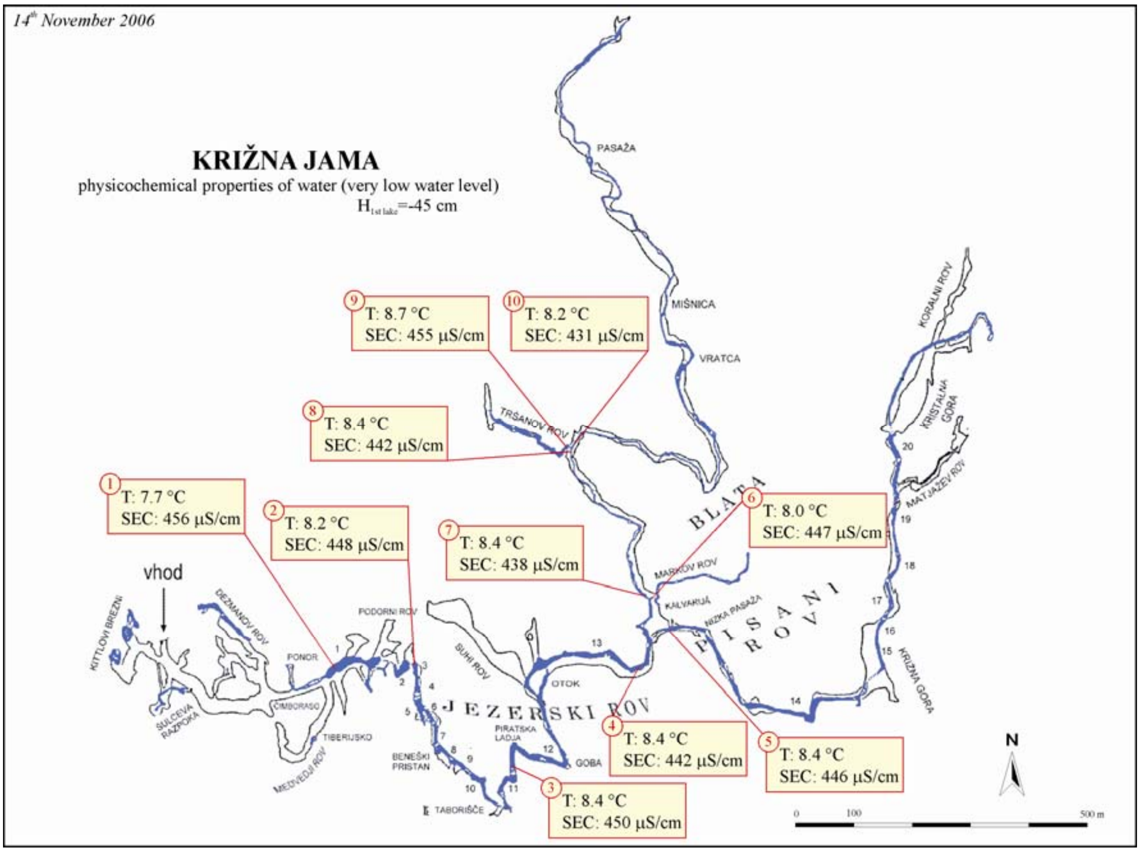
Measurement point	Location								Totala hardnes after Gams (1966, 1962; mg $CaCO_3$/l)
		X	Y	Z	Possition within the local karst massif	Frequancy of flooding (estimation)	Type of recharge	Presence of daylight	
54	Podpeška jama	476005	77275	435	middle	often	allogenic+autogenic (diffuse)	dark	207
55	Želnjske jame (Velika dvorana)	491400	56675	475	ponor	always	allogenic	dark	/
56	Markov spodmol (entrance part; location 2-upstream of the 1st lake)	430730	65990	555	ponor	rarely	allogenic	dark	/
57	Kozja luknja (location 6-in front of the cave)	440145	51710	550	spring	rarely	autogenic (diffuse)	dark	/
58	Golobina (entrance part)	456570	63140	575	ponor	often	autogenic (concentrated)	dark	221
59	Škratovka (entrance part)	443165	76080	452	spring	rarely	autogenic (concentrated)+autogenic (diffuse)	dark	/
60	Matijeva jama (location 3-entrance part of a cave)	443185	60720	547	spring+ponor	rarely	autogenic (diffuse)	dark	/
61	Jama 1 v Kotlu (entrance part)	478035	47335	400	spring	often	autogenic (diffuse)	dark	/
62	Reški/Mokri potok (ponor)	487930	46160	470	ponor	rarely	allogenic+autogenic (concentrated)	dark	/
63	Mali Obrh (spring)	459820	58928	580	spring	often	autogenic (concentrated)+autogenic (diffuse)	light	236
64	Žerovniščica (spring)	439450	92000	640	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	264
65	Izvir pri zajetju za HE Belica (spring)	478023	47141	390	spring	always	autogenic (diffuse)	light	/
66	Podštebrščica (spring)	457244	66904	565	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	245
67	Cemun (spring)	455052	63987	548	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	209
68	Podlomščica (spring)	472965	85680	348	spring	always	autogenic (diffuse)	light	268
69	Veliki Obrh (spring)	462301	61734	580	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	214
70	Križna jama (between 1st lake and Ponor)	458920	66910	600	middle	always	autogenic (diffuse)	dark	/
71	Mala Boka (Jelinčičeva dvorana; location 1-lower part of a passage)	383640	133072	646	middle	often	autogenic (diffuse)	dark	/
72	Mala Boka (Jelinčičeva dvorana; location 2-lower part of a passage)	383640	133072	646	middle	often	autogenic (diffuse)	dark	/
73	Mala Boka (kanjon Akob; location 3-middle part of passage)	383831	132729	604	middle	rarely	autogenic (diffuse)	dark	/
74	Mala Boka (kanjon Akob; location 4-upper part of passage)	383831	132729	604	middle	rarely	autogenic (diffuse)	dark	/
75	Mala Boka (Freatika: location 5-upper part of passage)	383299	133251	706	middle	rarely	autogenic (diffuse)	dark	/
76	Mala Boka (Freatika; location 6-lower part of passage)	383170	133279	716	middle	often	autogenic (diffuse)	dark	/
77	Mošenik (ponor)	488723	44590	500	ponor	always	allogenic	dark	/
78	Postojnska jama (Veliki dom; location 1-lower part of passage)	438490	71330	512	ponor	always	autogenic (concentrated)+allogenic	dark	157
79	Temenica (Zijalo/Jama Jezero pod Zijalom; location 1-lower part of passage)	505197	81752	253	spring	always	autogenic (concentrated)	dark	271
80	Temenica (Rupa 1 na Zemljančevem travniku/Rupa 1 sv. Ane)	504250	83138	260	ponor	always	autogenic (concentrated)	light	278
81	Timava (srednji izvir)	390839	72440	5	spring	always	autogenic (concentrated)+autogenic (diffuse)+allogenic	light	214
82	Turkova jama	456530	68940	570	middle	often	autogenic (diffuse)	dark	/
83	Velik Močilnik (izvir)	445509	90290	300	spring	always	autogenic (concentrated)+autogenic (diffuse)	light	184
84	Veliko Okence (izvir)	445780	89740	292	spring	always	autogenic (concentrated)+autogenic (diffuse)	dark	191
85	Zelške jame (vhodni del)	446220	72060	504	spring	always	autogenic (concentrated)+autogenic (diffuse)	dark	200

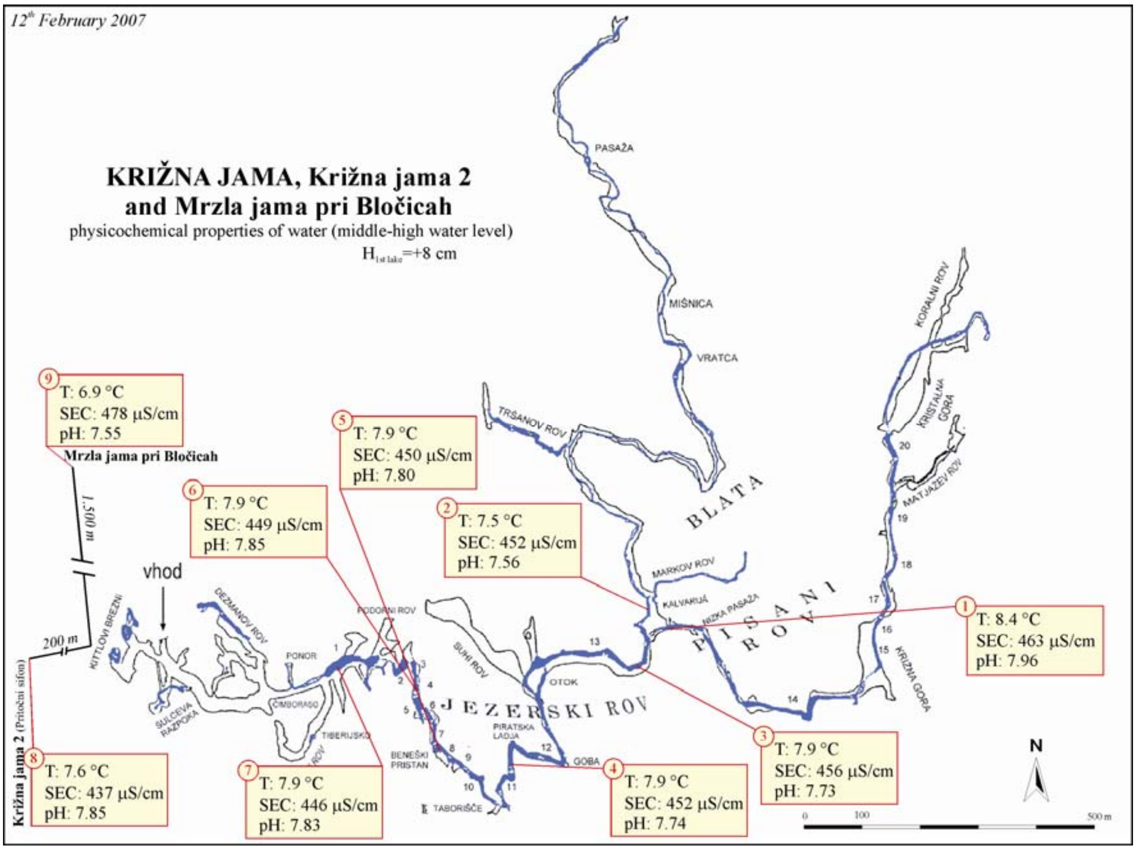
Measurement point	Location	Results						
		Exposure time (days)	Corrosion/deposition rate (g)	Corrosion/deposition rate (mm/a)	Corrasion	Biocorrosion	Sawing traces	Corrosion due to iron oxide
1	Lekinka (entrance part; location 1-lower part of passage)	242	-0,9173	-0,1664	no	no	no	low
2	Globočec (spring)	256	-0,5018	-0,0860	no	yes	yes (only at shaded side)	medium
3	Radeščica (spring)	256	-0,4820	-0,0828	no	yes	yes (only at shaded side)	low
4	Tominčev izvir (spring)	256	-0,4528	-0,0788	no	yes	yes (only at shaded side)	low
5	Velika Lebinca (entrance part of a cave)	400	-0,3068	-0,0339	no	no	no	medium
6	Ponikve v Odolini (entrance part of a cave)	247	-0,1436	-0,0247	no	no	no	absent
7	Bistra (Galetovi izviri; spring)	240	-0,1194	-0,0220	no	yes	no	low
8	Kolpa (few m upstream from confluence with Bilpa)	254	-0,0933	-0,0163	yes	yes	yes (only at shaded side)	low
9	Malni (spring)	249	-0,0855	-0,0149	no	yes	yes (only at shaded side)	absent
10	Jelovička jama (entrance part of a cave; location 1-lower part of passage)	254	-0,0874	-0,0146	yes	no	on both sides	medium
11	Predjama (entrance part; location 1-lower part of passage)	242	-0,0750	-0,0138	yes	no	on both sides	medium
12	Planinska jama (entrance part)	249	-0,0369	-0,0067	no	no	on both sides	medium
13	Poltarica (spring)	256	-0,0378	-0,0066	no	no	on both sides	medium
14	Temenica (Goriška vas-ponor)	256	-0,0367	-0,0062	no	yes	no	low
15	Bilpa (spring)	254	-0,0354	-0,0061	no	yes	yes (only at shaded side)	medium
16	Lipovka (spring)	256	-0,0283	-0,0049	no	yes	on both sides	medium
17	Postojnska jama (Spodnji Tartar; location 3)	255	-0,0263	-0,0046	no	no	on both sides	medium
18	Postojnska jama (Pivka jama; location 4)	255	-0,0261	-0,0045	no	no	on both sides	low
19	Mrzla jama pri Bločicah	248	-0,0239	-0,0043	no	no	on both sides	medium
20	Šica (Račna; spring)	253	-0,0229	-0,0040	no	yes	yes (only at shaded side)	low
21	Podstenjšek (spring)	303	-0,0266	-0,0038	no	yes	no	low
22	Rakov Škocjan (Veliki naravni most)	250	-0,0207	-0,0036	no	no	on both sides	low
23	Kozja luknja (location 2)	303	-0,0218	-0,0031	no	no	on both sides	high
24	Matijeva jama (at the sump; location 1)	333	-0,0235	-0,0031	no	no	on both sides	medium
25	Matijeva jama (at the sump; location 3-in the ceiling pocket)	333	-0,0219	-0,0029	no	no	on both sides	low
26	Bruhalnik za Javornikovo žago (spring; location 1-upper part of passage)	256	-0,0167	-0,0028	no	no	on both sides	low
27	Kotliči (spring)	250	-0,0151	-0,0027	no	yes	on both sides	low
28	Bruhalnik za Javornikovo žago (spring; location 2-lower part of passage)	256	-0,0151	-0,0025	no	no	on both sides	medium
29	Kompoljska jama (entrance part)	254	-0,0137	-0,0023	no	no	on both sides	low
30	Kozja luknja (location 1-the lowest part of passage)	303	-0,0147	-0,0021	no	no	on both sides	low
31	Matijeva jama (at the sump; location 2)	333	-0,0147	-0,0020	no	no	on both sides	medium
32	Lekinka (entrance part; location 2-middle part of passage)	242	-0,0102	-0,0019	no	no	on both sides	absent
33	Prečna/Temenica (spring)	256	-0,0096	-0,0017	no	yes	on both sides	low
34	Velika Karlovica (entrance part)	249	-0,0091	-0,0016	no	no	on both sides	low
35	Škocjanske jame (Swidovo razgledišče; location 1)	440	-0,0156	-0,0016	yes	no	on both sides	absent
36	Kozja luknja (location 3)	303	-0,0097	-0,0014	no	no	on both sides	low
37	Šratlova luknja (entrance part)	254	-0,0076	-0,0013	no	no	on both sides	low
38	Kozja luknja (location 5-near the entrance)	303	-0,0082	-0,0012	no	no	on both sides	absent
39	Labodnica (Lindnerjeva dvorana)	176	-0,0042	-0,0010	no	no	on both sides	absent
40	Škocjanske jame (Swidovo razgledišče; location 2)	440	-0,0081	-0,0008	yes	no	on both sides	absent
41	Kozja luknja (location 4)	303	-0,0057	-0,0008	no	no	on both sides	low
42	Viršnica (central part of a cave; location 1-lower part of passage)	254	-0,0044	-0,0008	no	no	on both sides	low
43	Lekinka (entrance part; location 3-upper part of passage)	242	-0,0042	-0,0007	no	no	on both sides	absent
44	Predjama (entrance part; location 2-upper part of passage)	242	-0,0037	-0,0007	no	no	on both sides	absent
45	Markov spodmol (entrance part; location 1-at the 1st lake)	242	-0,0034	-0,0006	no	no	on both sides	absent
46	Krška jama (entrance part)	256	-0,0032	-0,0005	no	no	on both sides	low
47	Temenica (Zijalo/Jama Jezero pod Zijalom; location 2-upper part of passage)	256	-0,0022	-0,0004	no	no	on both sides	low
48	Račiške ponikve (central part)	247	-0,0020	-0,0004	no	no	on both sides	absent
49	Jelovička jama (entrance part of a cave; location 2-upper part of passage)	254	-0,0020	-0,0003	yes	no	on both sides	absent
50	Podstenska/Finkova jama (entrance part-upper part of passage)	254	-0,0018	-0,0003	no	no	on both sides	absent
51	Viršnica (central part of a cave; location 2-upper part of passage)	254	-0,0010	-0,0002	no	no	on both sides	absent
52	Postojnska jama (Veliki dom; location 2-upper part of passage)	255	-0,0004	-0,0001	no	no	on both sides	absent
53	Mrzla jama pri Ložu	248	-0,0003	-0,0001	no	no	on both sides	absent

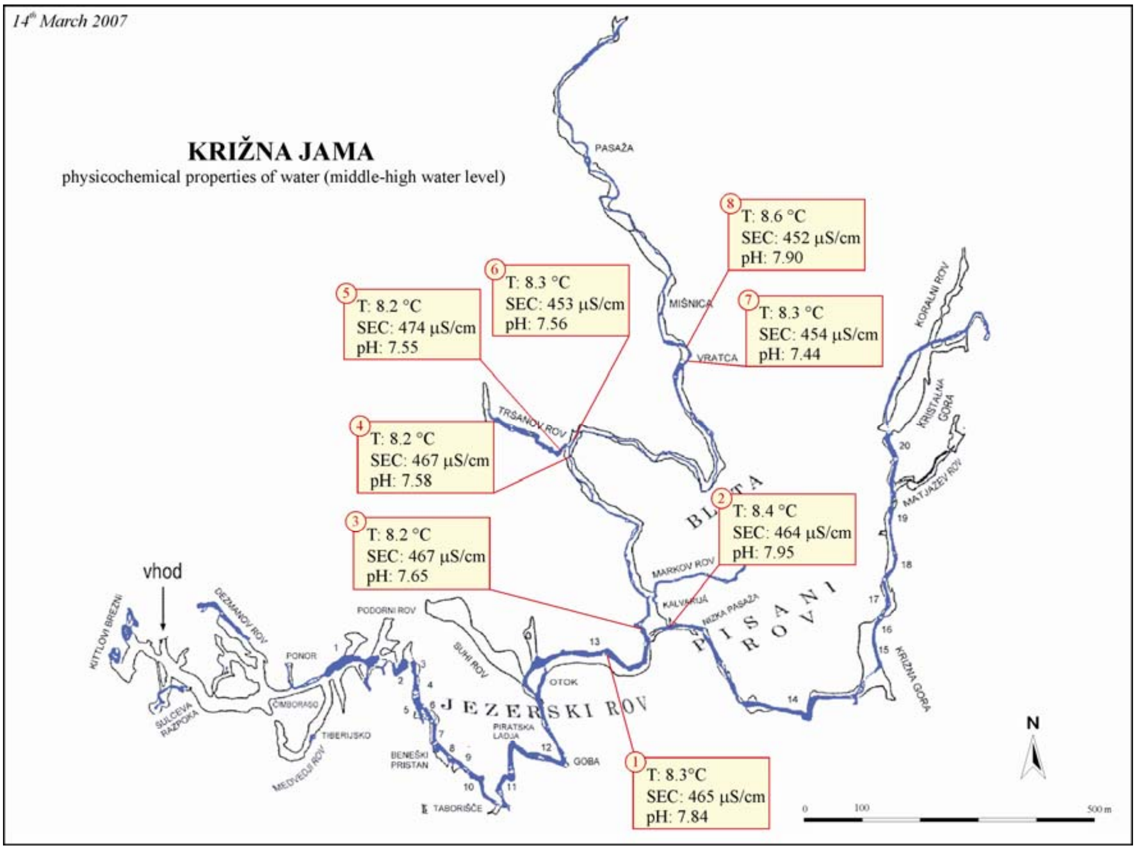
Measurement point		Results						
		Exposure time (days)	Corrosion/deposition rate (g)	Corrosion/deposition rate (mm/a)	Corrasion	Biocorrosion	Sawing traces	Corrosion due to iron oxide
54	Podpeška jama	254	0,0000	0,0000	no	no	on both sides	absent
55	Željske jame (Velika dvorana)	253	0,0003	0,0001	no	no	on both sides	absent
56	Markov spodmol (entrance part; location 2-upstream of the 1st lake)	242	0,0004	0,0001	no	no	on both sides	absent
57	Kozja luknja (location 6-in front of the cave)	285	0,0006	0,0001	no	no	on both sides	absent
58	Golobina (entrance part)	248	0,0006	0,0001	no	no	on both sides	absent
59	Škratovka (entrance part)	249	0,0009	0,0002	no	no	on both sides	absent
60	Matijeva jama (location 3-entrance part of a cave)	299	0,0012	0,0002	no	no	on both sides	absent
61	Jama 1 v Kotlu (entrance part)	254	0,0015	0,0003	no	no	on both sides	absent
62	Reški/Mokri potok (ponor)	248	0,0021	0,0004	no	no	on both sides	absent
63	Mali Obrh (spring)	248	0,0027	0,0005	no	no	on both sides	low
64	Žerovniščica (spring)	242	0,0050	0,0009	no	no	yes (only at shaded side)	low
65	Izvir pri zajetju za HE Belica (spring)	254	0,0059	0,0010	no	no	on both sides	absent
66	Podštebrščica (spring)	228	0,0497	0,0038	no	no	yes (only at shaded side)	low
67	Cemun (spring)	249	0,0337	0,0059	no	no	on both sides	absent
68	Podlomščica (spring)	253	0,0449	0,0078	no	no	on both sides	low
69	Veliki Obrh (spring)	248	0,0768	0,0138	no	no	yes (only at shaded side)	low
70	Križna jama (between 1st lake and Ponor)	253	0,5915	0,1012	no	no	no	absent
71	Mala Boka (Jelinčičeva dvorana; location 1-lower part of a passage)	not accesible	/	/	/	/	/	/
72	Mala Boka (Jelinčičeva dvorana; location 2-lower part of a passage)	not accesible	/	/	/	/	/	/
73	Mala Boka (kanjon Akob; location 3-middle part of passage)	not accesible	/	/	/	/	/	/
74	Mala Boka (kanjon Akob; location 4-upper part of passage)	not accesible	/	/	/	/	/	/
75	Mala Boka (Freatika: location 5-upper part of passage)	not accesible	/	/	/	/	/	/
76	Mala Boka (Freatika; location 6-lower part of passage)	not accesible	/	/	/	/	/	/
77	Mošenik (ponor)	broken	/	/	/	/	/	/
78	Postojnska jama (Veliki dom; location 1-lower part of passage)	broken	/	/	/	/	/	/
79	Temenica (Zijalo/Jama Jezero pod Zijalom; location 1-lower part of passage)	burried	/	/	/	/	/	/
80	Temenica (Rupa 1 na Zemljančevem travniku/Rupa 1 sv. Ane)	washed away	/	/	/	/	/	/
81	Timava (srednji izvir)	stolen	/	/	/	/	/	/
82	Turkova jama	not taken yet	/	/	/	/	/	/
83	Velik Močilnik (izvir)	stolen	/	/	/	/	/	/
84	Veliko Okence (izvir)	washed away	/	/	/	/	/	/
85	Zelške jame (vhodni del)	stolen	/	/	/	/	/	/

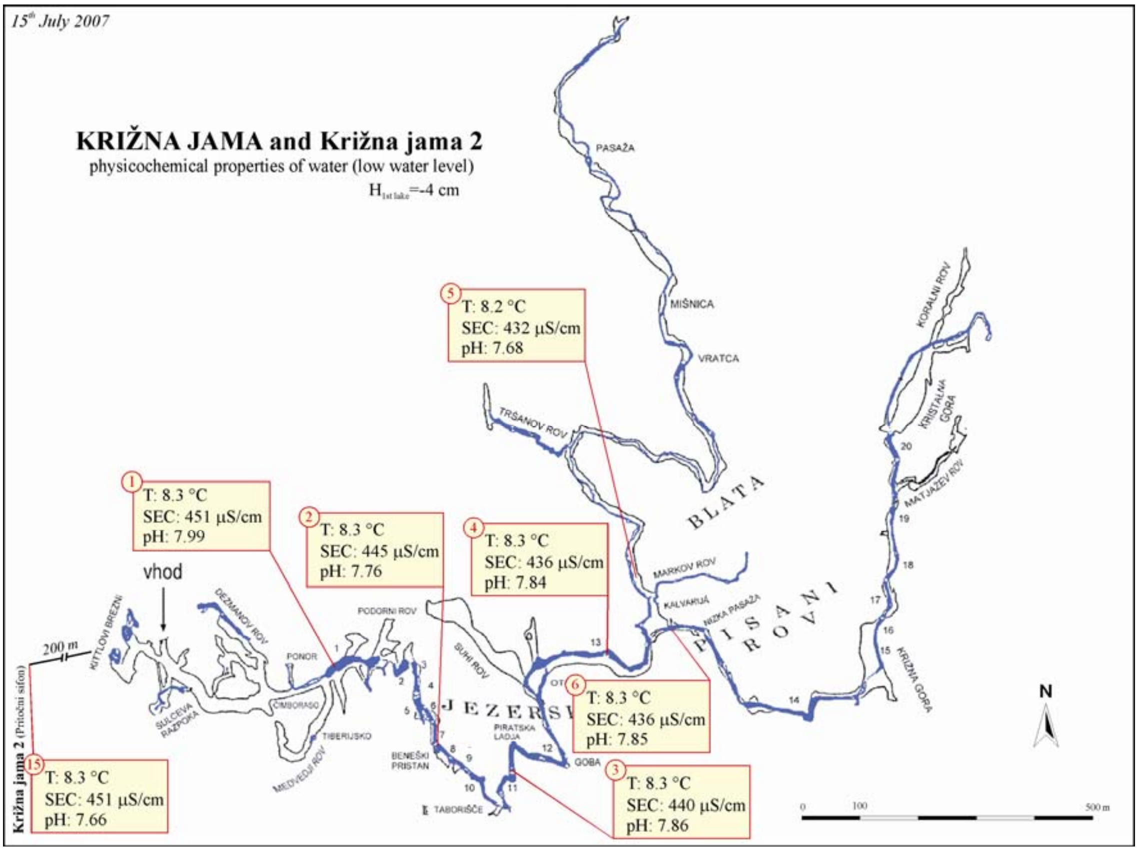
Appendix II: Temperature (T), specific electrical conductivity (SEC) and pH changes in Jezerski rov (Križna jama).



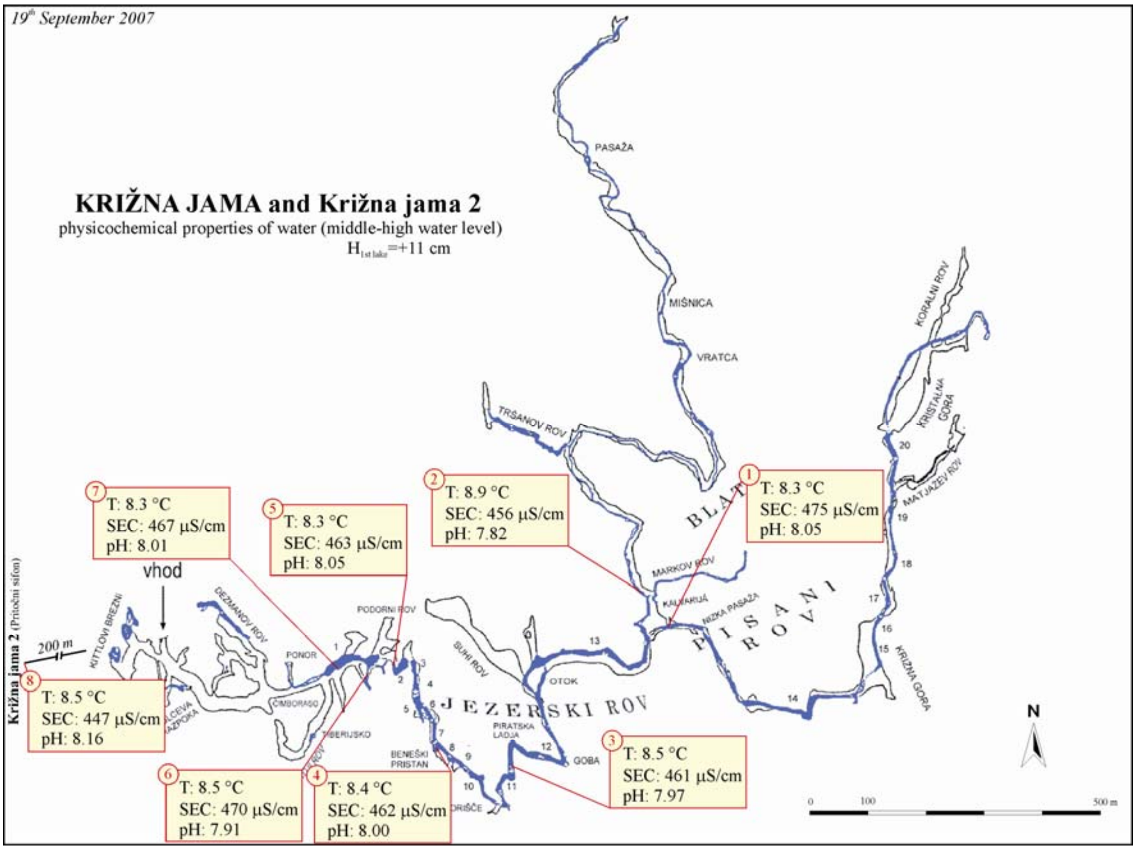



12th February 2007
KRIŽNA JAMA, Križna jama 2
and Mrzla jama pri Bločicah
physicochemical properties of water (middle-high water level)
$H_{1st\ lake}$=+8 cm
9 T: 6.9 °C SEC: 478 µS/cm pH: 7.55
Mrzla jama pri Bločicah
1.500 m
200 m
Križna jama 2 (Prižni sifon)
8 T: 7.6 °C SEC: 437 µS/cm pH: 7.85
6 T: 7.9 °C SEC: 449 µS/cm pH: 7.85
5 T: 7.9 °C SEC: 450 µS/cm pH: 7.80
7 T: 7.9 °C SEC: 446 µS/cm pH: 7.83
2 T: 7.5 °C SEC: 452 µS/cm pH: 7.56
4 T: 7.9 °C SEC: 452 µS/cm pH: 7.74
3 T: 7.9 °C SEC: 456 µS/cm pH: 7.73
1 T: 8.4 °C SEC: 463 µS/cm pH: 7.96
vhod
KITTLOVI BREZNI
DEZMANOV ROV
SULCEVA RAZPOKA
PONOR
CIMBORASO
TIBERIJSKO
PODORNI ROV
SUHI ROV
JEZERSKI ROV
BENEŠKI PRISTAN
TABORIŠČE
PIRATSKA LADJA
GOBA
OTOK
KALVARIJA
NIZKA PASAŽA
MARKOV ROV
PISANI ROV
BLATA
TRŠANOV ROV
PASAŽA
MIŠNICA
VRATCA
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
KRIŽNA GORA
N
0 100 500 m

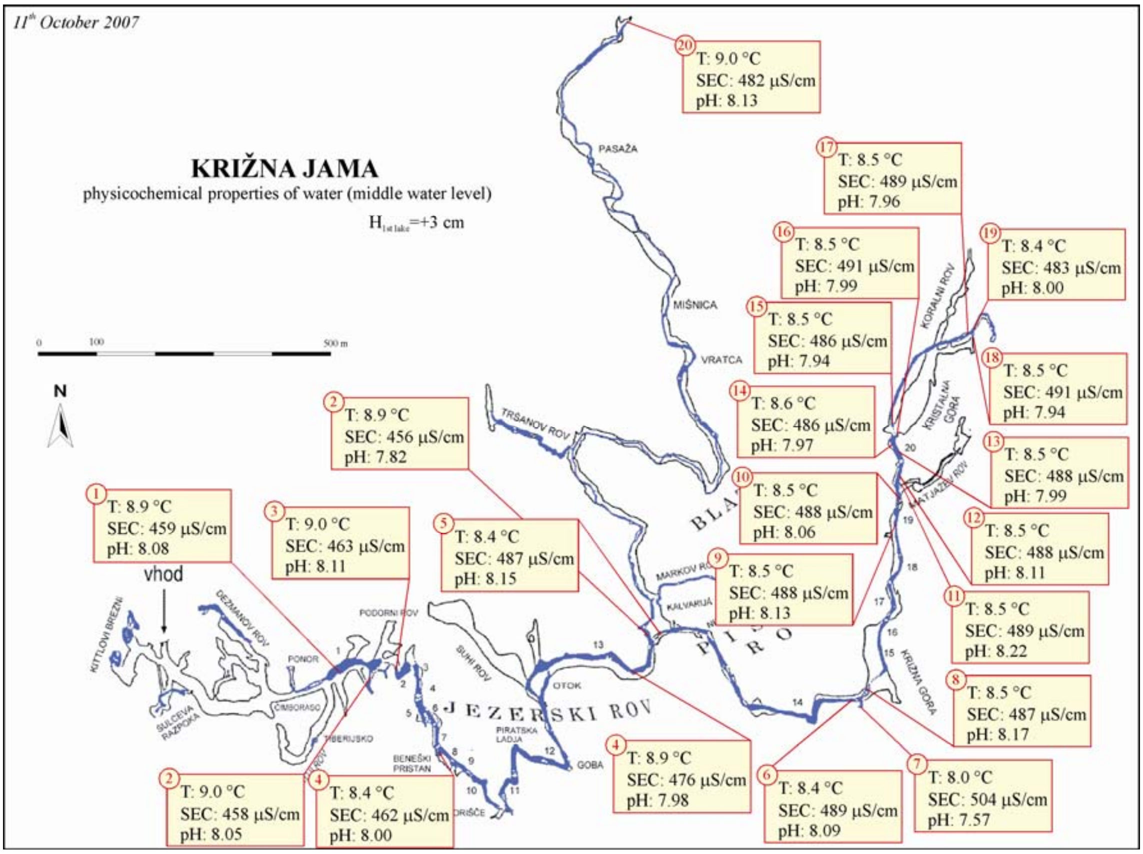

14th March 2007
KRIŽNA JAMA
physicochemical properties of water (middle-high water level)
8 T: 8.6 °C SEC: 452 µS/cm pH: 7.90
6 T: 8.3 °C SEC: 453 µS/cm pH: 7.56
5 T: 8.2 °C SEC: 474 µS/cm pH: 7.55
7 T: 8.3 °C SEC: 454 µS/cm pH: 7.44
4 T: 8.2 °C SEC: 467 µS/cm pH: 7.58
2 T: 8.4 °C SEC: 464 µS/cm pH: 7.95
3 T: 8.2 °C SEC: 467 µS/cm pH: 7.65
1 T: 8.3°C SEC: 465 µS/cm pH: 7.84
vhod
KITTLOVI BREZNI
DEZMANOV ROV
SULCEVA RAZPOKA
PONOR
CIMBORASO
TIBERIJSKO
MEDVEDJI ROV
PODORNI ROV
SUHI ROV
JEZERSKI ROV
BENEŠKI PRISTAN
TABORIŠČE
PIRATSKA LADJA
GOBA
OTOK
KALVARIJA
NIZKA PASAŽA
MARKOV ROV
PISANI ROV
BLATA
TRŠANOV ROV
PASAŽA
MIŠNICA
VRATCA
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
KRIŽNA GORA
N
0 100 500 m

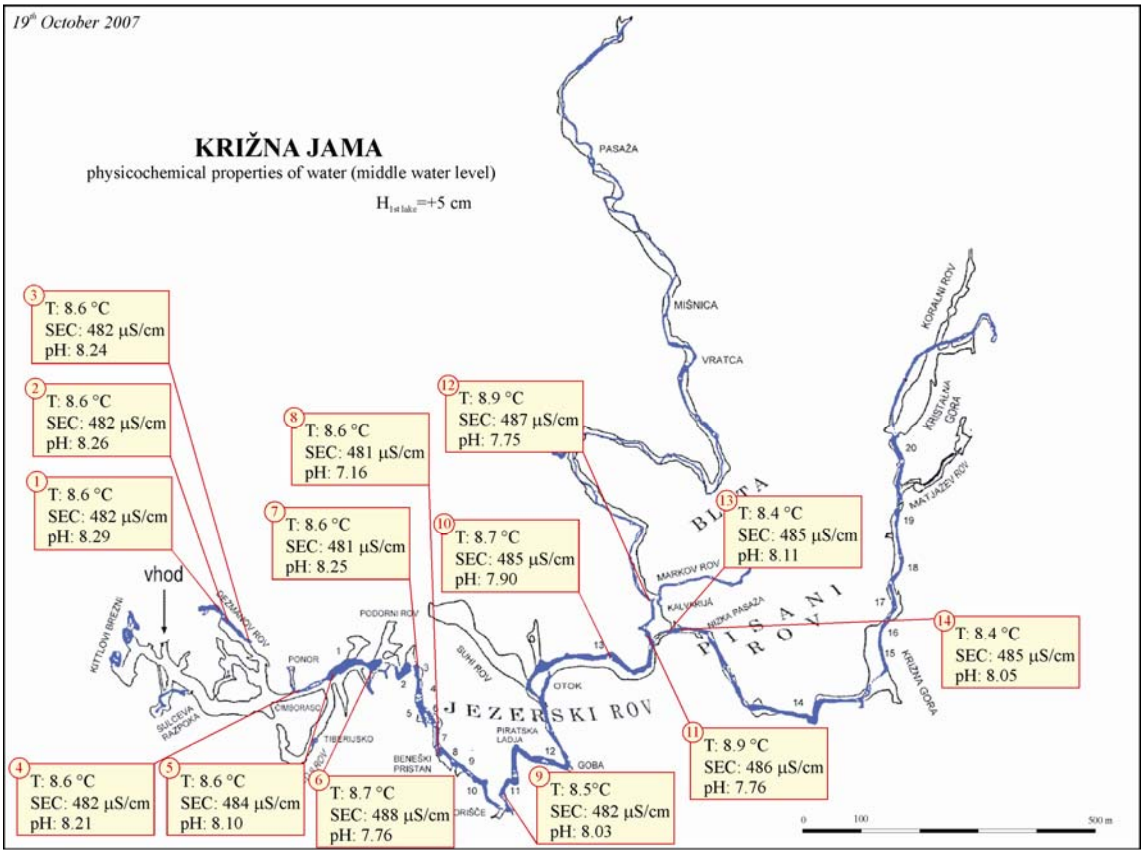


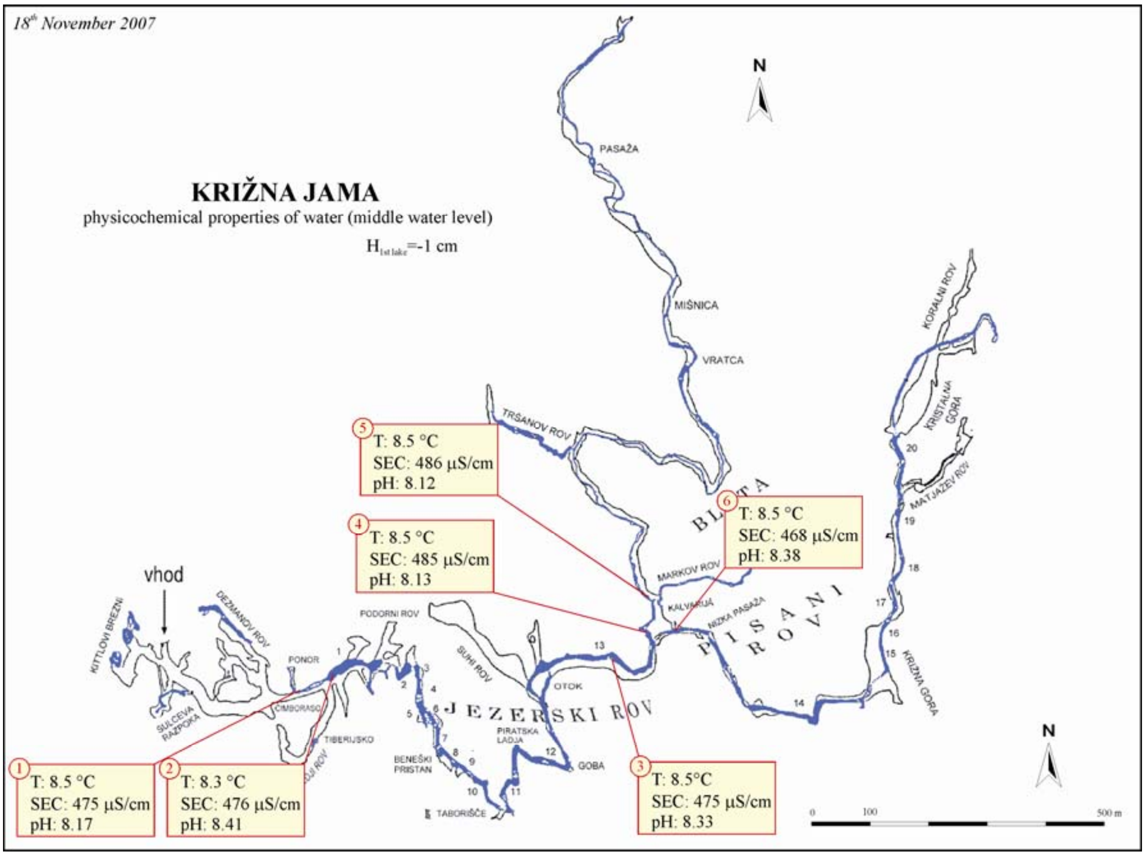
15th July 2007
KRIŽNA JAMA and Križna jama 2
physicochemical properties of water (low water level)
H1st lake=-4 cm
1 T: 8.3 °C SEC: 451 µS/cm pH: 7.99
2 T: 8.3 °C SEC: 445 µS/cm pH: 7.76
3 T: 8.3 °C SEC: 440 µS/cm pH: 7.86
4 T: 8.3 °C SEC: 436 µS/cm pH: 7.84
5 T: 8.2 °C SEC: 432 µS/cm pH: 7.68
6 T: 8.3 °C SEC: 436 µS/cm pH: 7.85
15 T: 8.3 °C SEC: 451 µS/cm pH: 7.66
vhod
Križna jama 2 (Pritočni sifon)
200 m
PASAŽA
MIŠNICA
VRATCA
TRŠANOV ROV
BLATA
MARKOV ROV
KALVARIJA
NIZKA PASAŽA
PISANI ROVI
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
KRIŽNA GORA
PODORNI ROV
SUHI ROV
JEZERSKI ROV
OTOK
PIRATSKA LADJA
GOBA
BENEŠKI PRISTAN
TABORIŠČE
PONOR
CIMBORASO
TIBERIJSKO
MEDVEDJI ROV
SULČEVA RAZPOKA
KITTLOVI BREZNI
DEŽMANOV ROV
N
0 100 500 m

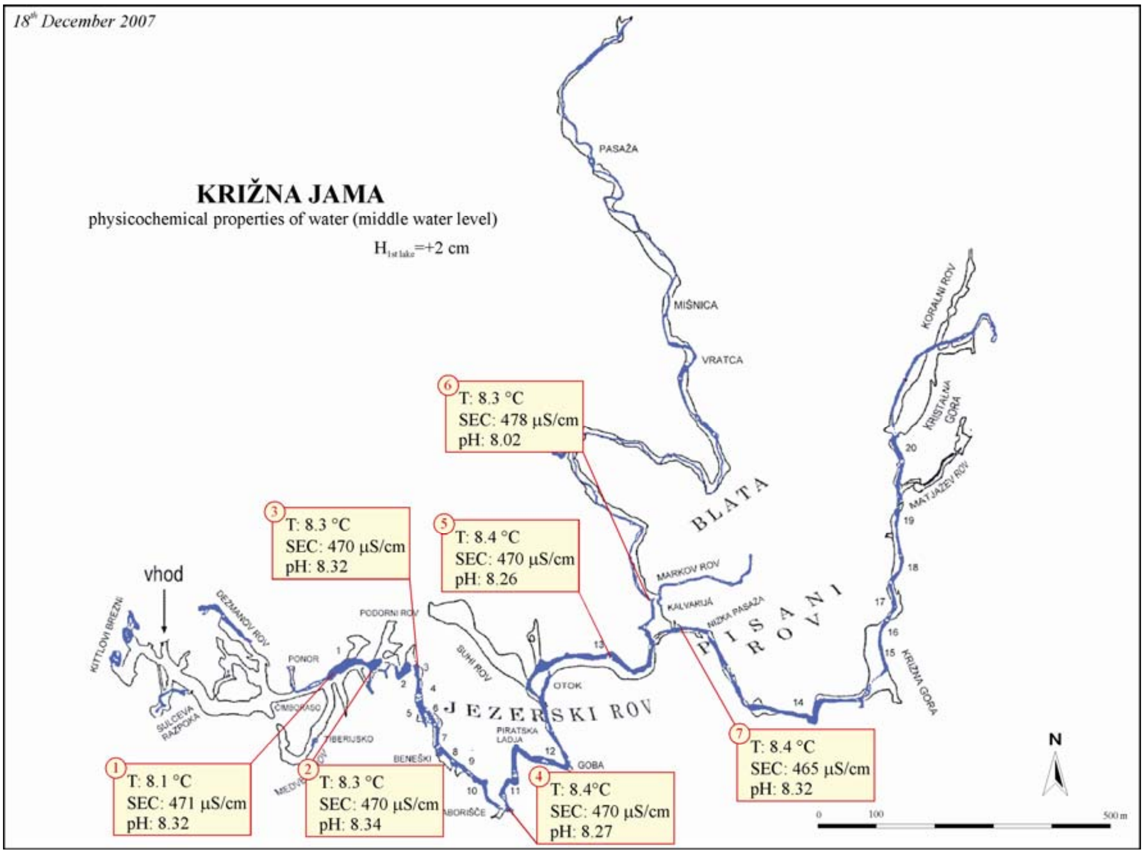


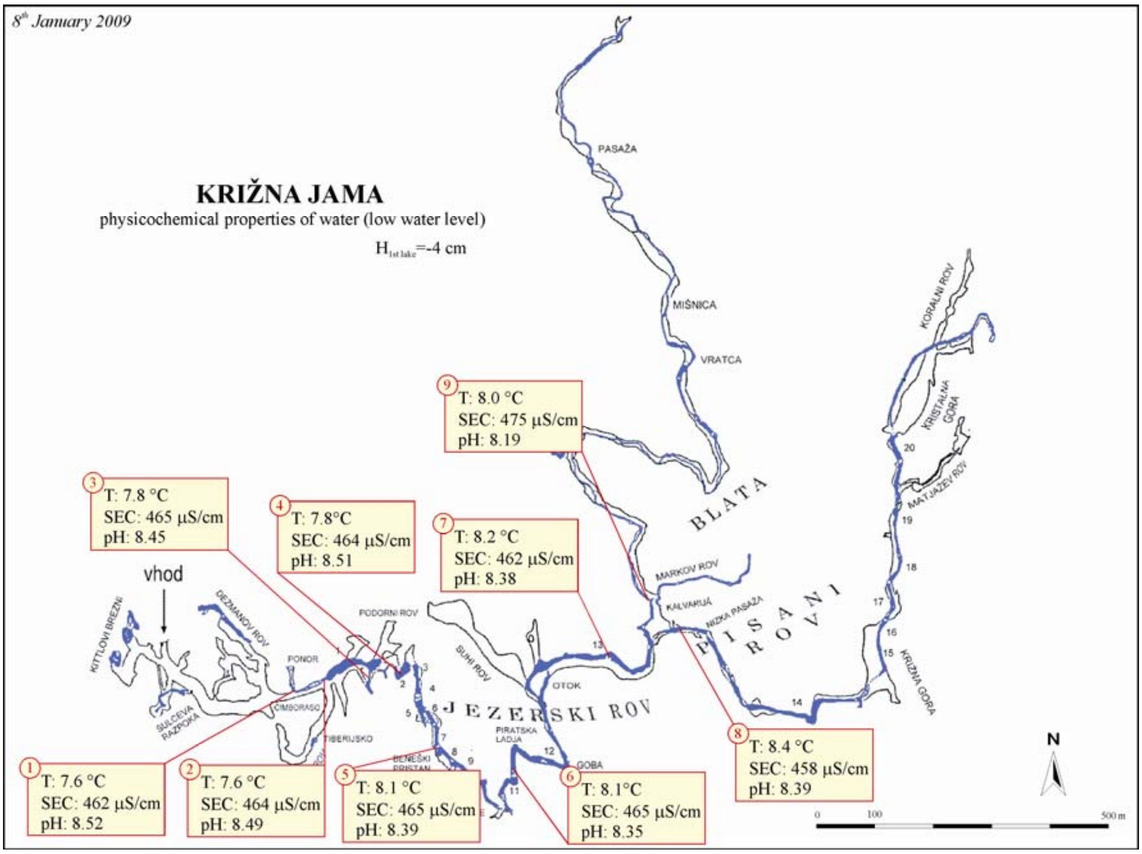
19th September 2007
KRIŽNA JAMA and Križna jama 2
physicochemical properties of water (middle-high water level)
H1st lake=+11 cm
1 T: 8.3 °C SEC: 475 µS/cm pH: 8.05
2 T: 8.9 °C SEC: 456 µS/cm pH: 7.82
3 T: 8.5 °C SEC: 461 µS/cm pH: 7.97
4 T: 8.4 °C SEC: 462 µS/cm pH: 8.00
5 T: 8.3 °C SEC: 463 µS/cm pH: 8.05
6 T: 8.5 °C SEC: 470 µS/cm pH: 7.91
7 T: 8.3 °C SEC: 467 µS/cm pH: 8.01
8 T: 8.5 °C SEC: 447 µS/cm pH: 8.16
vhod
Križna jama 2 (Pritočni sifon)
200 m
PASAŽA
MIŠNICA
VRATCA
TRŠANOV ROV
MARKOV ROV
KALVARIJA
NIZKA PASAŽA
PISANI ROVI
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
KRIŽNA GORA
PODORNI ROV
SUHI ROV
JEZERSKI ROV
OTOK
PIRATSKA LADJA
GOBA
BENEŠKI PRISTAN
PONOR
CIMBORASO
TIBERIJSKO
DEŽMANOV ROV
N
0 100 500 m


11th October 2007
KRIŽNA JAMA
physicochemical properties of water (middle water level)
H1st lake=+3 cm
0 100 500 m
N
vhod
1 T: 8.9 °C SEC: 459 μS/cm pH: 8.08
2 T: 8.9 °C SEC: 456 μS/cm pH: 7.82
2 T: 9.0 °C SEC: 458 μS/cm pH: 8.05
3 T: 9.0 °C SEC: 463 μS/cm pH: 8.11
4 T: 8.4 °C SEC: 462 μS/cm pH: 8.00
4 T: 8.9 °C SEC: 476 μS/cm pH: 7.98
5 T: 8.4 °C SEC: 487 μS/cm pH: 8.15
6 T: 8.4 °C SEC: 489 μS/cm pH: 8.09
7 T: 8.0 °C SEC: 504 μS/cm pH: 7.57
8 T: 8.5 °C SEC: 487 μS/cm pH: 8.17
9 T: 8.5 °C SEC: 488 μS/cm pH: 8.13
10 T: 8.5 °C SEC: 488 μS/cm pH: 8.06
11 T: 8.5 °C SEC: 489 μS/cm pH: 8.22
12 T: 8.5 °C SEC: 488 μS/cm pH: 8.11
13 T: 8.5 °C SEC: 488 μS/cm pH: 7.99
14 T: 8.6 °C SEC: 486 μS/cm pH: 7.97
15 T: 8.5 °C SEC: 486 μS/cm pH: 7.94
16 T: 8.5 °C SEC: 491 μS/cm pH: 7.99
17 T: 8.5 °C SEC: 489 μS/cm pH: 7.96
18 T: 8.5 °C SEC: 491 μS/cm pH: 7.94
19 T: 8.4 °C SEC: 483 μS/cm pH: 8.00
20 T: 9.0 °C SEC: 482 μS/cm pH: 8.13
PASAŽA
MIŠNICA
VRATCA
TRŠANOV ROV
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
MARKOV ROV
KALVARIJA
PISANI ROV
KRIŽNA GORA
PODORNI ROV
KITTLOVI BREZNI
DEŽMANOV ROV
PONOR
ČIMBORASO
SULCEVA RAZPOKA
TIBERIJSKO
SUHI ROV
OTOK
JEZERSKI ROV
PIRATSKA LADJA
BENEŠKI PRISTAN
GOBA


19th October 2007
KRIŽNA JAMA
physicochemical properties of water (middle water level)
H1st lake=+5 cm
0 100 500 m
vhod
1 T: 8.6 °C SEC: 482 μS/cm pH: 8.29
2 T: 8.6 °C SEC: 482 μS/cm pH: 8.26
3 T: 8.6 °C SEC: 482 μS/cm pH: 8.24
4 T: 8.6 °C SEC: 482 μS/cm pH: 8.21
5 T: 8.6 °C SEC: 484 μS/cm pH: 8.10
6 T: 8.7 °C SEC: 488 μS/cm pH: 7.76
7 T: 8.6 °C SEC: 481 μS/cm pH: 8.25
8 T: 8.6 °C SEC: 481 μS/cm pH: 7.16
9 T: 8.5°C SEC: 482 μS/cm pH: 8.03
10 T: 8.7 °C SEC: 485 μS/cm pH: 7.90
11 T: 8.9 °C SEC: 486 μS/cm pH: 7.76
12 T: 8.9 °C SEC: 487 μS/cm pH: 7.75
13 T: 8.4 °C SEC: 485 μS/cm pH: 8.11
14 T: 8.4 °C SEC: 485 μS/cm pH: 8.05
PASAŽA
MIŠNICA
VRATCA
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
BLATA
MARKOV ROV
KALVARIJA
PISANI ROV
KRIŽNA GORA
PODORNI ROV
KITTLOVI BREZNI
DEŽMANOV ROV
PONOR
ČIMBORASO
SULCEVA RAZPOKA
TIBERIJSKO
SUHI ROV
OTOK
JEZERSKI ROV
PIRATSKA LADJA
BENEŠKI PRISTAN
GOBA

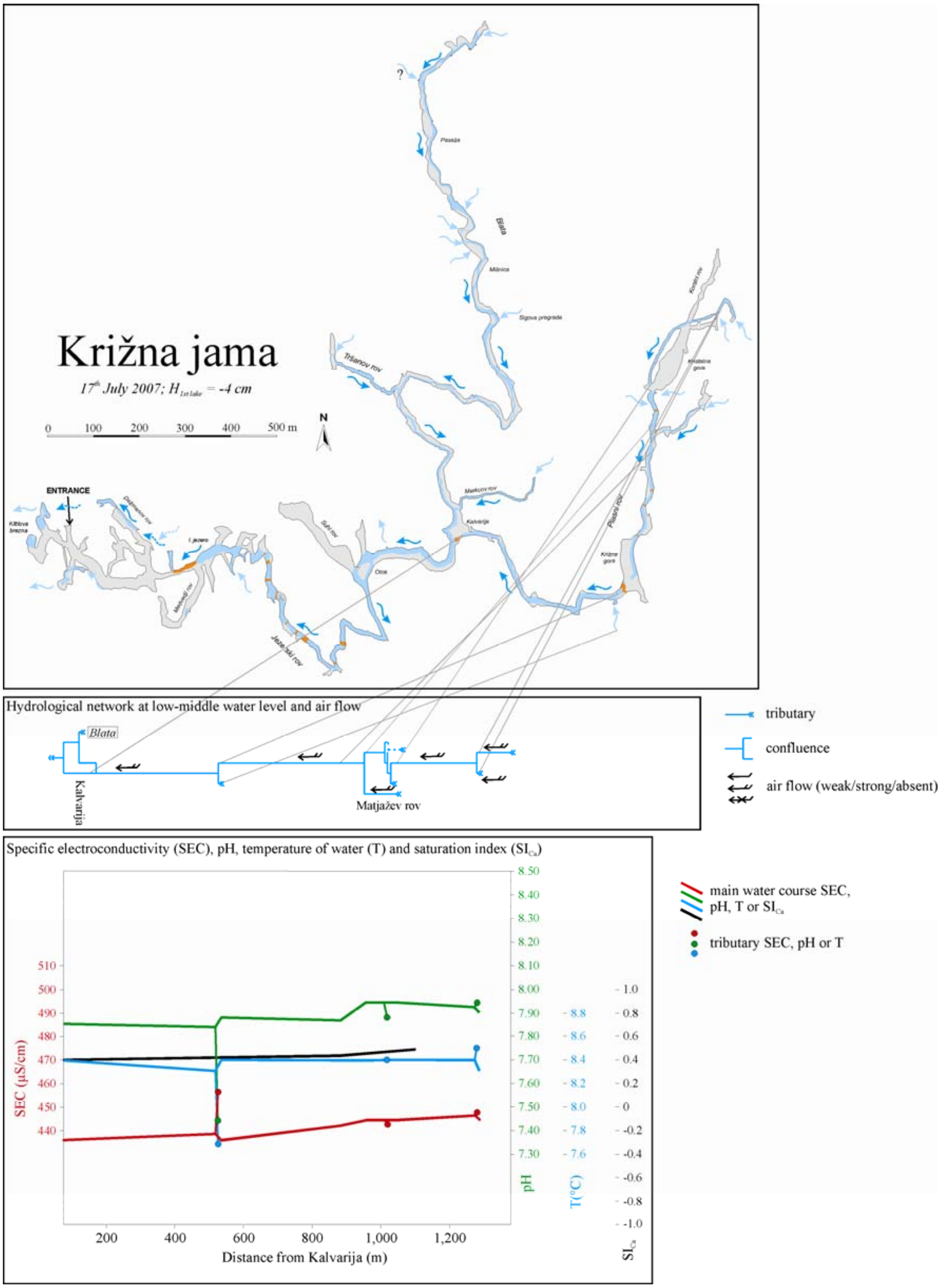

18th November 2007
KRIŽNA JAMA
physicochemical properties of water (middle water level)
H1st lake=-1 cm
N
PASAŽA
MIŠNICA
VRATCA
TRŠANOV ROV
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
BLATA
MARKOV ROV
KALVARIJA
NIZKA PASAŽA
PISANI ROV
KRIŽNA GORA
vhod
KITTLOVI BREZNI
DEŽMANOV ROV
PONOR
PODORNI ROV
ČIMBORASO
SULCEVA RAZPOKA
TIBERIJSKO
SUHI ROV
JEZERSKI ROV
OTOK
PIRATSKA LADJA
BENEŠKI PRISTAN
GOBA
TABORIŠČE
1: T: 8.5 °C SEC: 475 µS/cm pH: 8.17
2: T: 8.3 °C SEC: 476 µS/cm pH: 8.41
3: T: 8.5°C SEC: 475 µS/cm pH: 8.33
4: T: 8.5 °C SEC: 485 µS/cm pH: 8.13
5: T: 8.5 °C SEC: 486 µS/cm pH: 8.12
6: T: 8.5 °C SEC: 468 µS/cm pH: 8.38
0 100 500 m

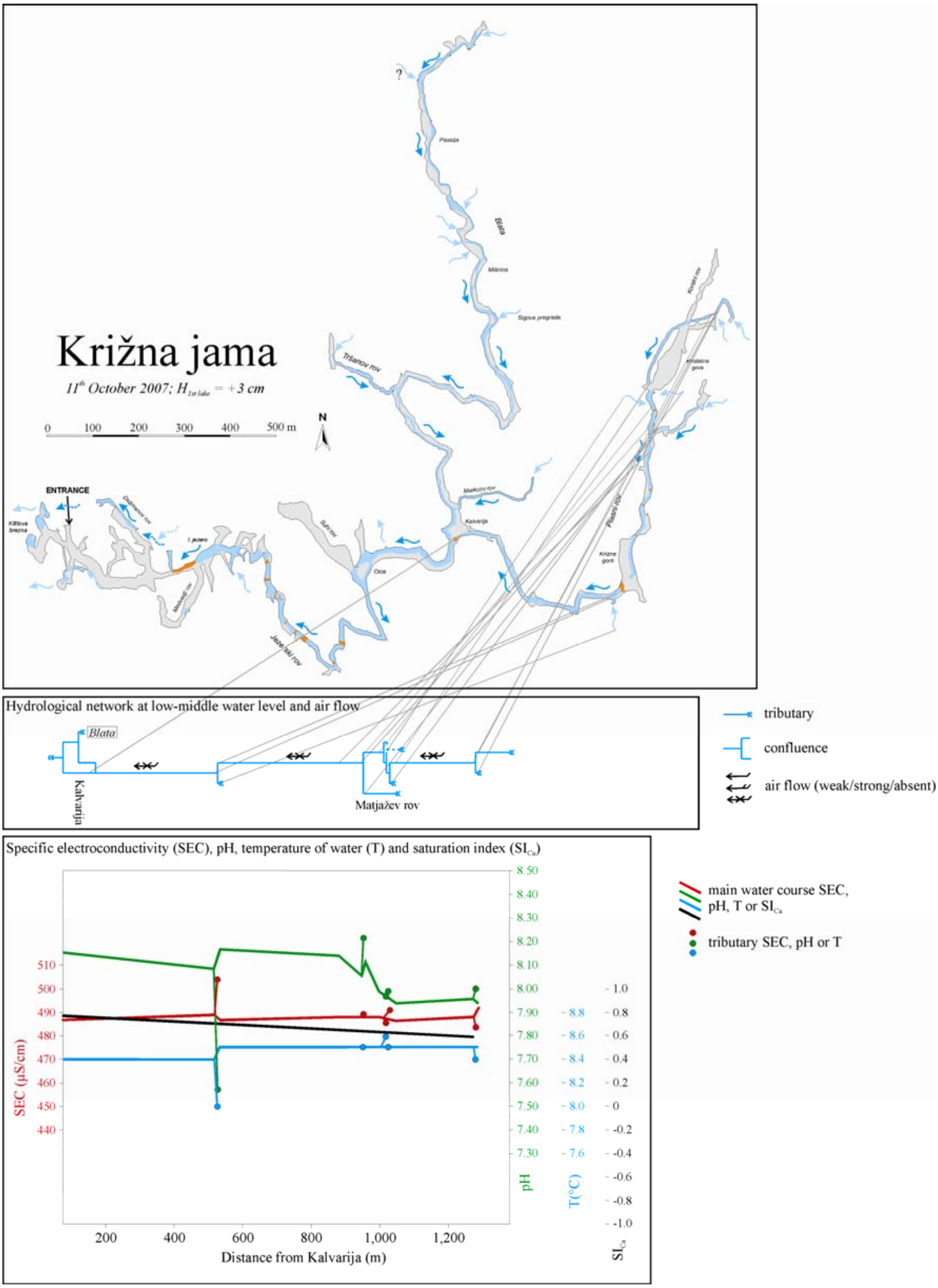

18th December 2007
KRIŽNA JAMA
physicochemical properties of water (middle water level)
H1st lake=+2 cm
PASAŽA
MIŠNICA
VRATCA
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
BLATA
MARKOV ROV
KALVARIJA
NIZKA PASAŽA
PISANI ROV
KRIŽNA GORA
vhod
KITTLOVI BREZNI
DEŽMANOV ROV
PONOR
PODORNI ROV
ČIMBORASO
SULCEVA RAZPOKA
TIBERIJSKO
SUHI ROV
JEZERSKI ROV
OTOK
PIRATSKA LADJA
BENEŠKI
GOBA
TABORIŠČE
1: T: 8.1 °C SEC: 471 µS/cm pH: 8.32
2: T: 8.3 °C SEC: 470 µS/cm pH: 8.34
3: T: 8.3 °C SEC: 470 µS/cm pH: 8.32
4: T: 8.4°C SEC: 470 µS/cm pH: 8.27
5: T: 8.4 °C SEC: 470 µS/cm pH: 8.26
6: T: 8.3 °C SEC: 478 µS/cm pH: 8.02
7: T: 8.4 °C SEC: 465 µS/cm pH: 8.32
N
0 100 500 m



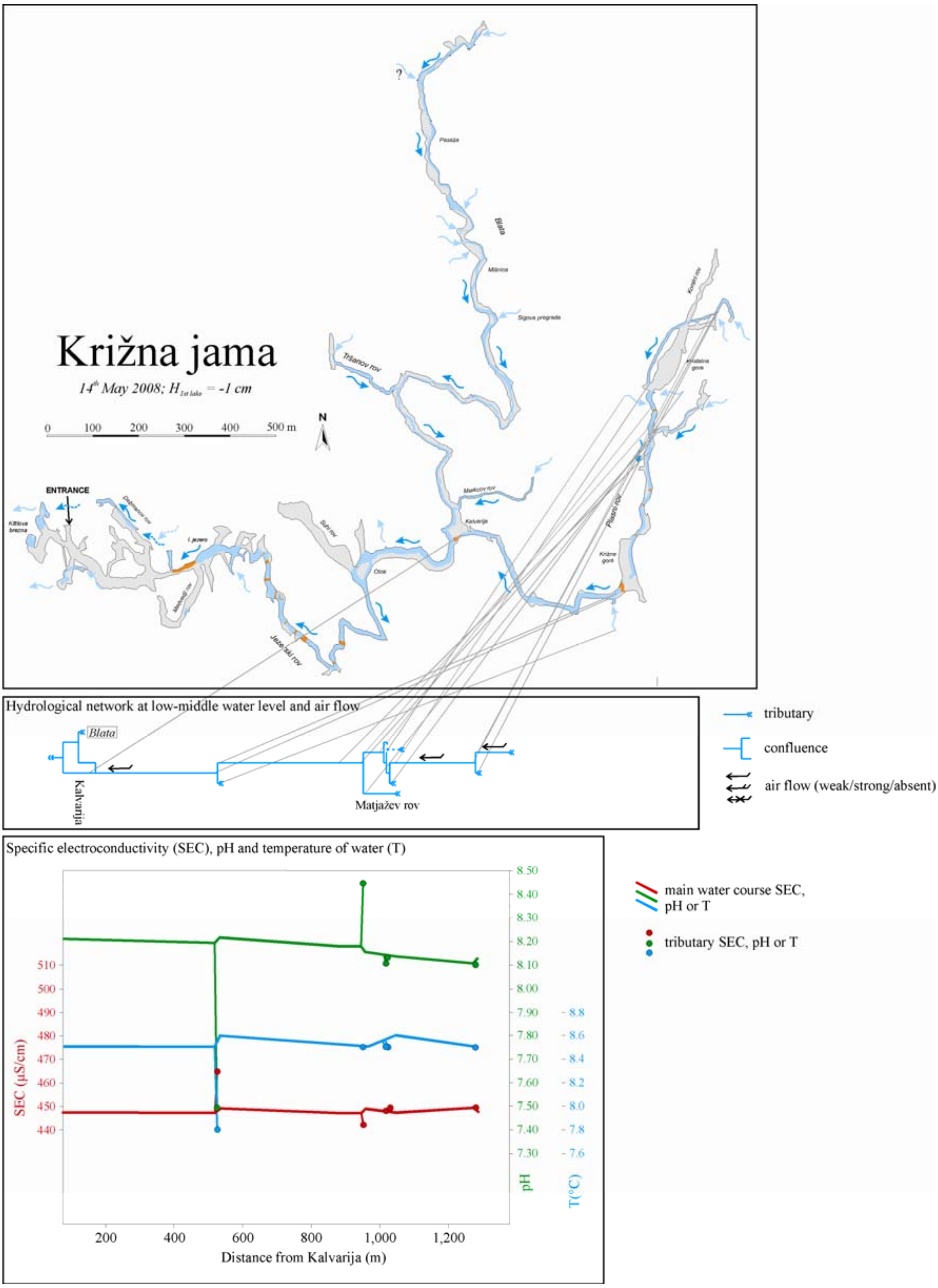
8th January 2009
KRIŽNA JAMA
physicochemical properties of water (low water level)
H1st lake=-4 cm
PASAŽA
MIŠNICA
VRATCA
BLATA
KORALNI ROV
KRISTALNA GORA
MATJAŽEV ROV
MARKOV ROV
KALVARIJA
NIZKA PASAŽA
PISANI ROV
KRIŽNA GORA
vhod
KITTLOVI BREZNI
DEZMANOV ROV
PONOR
PODORNI ROV
SUHI ROV
OTOK
JEZERSKI ROV
CIMBORASO
TIBERIJSKO
SULCEVA RAZPOKA
BENEŠKI PRISTAN
PIRATSKA LADJA
GOBA
1 T: 7.6 °C SEC: 462 µS/cm pH: 8.52
2 T: 7.6 °C SEC: 464 µS/cm pH: 8.49
3 T: 7.8 °C SEC: 465 µS/cm pH: 8.45
4 T: 7.8°C SEC: 464 µS/cm pH: 8.51
5 T: 8.1 °C SEC: 465 µS/cm pH: 8.39
6 T: 8.1°C SEC: 465 µS/cm pH: 8.35
7 T: 8.2 °C SEC: 462 µS/cm pH: 8.38
8 T: 8.4 °C SEC: 458 µS/cm pH: 8.39
9 T: 8.0 °C SEC: 475 µS/cm pH: 8.19
N
0
100
500 m

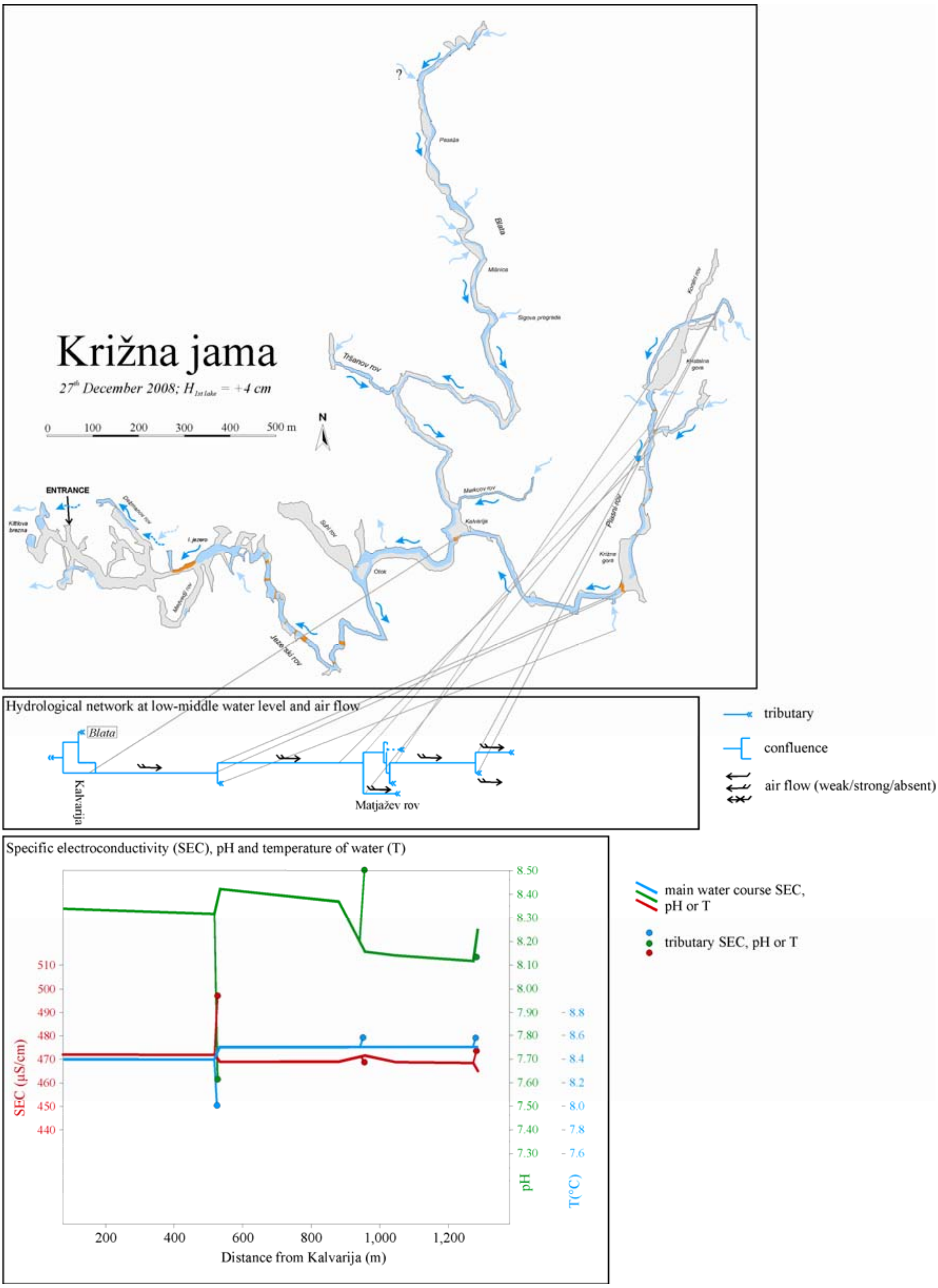
Appendix III: Specific electrical conductivity (SEC), temperature (T), pH and saturation index with respect to calcite (SI_{Ca}) changes in Pisani rov (Križna jama).



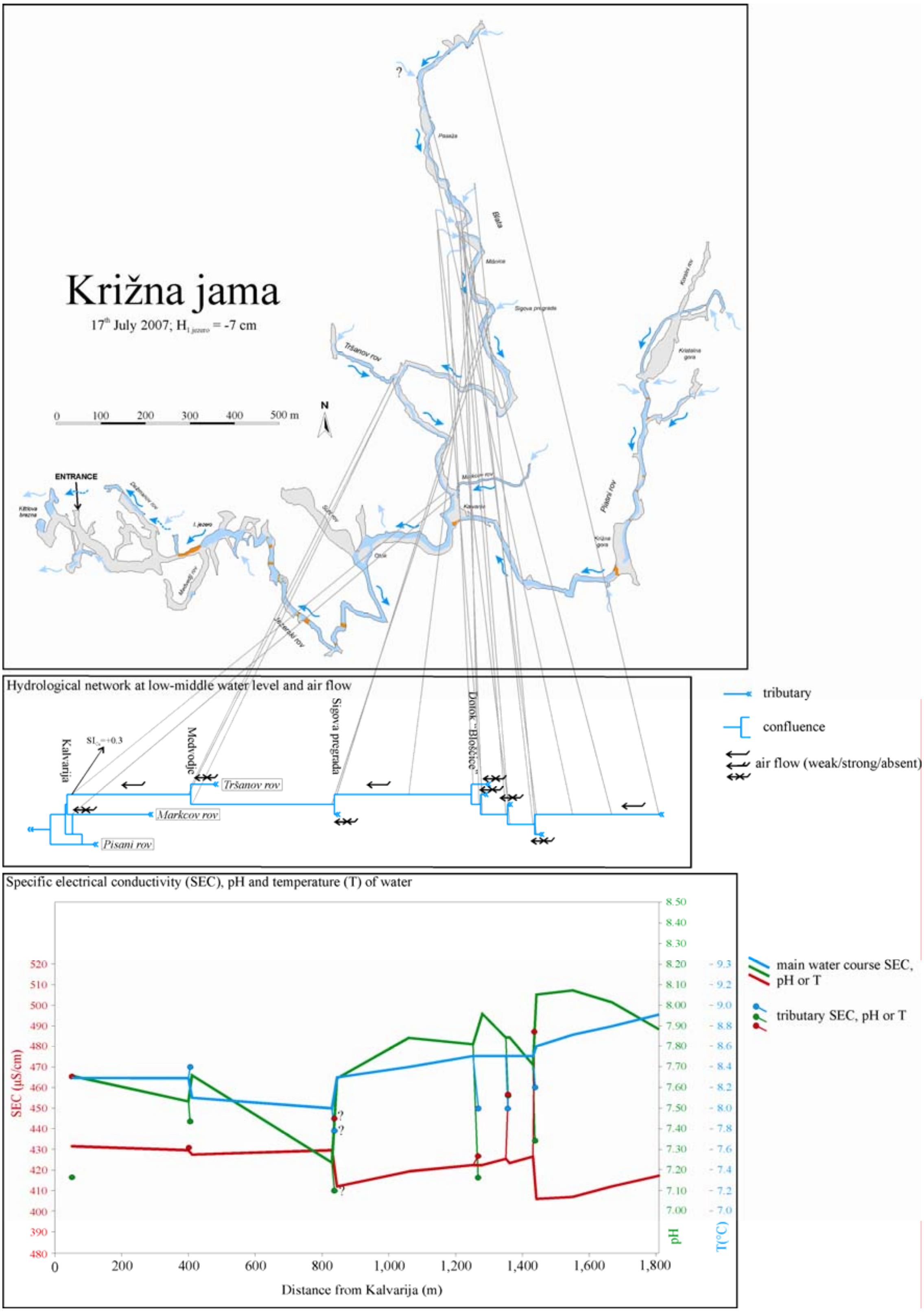


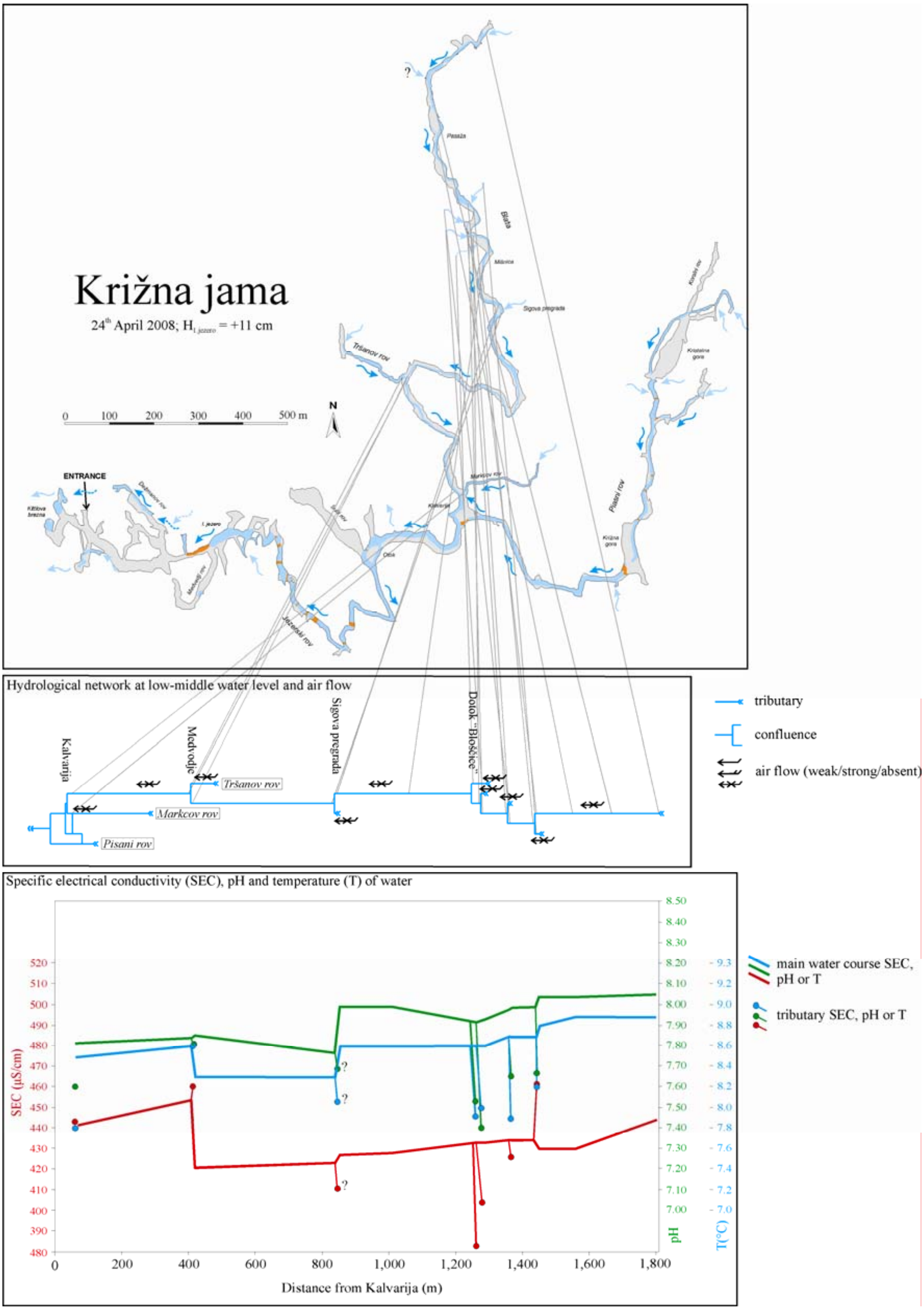
Križna jama
11th October 2007; $H_{1st\ lake}$ = +3 cm
0 100 200 300 400 500 m
N
ENTRANCE
Blata
Kalvarija
Otok
Hydrological network at low-middle water level and air flow
Blata
Kalvarija
Matjažev rov
tributary
confluence
air flow (weak/strong/absent)
Specific electroconductivity (SEC), pH, temperature of water (T) and saturation index (SI_{Ca})
SEC (µS/cm)
440 450 460 470 480 490 500 510
pH
7.30 7.40 7.50 7.60 7.70 7.80 7.90 8.00 8.10 8.20 8.30 8.40 8.50
T(°C)
7.6 7.8 8.0 8.2 8.4 8.6 8.8
SI_{Ca}
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0
200 400 600 800 1,000 1,200
Distance from Kalvarija (m)
main water course SEC, pH, T or SI_{Ca}
tributary SEC, pH or T


Križna jama
14th May 2008; H1st lake = -1 cm
0 100 200 300 400 500 m
N
ENTRANCE
Hydrological network at low-middle water level and air flow
Blata
Kalvarija
Matjažev rov
tributary
confluence
air flow (weak/strong/absent)
Specific electroconductivity (SEC), pH and temperature of water (T)
SEC (µS/cm)
440
450
460
470
480
490
500
510
pH
7.30
7.40
7.50
7.60
7.70
7.80
7.90
8.00
8.10
8.20
8.30
8.40
8.50
T(°C)
7.6
7.8
8.0
8.2
8.4
8.6
8.8
200 400 600 800 1,000 1,200
Distance from Kalvarija (m)
main water course SEC, pH or T
tributary SEC, pH or T

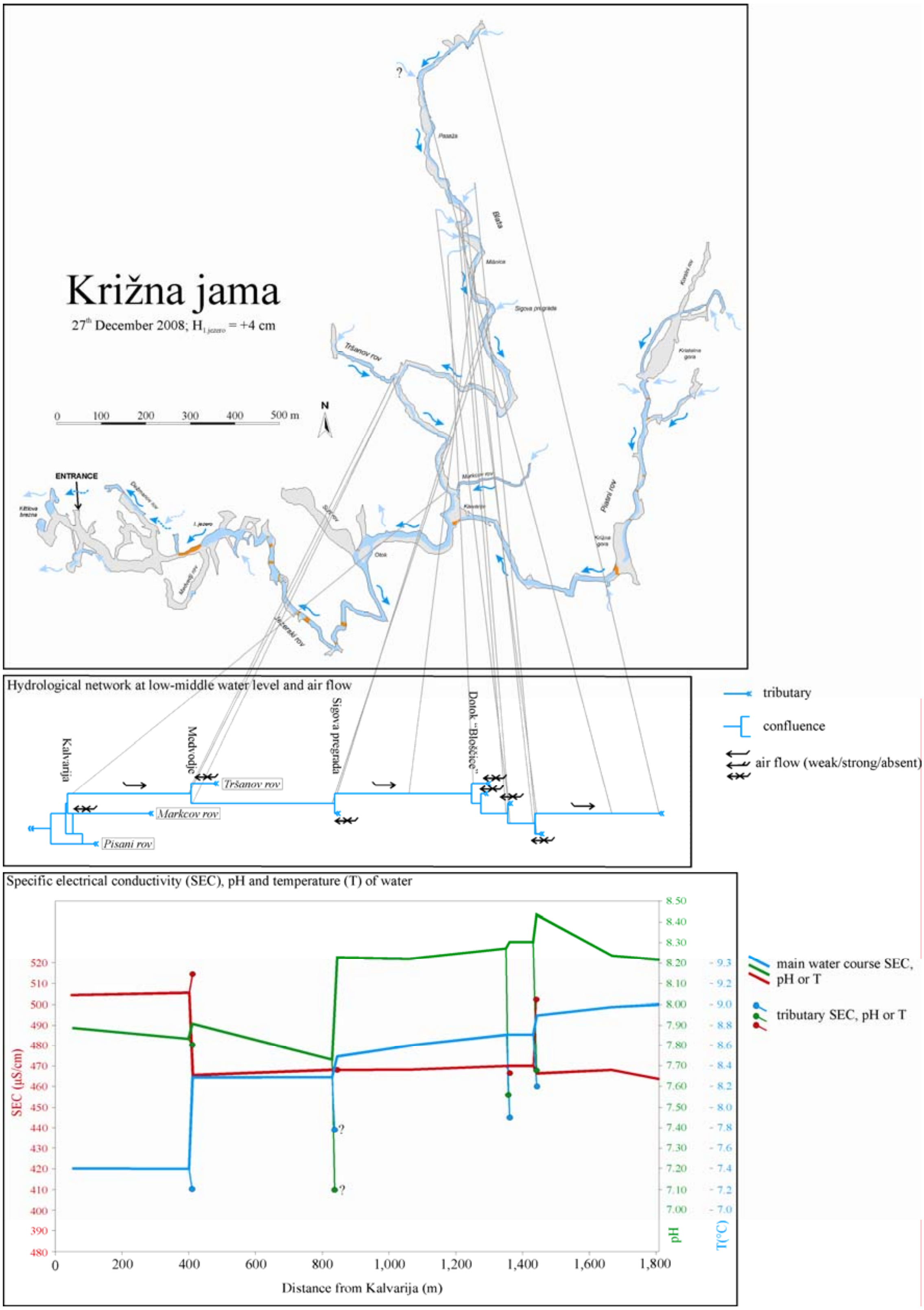

Križna jama
27th December 2008; H1st lake = +4 cm
0 100 200 300 400 500 m
N
ENTRANCE
Blata
Kalvarija
Otok
?
Hydrological network at low-middle water level and air flow
Blata
Kalvarija
Matjažev rov
tributary
confluence
air flow (weak/strong/absent)
Specific electroconductivity (SEC), pH and temperature of water (T)
SEC (µS/cm)
440
450
460
470
480
490
500
510
pH
7.30
7.40
7.50
7.60
7.70
7.80
7.90
8.00
8.10
8.20
8.30
8.40
8.50
T(°C)
7.6
7.8
8.0
8.2
8.4
8.6
8.8
200
400
600
800
1,000
1,200
Distance from Kalvarija (m)
main water course SEC, pH or T
tributary SEC, pH or T

Appendix IV: Specific electrical conductivity (SEC), temperature (T) and pH changes in Blata passage (Križna jama).



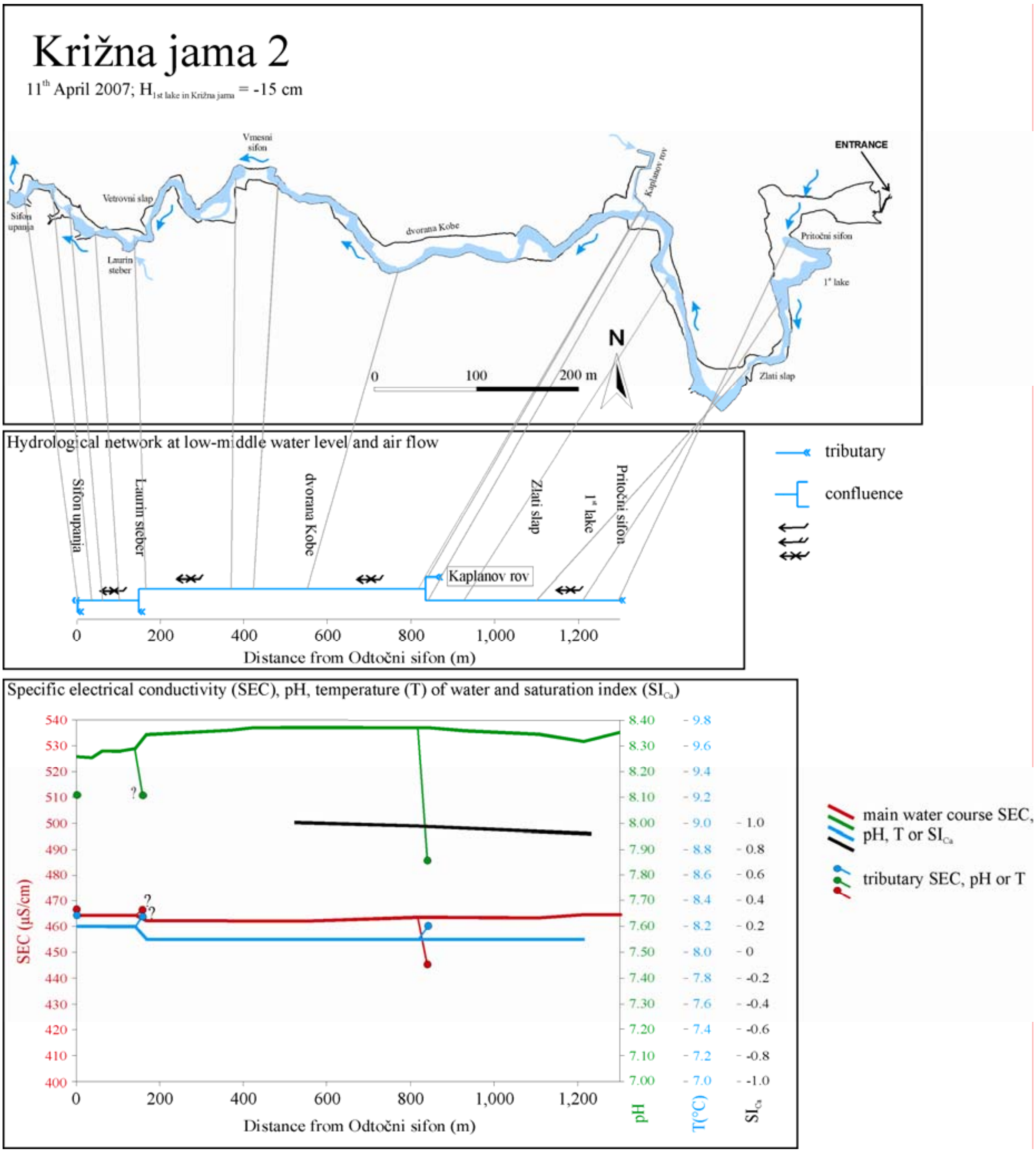


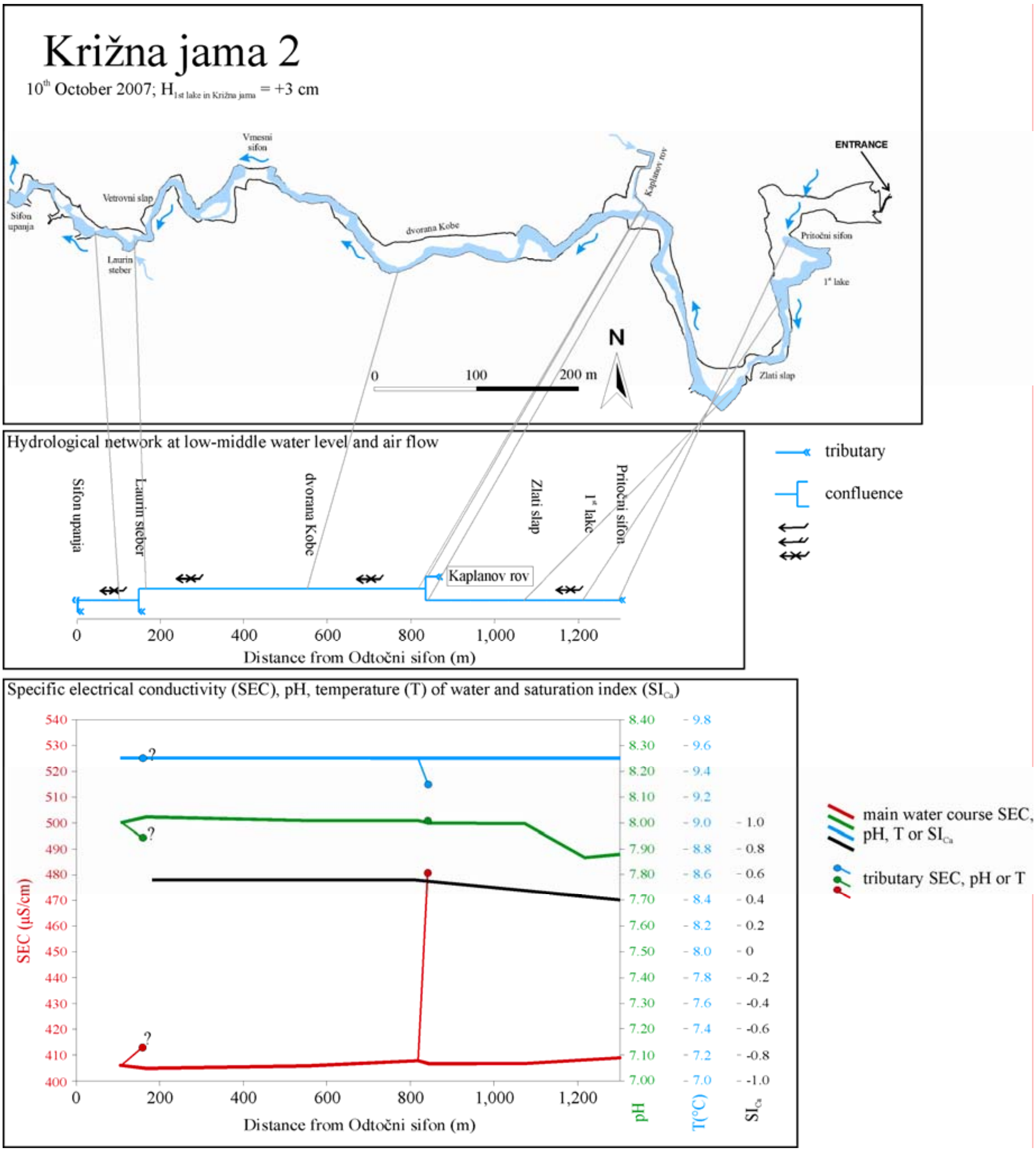
Križna jama
24th April 2008; H1.jezero = +11 cm
0
100
200
300
400
500 m
N
ENTRANCE
?
Hydrological network at low-middle water level and air flow
Kalvarija
Medvodje
Sigova pregrada
Dolok "Blošče"
Tršanov rov
Markcov rov
Pisani rov
tributary
confluence
air flow (weak/strong/absent)
Specific electrical conductivity (SEC), pH and temperature (T) of water
SEC (µS/cm)
pH
T(°C)
Distance from Kalvarija (m)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
480
390
400
410
420
430
440
450
460
470
480
490
500
510
520
7.00
7.10
7.20
7.30
7.40
7.50
7.60
7.70
7.80
7.90
8.00
8.10
8.20
8.30
8.40
8.50
7.0
7.2
7.4
7.6
7.8
8.0
8.2
8.4
8.6
8.8
9.0
9.2
9.3
main water course SEC, pH or T
tributary SEC, pH or T

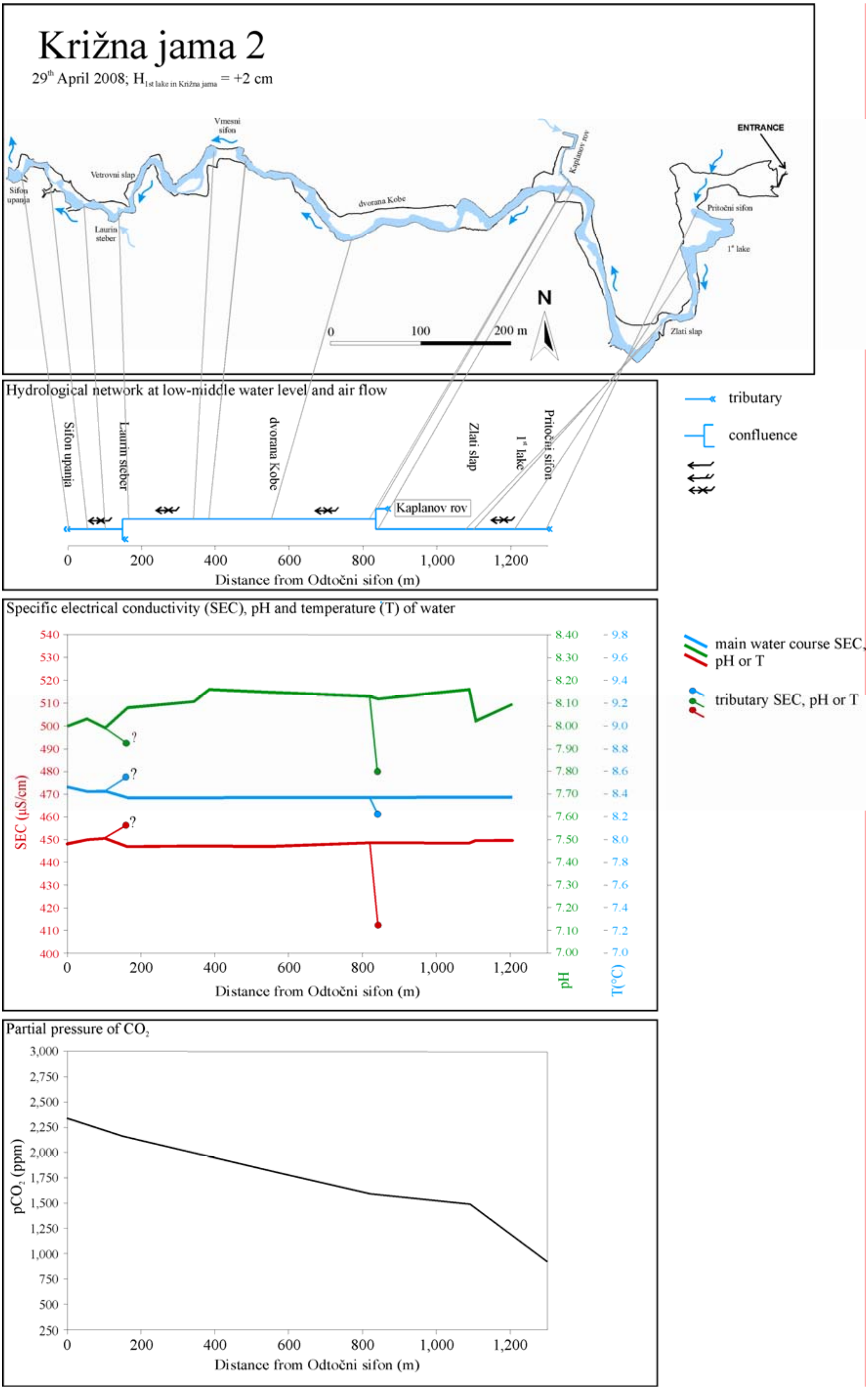


Križna jama
27th December 2008; H I jezero = +4 cm
0
100
200
300
400
500 m
N
ENTRANCE
Tršanov rov
Pisani rov
Hydrological network at low-middle water level and air flow
Kalvarija
Medvodje
Sigova pregrada
Dotok "Blaščice"
Tršanov rov
Markcov rov
Pisani rov
tributary
confluence
air flow (weak/strong/absent)
Specific electrical conductivity (SEC), pH and temperature (T) of water
SEC (µS/cm)
pH
T(°C)
Distance from Kalvarija (m)
main water course SEC, pH or T
tributary SEC, pH or T

Appendix V: Specific electrical conductivity (SEC), temperature (T), pH, saturation index with respect to calcite (SI_{Ca}) and air CO_2 concentration changes in Križna jama 2.




Križna jama 2
10th October 2007; H1st lake in Križna jama = +3 cm
Vmesni sifon
Kaplanov rov
ENTRANCE
Vetrovni slap
Sifon upanja
Laurin steber
dvorana Kobe
Pritočni sifon
1st lake
Zlati slap
N
0
100
200 m
Hydrological network at low-middle water level and air flow
Sifon upanja
Laurin steber
dvorana Kobe
Zlati slap
1st lake
Pritočni sifon
Kaplanov rov
tributary
confluence
Distance from Odtočni sifon (m)
Specific electrical conductivity (SEC), pH, temperature (T) of water and saturation index (SICa)
SEC (µS/cm)
pH
T(°C)
SICa
Distance from Odtočni sifon (m)
main water course SEC, pH, T or SICa
tributary SEC, pH or T


Križna jama 2
29th April 2008; H1st lake in Križna jama = +2 cm
ENTRANCE
Vmesni sifon
Vetrovni slap
Sifon upanja
Laurin steber
dvorana Kobe
Kaplanov rov
Pritočni sifon
1st lake
Zlati slap
N
0
100
200 m
Hydrological network at low-middle water level and air flow
Sifon upanja
Laurin steber
dvorana Kobe
Kaplanov rov
Zlati slap
1st lake
Pritočni sifon
Distance from Odtočni sifon (m)
tributary
confluence
Specific electrical conductivity (SEC), pH and temperature (T) of water
SEC (μS/cm)
pH
T(°C)
Distance from Odtočni sifon (m)
main water course SEC, pH or T
tributary SEC, pH or T
Partial pressure of CO2
pCO2 (ppm)
Distance from Odtočni sifon (m)

Appendix VI: Corrosion/flowstone deposition rates at KJ-1.

Beginning of measurements	End of measurements	Number of days	Corrosion/deposition (mm)	Corrosion/deposition rate (mm/15 days)
2006-02-14	2006-03-01	15	0.0021	**0.0021**
2006-03-01	2006-03-16	15	0.0001	**0.0001**
2006-03-16	2006-03-31	15	0.0001	**0.0001**
2006-03-31	2006-04-15	15	0.0002	**0.0002**
2006-04-15	2006-04-30	15	0.0001	**0.0001**
2006-04-30	2006-05-15	15	0.0002	**0.0002**
2006-05-15	2006-06-02	18	-0.0001	**-0.0001**
2006-06-02	2006-06-17	15	0.0001	**0.0001**
2006-06-17	2006-07-02	15	0.0001	**0.0001**
2006-07-02	2006-07-17	15	-0.0001	**-0.0001**
2006-07-17	2006-08-01	15	0.0001	**0.0001**
2006-08-01	2006-08-16	15	0.0000	**0.0000**
2006-08-16	2006-08-31	15	0.0000	**0.0000**
2006-08-31	2006-09-15	15	0.0000	**0.0000**
2006-09-15	2006-09-30	15	0.0001	**0.0001**
2006-09-30	2006-10-15	15	0.0000	**0.0000**
2006-10-15	2006-10-30	15	-0.0001	**-0.0001**
2006-10-30	2006-11-14	15	0.0000	**0.0000**
2006-11-14	2006-11-29	15	0.0002	**0.0002**
2006-11-29	2006-12-14	15	-0.0002	**-0.0002**
2006-12-14	2006-12-29	15	0.0000	**0.0000**
2006-12-29	2007-01-13	15	0.0001	**0.0001**
2007-01-13	2007-01-28	15	0.0036	**0.0036**
2007-01-28	2007-02-12	15	0.0000	**0.0000**
2007-02-12	2007-03-01	17	0.0001	**0.0001**
2007-03-01	2007-03-16	15	0.0000	**0.0000**
2007-03-16	2007-03-31	15	0.0003	**0.0003**
2007-03-31	2007-04-15	15	0.0001	**0.0001**
2007-04-15	2007-05-01	16	0.0002	**0.0001**
2007-05-01	2007-05-16	15	0.0002	**0.0002**
2007-05-16	2007-05-31	15	0.0004	**0.0004**
2007-05-31	2007-06-15	15	0.0001	**0.0001**
2007-06-15	2007-06-30	15	0.0000	**0.0000**
2007-06-30	2007-07-15	15	0.0000	**0.0000**
2007-07-15	2007-07-29	14	-0.0001	**-0.0001**
2007-07-29	2007-08-17	19	0.0000	**0.0000**
2007-08-17	2007-09-04	18	0.0001	**0.0001**
2007-09-04	2007-09-19	15	0.0000	**0.0000**
2007-09-19	2007-10-04	15	-0.0001	**-0.0001**
2007-10-04	2007-10-19	15	-0.0003	**-0.0003**
2007-10-19	2007-11-03	15	-0.0002	**-0.0002**
2007-11-03	2007-11-18	15	-0.0001	**-0.0001**
2007-11-18	2007-12-03	15	0.0032	**0.0032**
2007-12-03	2007-12-18	15	0.0001	**0.0001**
2007-12-18	2008-01-02	15	0.0159	**0.0159**
2008-01-02	2008-01-18	16	0.0012	**0.0012**
2008-01-18	2008-02-02	15	0.0097	**0.0097**
2008-02-02	2008-02-17	15	0.0003	**0.0003**
2008-02-17	2008-03-03	15	0.0170	**0.0170**
2008-03-03	2008-03-19	16	0.0019	**0.0017**
2008-03-19	2008-04-18	30	0.0005	**0.0002**
2008-04-18	2008-05-03	15	0.0002	**0.0002**
2008-05-03	2008-05-18	15	0.0002	**0.0002**
2008-05-18	2008-06-02	15	0.0002	**0.0002**
2008-06-02	2008-06-17	15	0.0001	**0.0001**
2008-06-17	2008-07-02	15	0.0001	**0.0001**
2008-07-02	2008-07-17	15	0.0000	**0.0000**
2008-07-17	2008-08-18	32	-0.0004	**-0.0002**
2008-08-18	2008-09-02	15	-0.0001	**-0.0001**
2008-09-02	2008-09-17	15	0.0001	**0.0001**
2008-09-17	2008-10-02	15	0.0000	**0.0000**
2008-10-02	2008-10-17	15	-0.0002	**-0.0002**
2008-10-17	2008-11-05	19	-0.0004	**-0.0003**
2008-11-05	2008-11-20	15	-0.0001	**-0.0001**
2008-11-20	2008-12-09	19	0.0011	**0.0008**
2008-12-09	2008-12-24	15	-0.0001	**-0.0001**
2008-12-24	2009-01-08	15	0.0009	**0.0009**
2009-01-08	2009-01-23	15	0.0039	**0.0039**
2009-01-23	2009-02-17	25	-0.0001	**-0.0001**
2009-02-17	2009-03-04	15	0.0017	**0.0017**
2009-03-04	2009-03-19	15	0.0000	**0.0000**
2009-03-19	2009-04-05	17	0.0041	**0.0036**

Appendix VII: Corrosion/flowstone deposition at KJ-2.

Beginning of measurements	End of measurements	Number of days	Corrosion/flowstone deposition at different height (mm)										
			-37.5	-32.5	-27.5	-22.5	-17.5	-12.5	-7.5	-2.5	2.5	7.5	12.5
2006-05-15	2006-06-02	18	0.0002	0.0004	0.0003	0.0002	0.0002	0.0003	0.0002	0.0002	0.0000	0.0000	0.0001
2006-06-02	2006-06-17	15	0.0005	0.0005	0.0006	0.0005	0.0006	0.0006	0.0006	0.0006	0.0005	0.0004	0.0005
2006-06-17	2006-07-02	15	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0001	0.0000
2006-07-02	2006-07-17	15	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
2006-07-17	2006-08-01	15	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
2006-08-01	2006-08-16	15	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000
2006-08-16	2006-08-31	15	-0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	-0.0001	-0.0001
2006-08-31	2006-09-15	15	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
2006-09-15	2006-09-30	15	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
2006-09-30	2006-10-15	15	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0000	-0.0001	-0.0001	-0.0002	-0.0001
2006-10-15	2006-10-30	15	0.0000	-0.0002	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	-0.0002	-0.0002	0.0000	-0.0001
2006-10-30	2006-11-14	15	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
2006-11-14	2006-11-29	15	0.0001	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002	0.0003	0.0002	0.0001	0.0002
2006-11-29	2006-12-14	15	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000
2006-12-14	2006-12-29	15	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0000	0.0000
2006-12-29	2007-01-13	15	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000
2007-01-13	2007-01-28	15	0.0001	0.0002	0.0002	0.0001	0.0002	0.0002	0.0004	0.0003	0.0001	0.0000	0.0000
2007-01-28	2007-02-12	15	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001
2007-02-12	2007-03-01	17	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000
2007-03-01	2007-03-16	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001
2007-03-16	2007-03-31	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-03-31	2007-04-15	15	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
2007-04-15	2007-05-01	16	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000
2007-05-01	2007-05-16	15	0.0001	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000
2007-05-16	2007-05-31	15	0.0000	0.0001	0.0002	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	-0.0001	0.0000
2007-05-31	2007-06-15	15	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-06-15	2007-06-30	15	-0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-06-30	2007-07-15	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2007-07-15	2007-07-29	14	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2007-07-29	2007-08-17	19	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-08-17	2007-09-04	18	-0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-09-04	2007-09-19	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-09-19	2007-10-04	15	0.0000	-0.0001	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
2007-10-04	2007-10-19	15	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000
2007-10-19	2007-11-03	15	-0.0001	0.0000	0.0000	-0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-11-03	2007-11-18	15	0.0000	0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000
2007-11-18	2007-12-03	15	0.0005	0.0006	0.0004	0.0005	0.0008	0.0010	0.0010	0.0002	0.0001	0.0000	0.0000
2007-12-03	2007-12-18	15	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	-0.0002	0.0001	0.0001	0.0000
2007-12-18	2007-01-02	15	0.0006	0.0008	0.0006	0.0008	0.0008	0.0012	0.0014	0.0011	0.0001	0.0000	0.0000
2008-01-02	2008-01-18	16	-0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000
2008-01-18	2008-02-02	15	0.0005	0.0006	0.0004	0.0005	0.0007	0.0009	0.0011	0.0009	0.0001	0.0000	0.0000
2008-02-02	2008-02-17	15	0.0000	0.0000	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000
2008-02-17	2008-03-03	15	0.0003	0.0005	0.0005	0.0010	0.0013	0.0015	0.0011	0.0010	0.0000	0.0000	0.0000
2008-03-03	2008-03-19	16	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0000	0.0001	0.0000
2008-03-19	2008-04-18	30	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
2008-04-18	2008-05-03	15	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
2008-05-03	2008-05-18	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2008-05-18	2008-06-02	15	0.0001	0.0000	0.0000	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0001	0.0000	0.0001
2008-06-02	2008-06-17	15	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000
2008-06-17	2008-07-02	15	-0.0001	-0.0001	-0.0002	0.0000	0.0002	-0.0002	0.0000	-0.0002	-0.0001	-0.0002	0.0000
2008-07-02	2008-07-17	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-07-17	2008-08-18	32	-0.0001	0.0000	0.0000	-0.0003	-0.0007	0.0000	-0.0001	0.0000	-0.0001	0.0001	-0.0002
2008-08-18	2008-09-02	15	0.0000	0.0000	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0001	0.0000
2008-09-02	2008-09-17	15	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000
2008-09-17	2008-10-02	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000
2008-10-02	2008-10-17	15	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000
2008-10-17	2008-11-05	19	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000
2008-11-05	2008-11-20	15	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001
2008-11-20	2008-12-09	19	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0001	-0.0002	0.0002	0.0000	-0.0001	-0.0001
2008-12-09	2008-12-24	15	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
2008-12-24	2009-01-08	15	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0001	0.0004	0.0000	0.0000	0.0000
2009-01-08	2009-01-23	15	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
2009-01-23	2009-02-17	25	-0.0001	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000
2009-02-17	2009-03-04	15	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000
2009-03-04	2009-03-19	15	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0001	0.0000	0.0000
2009-03-19	2009-04-05	17	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000

Beginning of measurements	End of measurements	Number of days	Corrosion/flowstone deposition at different height (mm)									
			17.5	22.5	27.5	32.5	37.5	42.5	47.5	57.5	72.5	92.5
2006-05-15	2006-06-02	18	0.0001	0.0001	0.0002	0.0000	0.0001	0.0000	0.0001	/	/	/
2006-06-02	2006-06-17	15	0.0005	0.0005	0.0006	0.0005	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005
2006-06-17	2006-07-02	15	0.0004	0.0000	0.0000	0.0001	0.0001	0.0000	-0.0001	0.0000	0.0000	0.0001
2006-07-02	2006-07-17	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2006-07-17	2006-08-01	15	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000
2006-08-01	2006-08-16	15	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000
2006-08-16	2006-08-31	15	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	-0.0001	-0.0001	-0.0001	-0.0001	0.0000
2006-08-31	2006-09-15	15	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2006-09-15	2006-09-30	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000
2006-09-30	2006-10-15	15	-0.0002	-0.0001	-0.0001	-0.0002	-0.0001	-0.0001	-0.0001	-0.0002	-0.0001	-0.0001
2006-10-15	2006-10-30	15	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	-0.0001	-0.0002	-0.0001
2006-10-30	2006-11-14	15	0.0001	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000
2006-11-14	2006-11-29	15	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001
2006-11-29	2006-12-14	15	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2006-12-14	2006-12-29	15	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2006-12-29	2007-01-13	15	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-01-13	2007-01-28	15	0.0001	0.0000	0.0001	-0.0001	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0001
2007-01-28	2007-02-12	15	0.0001	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000
2007-02-12	2007-03-01	17	-0.0001	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-03-01	2007-03-16	15	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	-0.0002	0.0000	0.0000	0.0000
2007-03-16	2007-03-31	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-03-31	2007-04-15	15	0.0001	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-04-15	2007-05-01	16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	-0.0001
2007-05-01	2007-05-16	15	0.0000	0.0000	0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
2007-05-16	2007-05-31	15	0.0000	0.0000	0.0001	0.0000	0.0000	-0.0001	0.0000	0.0001	0.0000	0.0000
2007-05-31	2007-06-15	15	0.0001	0.0000	-0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	-0.0001
2007-06-15	2007-06-30	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-06-30	2007-07-15	15	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-07-15	2007-07-29	14	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-07-29	2007-08-17	19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-08-17	2007-09-04	18	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0001
2007-09-04	2007-09-19	15	0.0002	0.0000	0.0000	-0.0001	0.0000	-0.0001	0.0001	0.0000	0.0000	0.0000
2007-09-19	2007-10-04	15	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-10-04	2007-10-19	15	-0.0001	0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0001	0.0001	-0.0001	0.0000
2007-10-19	2007-11-03	15	-0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0001	-0.0001
2007-11-03	2007-11-18	15	0.0000	0.0000	-0.0001	0.0001	0.0001	0.0000	0.0000	-0.0001	0.0001	0.0000
2007-11-18	2007-12-03	15	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-12-03	2007-12-18	15	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-12-18	2007-01-02	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-01-02	2008-01-18	16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-01-18	2008-02-02	15	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-02-02	2008-02-17	15	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
2008-02-17	2008-03-03	15	0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000
2008-03-03	2008-03-19	16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
2008-03-19	2008-04-18	30	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001	-0.0001	0.0000	0.0000
2008-04-18	2008-05-03	15	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
2008-05-03	2008-05-18	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000
2008-05-18	2008-06-02	15	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-06-02	2008-06-17	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-06-17	2008-07-02	15	0.0001	0.0000	-0.0002	-0.0002	-0.0002	-0.0002	0.0002	0.0002	-0.0003	-0.0001
2008-07-02	2008-07-17	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-07-17	2008-08-18	32	-0.0004	-0.0001	0.0001	0.0001	0.0001	0.0001	-0.0002	-0.0002	0.0002	0.0000
2008-08-18	2008-09-02	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-09-02	2008-09-17	15	0.0000	0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000
2008-09-17	2008-10-02	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2008-10-02	2008-10-17	15	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001
2008-10-17	2008-11-05	19	0.0000	0.0001	0.0000	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000
2008-11-05	2008-11-20	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-11-20	2008-12-09	19	0.0000	-0.0001	0.0000	-0.0001	0.0001	0.0000	0.0000	0.0000	-0.0001	0.0000
2008-12-09	2008-12-24	15	0.0002	0.0001	0.0002	0.0000	0.0002	0.0001	-0.0001	-0.0001	0.0001	0.0000
2008-12-24	2009-01-08	15	-0.0001	0.0000	-0.0001	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001
2009-01-08	2009-01-23	15	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
2009-01-23	2009-02-17	25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2009-02-17	2009-03-04	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2009-03-04	2009-03-19	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2009-03-19	2009-04-05	17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0001

Appendix VIII: Corrosion/flowstone deposition and flowstone deposition rates rates at KJ-7, KJ-6 (iron), KJ-6 (inox), KJ-5 (iron), KJ-5 (inox), KJ-4 (iron), KJ-4 (inox), KJ-3 (inox), KJ2-1 (iron), KJ2-1-1 (inox), KJ2-2 (iron) and KJ2-2-1 (inox).

Beginning of measurements	End of measurements	Number of days	Corrosion/flowstone deposition (mm)											
			KJ-7 (inox)	KJ-6 (iron)	KJ-6 (inox)	KJ-5 (iron)	KJ-5 (inox)	KJ-4 (iron)	KJ-4 (inox)	KJ-3 (inox)	KJ2-1 (iron)	KJ2-1-1 (inox)	KJ2-2 (iron)	KJ2-2-1 (inox)
2006-08-16	2006-09-15	30	/	-0.0002	/	0.0000	/	-0.0001	/	/	0.0000	/	0.0000	/
2006-09-15	2006-10-15	30	/	-0.0001	/	-0.0001	/	-0.0003	/	/	-0.0001	/	-0.0005	/
2006-10-15	2006-11-14	30	/	0.0000	/	-0.0001	/	-0.0005	/	/	-0.0004	/	-0.0006	/
2006-11-14	2006-12-14	30	/	0.0004	/	0.0000	/	-0.0003	/	/	-0.0002	/	-0.0004	/
2006-12-14	2007-01-13	30	/	0.0070	/	-0.0002	/	-0.0006	/	/	-0.0006	/	-0.0004	/
2007-01-13	2007-02-12	30	/	0.0022	/	-0.0004	/	-0.0004	/	0.0056	-0.0007	/	-0.0006	/
2007-02-12	2007-03-16	32	/	0.0011	/	-0.0003	/	-0.0015	/	0.0001	-0.0001	/	-0.0011	/
2007-03-16	2007-04-15	30	/	0.0016	/	-0.0001	/	-0.0006	/	0.0007	0.0001	/	-0.0005	/
2007-04-15	2007-05-16	31	/	0.0002	/	0.0001	/	-0.0003	/	0.0007	0.0001	/	0.0003	/
2007-05-16	2007-06-15	30	/	0.0003	/	0.0003	/	-0.0007	/	0.0004	-0.0001	/	-0.0005	/
2007-06-15	2007-07-15	30	/	-0.0002	/	0.0001	/	-0.0005	/	-0.0001	-0.0004	/	-0.0009	/
2007-07-15	2007-09-19	66	-0.0001	-0.0002	/	-0.0002	/	-0.0010	/	0.0002	-0.0008	/	-0.0015	/
2007-09-19	2007-10-19	30	-0.0001	-0.0003	/	-0.0005	/	-0.0008	/	-0.0001	-0.0007	/	-0.0012	/
2007-10-19	2007-11-18	30	-0.0002	0.0002	/	-0.0005	/	-0.0014	/	0.0001	-0.0010	/	-0.0012	/
2007-11-18	2007-12-18	30	0.0001	0.0066	/	-0.0001	/	-0.0008	/	0.0064	-0.0003	0.0000	-0.0009	0.0002
2007-12-18	2008-01-18	31	0.0001	0.0113	0.0103	0.0000	0.0014	0.0005	0.0031	0.0226	-0.0003	0.0003	-0.0008	0.0000
2008-01-18	2008-02-17	30 (0 for KJ-3)	0.0001	0.0124	/	0.0000	/	0.0000	/	0.0399	-0.0001	0.0002	-0.0004	0.0003
2008-02-17	2008-03-19	31 (61 for KJ-3)	0.0001	0.0119	0.0112	0.0001	0.0017	0.0020	0.0038		-0.0002	0.0003	-0.0005	0.0002
2008-03-19	2008-04-18	30	0.0003	0.0022	0.0008	0.0002	0.0004	0.0000	0.0003	0.0003	-0.0001	0.0003	-0.0002	0.0002
2008-04-18	2008-05-18	30	0.0003	0.0006	0.0006	0.0000	0.0005	-0.0001	0.0003	0.0006	0.0000	0.0006	-0.0001	0.0006
2008-05-18	2008-06-17	30	0.0001	0.0003	0.0002	0.0002	0.0002	0.0000	0.0002	0.0002	-0.0001	0.0004	-0.0002	0.0005
2008-06-17	2008-07-17	30	0.0000	0.0001	0.0001	-0.0001	0.0002	-0.0003	0.0000	0.0001	-0.0004	0.0001	-0.0006	0.0002
2008-07-17	2008-09-02	47	-0.0001	0.0000	0.0000	0.0000	0.0002	-0.0004	0.0001	-0.0003	-0.0009	-0.0001	-0.0011	-0.0001
2008-09-02	2008-10-02	30	-0.0002	-0.0001	0.0000	0.0000	0.0000	-0.0005	0.0000	0.0000	-0.0005	0.0000	-0.0005	-0.0001
2008-10-02	2008-11-05	34 (0 for Križna jama 2)	-0.0001	-0.0001	-0.0002	-0.0001	-0.0001	-0.0007	-0.0002	-0.0002	-0.0009	-0.0002	-0.0016	-0.0001
2008-11-05	2008-12-09	34 (68 for Križna jama 2)	-0.0003	0.0007	0.0011	-0.0003	-0.0003	-0.0007	-0.0002	0.0026				
2008-12-09	2009-01-08	30	-0.0001	0.0004	0.0001	-0.0002	-0.0003	-0.0006	-0.0001	-0.0001	-0.0009	-0.0002	-0.0011	-0.0003
2009-01-08	2009-02-17	40	0.0000	0.0038	0.0042	0.0000	0.0002	-0.0005	0.0001	0.0113	-0.0002	0.0002	-0.0005	0.0003
2009-02-17	2009-03-19	30	0.0000	0.0023	0.0017	-0.0005	0.0002	-0.0001	0.0001	0.0011	-0.0002	0.0002	-0.0003	0.0002

Beginning of measurements	End of measurements	Number of days	Corrosion/flowstone deposition (mm/30 days)											
			KJ-7 (inox)	KJ-6 (iron)	KJ-6 (inox)	KJ-5 (iron)	KJ-5 (inox)	KJ-4 (iron)	KJ-4 (inox)	KJ-3 (inox)	KJ2-1 (iron)	KJ2-1-1 (inox)	KJ2-2 (iron)	KJ2-2-1 (inox)
2006-08-16	2006-09-15	30	/	-0.0002	/	0.0000	/	-0.0001	/	/	0.0000	/	0.0000	/
2006-09-15	2006-10-15	30	/	-0.0001	/	-0.0001	/	-0.0003	/	/	-0.0001	/	-0.0005	/
2006-10-15	2006-11-14	30	/	0.0000	/	-0.0001	/	-0.0005	/	/	-0.0004	/	-0.0006	/
2006-11-14	2006-12-14	30	/	0.0004	/	0.0000	/	-0.0003	/	/	-0.0002	/	-0.0004	/
2006-12-14	2007-01-13	30	/	0.0070	/	-0.0002	/	-0.0006	/	/	-0.0006	/	-0.0004	/
2007-01-13	2007-02-12	30	/	0.0022	/	-0.0004	/	-0.0004	/	0.0056	-0.0007	/	-0.0006	/
2007-02-12	2007-03-16	32	/	0.0010	/	-0.0003	/	-0.0014	/	0.0000	-0.0001	/	-0.0010	/
2007-03-16	2007-04-15	30	/	0.0016	/	-0.0001	/	-0.0006	/	0.0007	0.0001	/	-0.0005	/
2007-04-15	2007-05-16	31	/	0.0001	/	0.0001	/	-0.0002	/	0.0007	0.0001	/	0.0002	/
2007-05-16	2007-06-15	30	/	0.0003	/	0.0003	/	-0.0007	/	0.0004	-0.0001	/	-0.0005	/
2007-06-15	2007-07-15	30	/	-0.0002	/	0.0001	/	-0.0005	/	-0.0001	-0.0004	/	-0.0009	/
2007-07-15	2007-09-19	66	0.0000	-0.0001	/	-0.0001	/	-0.0004	/	0.0001	-0.0004	/	-0.0007	/
2007-09-19	2007-10-19	30	-0.0001	-0.0003	/	-0.0005	/	-0.0008	/	-0.0001	-0.0007	/	-0.0012	/
2007-10-19	2007-11-18	30	-0.0002	0.0002	/	-0.0005	/	-0.0014	/	0.0001	-0.0010	/	-0.0012	/
2007-11-18	2007-12-18	30	0.0001	0.0066	/	-0.0001	/	-0.0008	/	0.0064	-0.0003	0.0000	-0.0009	0.0002
2007-12-18	2008-01-18	31	0.0001	0.0110	0.0100	0.0000	0.0013	0.0004	0.0030	0.0219	-0.0003	0.0003	-0.0008	0.0000
2008-01-18	2008-02-17	30 (0 for KJ-3)	0.0001	0.0124	/	0.0000	/	0.0000	/	0.0196	-0.0001	0.0002	-0.0004	0.0003
2008-02-17	2008-03-19	31 (61 for KJ-3)	0.0001	0.0115	0.0108	0.0001	0.0016	0.0020	0.0036		-0.0002	0.0003	-0.0005	0.0002
2008-03-19	2008-04-18	30	0.0003	0.0022	0.0008	0.0002	0.0004	0.0000	0.0003	0.0003	-0.0001	0.0003	-0.0002	0.0002
2008-04-18	2008-05-18	30	0.0003	0.0006	0.0006	0.0000	0.0005	-0.0001	0.0003	0.0006	0.0000	0.0006	-0.0001	0.0006
2008-05-18	2008-06-17	30	0.0001	0.0003	0.0002	0.0002	0.0002	0.0000	0.0002	0.0002	-0.0001	0.0004	-0.0002	0.0005
2008-06-17	2008-07-17	30	0.0000	0.0001	0.0001	-0.0001	0.0002	-0.0003	0.0000	0.0001	-0.0004	0.0001	-0.0006	0.0002
2008-07-17	2008-09-02	47	0.0000	0.0000	0.0000	0.0000	0.0001	-0.0003	0.0001	-0.0002	-0.0006	0.0000	-0.0007	-0.0001
2008-09-02	2008-10-02	30	-0.0002	-0.0001	0.0000	0.0000	0.0000	-0.0005	0.0000	0.0000	-0.0005	0.0000	-0.0005	-0.0001
2008-10-02	2008-11-05	34 (0 for Križna jama 2)	-0.0001	-0.0001	-0.0002	-0.0001	-0.0001	-0.0006	-0.0002	-0.0002	-0.0004	-0.0001	-0.0007	0.0000
2008-11-05	2008-12-09	34 (68 for Križna jama 2)	-0.0003	0.0006	0.0010	-0.0003	-0.0003	-0.0007	-0.0002	0.0023				
2008-12-09	2009-01-08	30	-0.0001	0.0004	0.0001	-0.0002	-0.0003	-0.0006	-0.0001	-0.0001	-0.0009	-0.0002	-0.0011	-0.0003
2009-01-08	2009-02-17	40	0.0000	0.0029	0.0032	0.0000	0.0001	-0.0003	0.0001	0.0085	-0.0002	0.0001	-0.0003	0.0002
2009-02-17	2009-03-19	30	0.0000	0.0023	0.0017	-0.0005	0.0002	-0.0001	0.0001	0.0011	-0.0002	0.0002	-0.0003	0.0002

Appendix IX: Corrosion/flowstone deposition rates at L-1.

Beginning of	End of	Number of	Max. height of	Corrosion/flowstone deposition at different height (mm)											Corrosion/flowstone deposition rate at different height (mm/15 days)										
measurements	measurements	days	water (cm)	-7.5	-2.5	2.5	7.5	12.5	17.5	27.5	42.5	62.5	87.5	117.5	-7.5	-2.5	2.5	7.5	12.5	17.5	27.5	42.5	62.5	87.5	117.5
2006-09-25	2006-10-10	15	/	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	/	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	/
2006-10-10	2006-10-30	20	-5	0.0003	0.0000	-0.0001	0.0001	0.0000	0.0001	0.0001	-0.0001	-0.0001	-0.0001	-0.0001	0.0003	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	-0.0001	-0.0001	-0.0001	-0.0001
2006-10-30	2006-11-14	15	-5	/	/	/	/	/	/	/	/	/	/	/	-0.0013	-0.0012	-0.0013	-0.0009	-0.0005	-0.0001	0.0000	-0.0001	0.0001	0.0001	0.0001
2006-11-14	2006-11-29	15	0	-0.0001	0.0000	0.0000	-0.0001	0.0001	-0.0001	-0.0001	0.0001	0.0000	0.0000	0.0001	-0.0001	0.0000	0.0000	-0.0001	0.0001	-0.0001	-0.0001	0.0001	0.0000	0.0000	0.0001
2006-11-29	2006-12-14	15	15	-0.0025*	-0.0024*	-0.0025*	-0.0019*	-0.0011*	-0.0005*	0.0001*	-0.0002*	0.0001*	0.0001*	0.0002*	-0.0013	-0.0012	-0.0013	-0.0009	-0.0005	-0.0001	0.0000	-0.0001	0.0001	0.0001	0.0001
2006-12-14	2006-12-29	15	15	-0.0024	-0.0025	-0.0019	-0.0012	-0.0007	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0024	-0.0025	-0.0019	-0.0012	-0.0007	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000
2006-12-29	2007-01-13	15	23	-0.0040	-0.0037	-0.0033	-0.0013	-0.0009	-0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0040	-0.0037	-0.0033	-0.0013	-0.0009	-0.0005	0.0000	0.0000	0.0000	0.0000	0.0000
2007-01-13	2007-01-28	15	35	-0.0025	-0.0022	-0.0020	-0.0012	-0.0008	-0.0010	-0.0005	0.0000	0.0000	0.0000	0.0000	-0.0025	-0.0022	-0.0020	-0.0012	-0.0008	-0.0010	-0.0005	0.0000	0.0000	0.0000	0.0000
2007-01-28	2007-02-12	15	35	-0.0044	-0.0047	-0.0032	-0.0022	-0.0029	-0.0028	-0.0008	0.0000	0.0000	0.0000	0.0000	-0.0044	-0.0047	-0.0032	-0.0022	-0.0029	-0.0028	-0.0008	0.0000	0.0000	0.0000	0.0000
2007-02-12	2007-03-01	17	120	-0.0040	-0.0058	-0.0046	-0.0033	-0.0032	-0.0019	-0.0012	-0.0012	-0.0006	-0.0004	-0.0004	-0.0035	-0.0051	-0.0040	-0.0029	-0.0029	-0.0017	-0.0010	-0.0011	-0.0005	-0.0004	-0.0003
2007-03-01	2007-03-16	15	15	-0.0030	-0.0031	-0.0027	-0.0019	-0.0009	0.0000	0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0030	-0.0031	-0.0027	-0.0019	-0.0009	0.0000	0.0001	0.0000	-0.0001	0.0000	0.0000
2007-03-16	2007-03-31	15	15	-0.0047	-0.0050	-0.0040	-0.0040	-0.0014	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	-0.0047	-0.0050	-0.0040	-0.0040	-0.0014	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-03-31	2007-04-15	15	5	-0.0011	-0.0016	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	-0.0011	-0.0016	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
2007-04-15	2007-05-01	16	0	-0.0003	-0.0002	-0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	-0.0001	-0.0003	-0.0002	-0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2007-05-01	2007-05-16	15	-5	-0.0006	0.0000	-0.0001	0.0000	-0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	-0.0001	-0.0006	0.0000	-0.0001	0.0000	-0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	-0.0001
2007-05-16	2007-05-31	15	-5	-0.0008	-0.0001	0.0001	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0001	0.0001	-0.0008	-0.0001	0.0001	-0.0001	0.0000	-0.0001	-0.0001	0.0000	0.0000	0.0001	0.0001
2007-05-31	2007-06-15	15	-5	-0.0002	-0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	-0.0002	-0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
2007-06-15	2007-06-30	15	-5	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-06-30	2007-07-15	15	-5	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2007-07-15	2007-07-29	14	-5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2007-07-29	2007-08-17	19	-5	0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
2007-08-17	2007-09-04	18	-5	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000
2007-09-04	2007-09-19	15	80	-0.0004	-0.0007	-0.0006	-0.0004	-0.0003	-0.0002	-0.0001	-0.0001	-0.0001	0.0000	0.0000	-0.0004	-0.0007	-0.0006	-0.0004	-0.0003	-0.0002	-0.0001	-0.0001	-0.0001	0.0000	0.0000
2007-09-19	2007-10-04	15	40	-0.0048	-0.0048	-0.0044	-0.0028	-0.0020	-0.0016	-0.0010	-0.0002	0.0000	0.0000	0.0000	-0.0048	-0.0048	-0.0044	-0.0028	-0.0020	-0.0016	-0.0010	-0.0002	0.0000	0.0000	0.0000
2007-10-04	2007-10-19	15	48	-0.0045	-0.0041	-0.0032	-0.0019	-0.0015	-0.0011	-0.0008	-0.0005	0.0000	-0.0001	0.0001	-0.0045	-0.0041	-0.0032	-0.0019	-0.0015	-0.0011	-0.0008	-0.0005	0.0000	-0.0001	0.0001
2007-10-19	2007-11-03	15	23	-0.0063	-0.0055	-0.0057	-0.0024	-0.0006	-0.0004	0.0000	-0.0001	0.0000	-0.0001	0.0002	-0.0063	-0.0055	-0.0057	-0.0024	-0.0006	-0.0004	0.0000	-0.0001	0.0000	-0.0001	0.0002
2007-11-03	2007-11-18	15	5	-0.0025	-0.0027	-0.0007	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0025	-0.0027	-0.0007	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000
2007-11-18	2007-12-03	15	12	-0.0029	-0.0027	-0.0020	-0.0015	-0.0002	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	-0.0029	-0.0027	-0.0020	-0.0015	-0.0002	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000
2007-12-03	2007-12-18	15	12	-0.0031	-0.0034	-0.0029	-0.0015	-0.0004	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	-0.0031	-0.0034	-0.0029	-0.0015	-0.0004	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
2007-12-18	2007-01-02	15	0	0.0000	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-01-02	2008-01-18	16	40	-0.0053	-0.0053	-0.0050	-0.0030	-0.0016	-0.0010	-0.0007	-0.0002	0.0000	0.0000	0.0000	-0.0050	-0.0050	-0.0047	-0.0028	-0.0015	-0.0010	-0.0007	-0.0002	0.0000	0.0000	0.0000
2008-01-18	2008-02-02	15	30	-0.0031	-0.0023	-0.0021	-0.0012	-0.0006	-0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0031	-0.0023	-0.0021	-0.0012	-0.0006	-0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
2008-02-02	2008-02-17	15	27	-0.0029	-0.0027	-0.0026	-0.0022	-0.0022	-0.0005	-0.0001	0.0001	0.0000	0.0000	0.0000	-0.0029	-0.0027	-0.0026	-0.0022	-0.0022	-0.0005	-0.0001	0.0001	0.0000	0.0000	0.0000
2008-02-17	2008-03-03	15	0	-0.0003	-0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000	-0.0003	-0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	0.0000
2008-03-03	2008-03-19	16	26	-0.0046	-0.0049	-0.0047	-0.0020	-0.0007	-0.0006	-0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0043	-0.0046	-0.0044	-0.0019	-0.0006	-0.0006	-0.0001	0.0000	-0.0001	0.0000	0.0000
2008-03-19	2008-04-18	30	35	-0.0174	-0.0184	-0.0160	-0.0094	-0.0070	-0.0042	-0.0012	0.0000	0.0000	0.0000	0.0000	-0.0087	-0.0092	-0.0080	-0.0047	-0.0035	-0.0021	-0.0006	0.0000	0.0000	0.0000	0.0000
2008-04-18	2008-05-03	15	35	-0.0072	-0.0085	-0.0088	-0.0056	-0.0020	-0.0007	-0.0001	0.0000	0.0001	0.0000	0.0000	-0.0072	-0.0085	-0.0088	-0.0056	-0.0020	-0.0007	-0.0001	0.0000	0.0001	0.0000	0.0000
2008-05-03	2008-05-18	15	10	-0.0023	-0.0027	-0.0016	-0.0004	0.0000	-0.0001	-0.0001	0.0000	0.0001	0.0000	0.0001	-0.0023	-0.0027	-0.0016	-0.0004	0.0000	-0.0001	-0.0001	0.0000	0.0001	0.0000	0.0001
2008-05-18	2008-06-02	15	23	-0.0057	-0.0061	-0.0056	-0.0038	-0.0019	-0.0008	0.0000	0.0000	0.0000	0.0000	-0.0001	-0.0057	-0.0061	-0.0056	-0.0038	-0.0019	-0.0008	0.0000	0.0000	0.0000	0.0000	-0.0001
2008-06-02	2008-06-17	15	0	-0.0008	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0008	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-06-17	2008-07-02	15	35	-0.0019	-0.0023	-0.0023	-0.0015	-0.0012	-0.0009	-0.0004	0.0000	0.0000	0.0000	0.0000	-0.0019	-0.0023	-0.0023	-0.0015	-0.0012	-0.0009	-0.0004	0.0000	0.0000	0.0000	0.0000
2008-07-02	2008-07-17	15	0	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-07-17	2008-08-18	32	0	-0.0014	-0.0004	0.0000	0.0000	-0.0001	0.0000	0.0001	0.0000	0.0000	-0.0001	0.0000	-0.0006	-0.0002	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2008-08-18	2008-09-02	15	3	-0.0016	-0.0007	-0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	-0.0016	-0.0007	-0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000
2008-09-02	2008-09-17	15	0	-0.0007	-0.0005	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000	-0.0007	-0.0005	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0000
2008-09-17	2008-10-02	15	0	-0.0006	-0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0006	-0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2008-10-02	2008-10-17	15	5	-0.0003	-0.0005	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	-0.0003	-0.0005	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
2008-10-17	2008-11-05	19	53	-0.0065	-0.0062	-0.0046	-0.0023	-0.0014	-0.0006	-0.0002	0.0000	0.0000	0.0000	0.0000	-0.0051	-0.0049	-0.0036	-0.0018	-0.0011	-0.0005	-0.0002	0.0000	0.0000	0.0000	0.0000
2008-11-05	2008-11-20	15	23	-0.0062	-0.0066	-0.0060	-0.0029	-0.0007	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	-0.0062	-0.0066	-0.0060	-0.0029	-0.0007	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001
2008-11-20	2008-12-09	19	130	-0.0054	-0.0061	-0.0050	-0.0031	-0.0020	-0.0027	-0.0012	-0.0012	-0.0008	-0.0005	-0.0002	-0.0042	-0.0049	-0.0039	-0.0024	-0.0016	-0.0021	-0.0010	-0.0010	-0.0006	-0.0004	-0.0002
2008-12-09	2008-12-24	15	730	-0.0061	-0.0060	-0.0059	-0.0050	-0.0030	-0.0027	-0.0017	-0.0024	-0.0015	-0.0011	-0.0010	-0.0061	-0.0060	-0.0059	-0.0050	-0.0030	-0.0027	-0.0017	-0.0024	-0.0015	-0.0011	-0.0010
2008-12-24	2009-01-08	15	0	-0.0011	-0.0002	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	-0.0011	-0.0002	0.0000	0.0000	0.0000	-0.0001	0.0000	0.0001	0.0001	0.0000	0.0000
2009-01-08	2008-01-23	15	45	-0.0024	-0.0021	-0.0018	-0.0019	-0.0015	-0.0011	-0.0005	-0.0001	0.0000	0.0000	0.0000	-0.0024	-0.0021	-0.0018	-0.0019	-0.0015	-0.0011	-0.0005	-0.0001	0.0000	0.0000	0.0000
2008-01-23	2009-02-17	25	50	-0.0114	-0.0124	-0.0094	-0.0067	-0.0040	-0.0034	-0.0021	-0.0002	0.0000	0.0000	0.0000	-0.0069	-0.0075	-0.0056	-0.0040	-0.0024	-0.0020	-0.0012	-0.0001	0.0000	0.0000	0.0000
2009-02-17	2009-03-04	15	0	-0.0008	-0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0001	0.0001	-0.0008	-0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0001	0.0000	-0.0001	0.0001
2009-03-04	2009-03-19	15	23	-0.0040	-0.0033	-0.0030	-0.0025	-0.0016	-0.0007	0.0001	0.0001	0.0000	-0.0001	0.0000	-0.0040	-0.0033	-0.0030	-0.0025	-0.0016	-0.0007	0.0001	0.0001	0.0000	-0.0001	0.0000
2009-03-19	2009-04-05	17	150	-0.0052	-0.0063	-0.0053	-0.0037	-0.0031	-0.0022	-0.0020	-0.0018	-0.0017	-0.0020	-0.0026	-0.0046	-0.0055	-0.0047	-0.0033	-0.0027	-0.0019	-0.0018	-0.0016	-0.0015	-0.0018	-0.0023

** values for measurement periods 2006-10-30 - 2006-11-14 and 2006-11-29 - 2006-12-14 are combined*

Appendix X: Corrosion/flowstone deposition rates at L-2, L-1, L-3, L-4, L-5, L-6.

Beginning of measurements	End of measurements	Number of days	Max. height of water (cm)	Corrosion/flowstone deposition (mm)						Corrosion/flowstone deposition rate (mm/15 days)					
				L-2	L-1	L-3	L-4	L-5	L-6	L-2	L-1	L-3	L-4	L-5	L-6
2006-09-25	2006-10-10	15	/	/	/	/	/	/	/	/	/	/	/	/	/
2006-10-10	2006-10-30	20	-5	/	0.0003	/	0.0001	/	/	/	0.0003	/		/	/
2006-10-30	2006-11-14	15	-5	/	/	0.0001	0.0001	/	/	/	/	0.0001	0.0001	/	/
2006-11-14	2006-11-29	15	0	/	-0.0001	-0.0002	0.0000	/	/	/	-0.0001	-0.0002	0.0000	/	/
2006-11-29	2006-12-14	15	15	/	-0.0025	-0.0020	-0.0018	/	/	/	-0.0025	-0.0020	-0.0018	/	/
2006-12-14	2006-12-29	15	15	/	-0.0024	-0.0020	-0.0016	/	/	/	-0.0024	-0.0020	-0.0016	/	/
2006-12-29	2007-01-13	15	23	/	-0.0040	-0.0037	-0.0029	/	/	/	-0.0040	-0.0037	-0.0029	/	/
2007-01-13	2007-01-28	15	35	/	-0.0025	-0.0027	-0.0026	/	/	/	-0.0025	-0.0027	-0.0026	/	/
2007-01-28	2007-02-12	15	35	/	-0.0044	-0.0040	-0.0046	/	/	/	-0.0044	-0.0040	-0.0046	/	/
2007-02-12	2007-03-01	17	120	/	-0.0038	-0.0049	-0.0052	/	/	/	-0.0033	-0.0044	-0.0046	/	/
2007-03-01	2007-03-16	15	15	/	-0.0030	-0.0034	-0.0023	/	/	/	-0.0030	-0.0034	-0.0023	/	/
2007-03-16	2007-03-31	15	15	/	-0.0047	-0.0038	-0.0052	/	/	/	-0.0047	-0.0038	-0.0052	/	/
2007-03-31	2007-04-15	15	5	/	-0.0011	-0.0002	-0.0003	/	/	/	-0.0011	-0.0002	-0.0003	/	/
2007-04-15	2007-05-01	16	0	-0.0004	-0.0002	0.0003	0.0001	-0.0002	-0.0001	-0.0004	-0.0002	0.0003	0.0001	-0.0002	-0.0001
2007-05-01	2007-05-16	15	-5	-0.0004	-0.0006	0.0002	0.0000	-0.0002	-0.0003	-0.0004	-0.0006	0.0002	0.0000	-0.0002	-0.0003
2007-05-16	2007-05-31	15	-5	0.0000	-0.0008	0.0001	0.0002	0.0002	-0.0001	0.0000	-0.0008	0.0001	0.0002	0.0002	-0.0001
2007-05-31	2007-06-15	15	-5	-0.0001	-0.0002	-0.0002	0.0000	0.0002	0.0001	-0.0001	-0.0002	-0.0002	0.0000	0.0002	0.0001
2007-06-15	2007-06-30	15	-5	0.0001	-0.0002	0.0000	0.0000	0.0000	0.0002	0.0001	-0.0002	0.0000	0.0000	0.0000	0.0002
2007-06-30	2007-07-15	15	-5	-0.0016	0.0001	0.0001	0.0001	0.0001	0.0002	-0.0016	0.0001	0.0001	0.0001	0.0001	0.0002
2007-07-15	2007-07-29	14	-5	0.0002	0.0000	0.0000	0.0000	0.0001	0.0000	0.0002	0.0000	0.0000	0.0001	0.0001	0.0000
2007-07-29	2007-08-17	19	-5	-0.0002	0.0001	0.0000	-0.0001	0.0002	0.0000	-0.0001	0.0001	0.0000	-0.0001	0.0002	0.0000
2007-08-17	2007-09-04	18	-5	-0.0001	-0.0001	0.0000	-0.0001	0.0000	-0.0001	-0.0001	-0.0001	0.0000	-0.0001	0.0000	-0.0001
2007-09-04	2007-09-19	15	80	-0.0010	-0.0004	-0.0005	-0.0004	-0.0003	-0.0002	-0.0010	-0.0004	-0.0005	-0.0004	-0.0003	-0.0002
2007-09-19	2007-10-04	15	40	-0.0067	-0.0048	-0.0042	-0.0042	/*	/*	-0.0067	-0.0048	-0.0042	-0.0042	-0.0077	-0.0060
2007-10-04	2007-10-19	15	48	-0.0079	-0.0045	-0.0036	-0.0036	-0.0026	-0.0021	-0.0079	-0.0045	-0.0036	-0.0036	-0.0026	-0.0021
2007-10-19	2007-11-03	15	23	-0.0090	-0.0062	-0.0061	-0.0052	-0.0153*	-0.0119*	-0.0090	-0.0062	-0.0061	-0.0052	-0.0077	-0.0060
2007-11-03	2007-11-18	15	5	-0.0049	-0.0025	-0.0021	-0.0014	-0.0008	-0.0005	-0.0049	-0.0025	-0.0021	-0.0014	-0.0008	-0.0005
2007-11-18	2007-12-03	15	12	-0.0057	-0.0029	-0.0031	-0.0023	-0.0027	-0.0020	-0.0057	-0.0029	-0.0031	-0.0023	-0.0027	-0.0020
2007-12-03	2007-12-18	15	12	-0.0033	-0.0030	-0.0032	-0.0019	-0.0020	-0.0018	-0.0033	-0.0030	-0.0032	-0.0019	-0.0020	-0.0018
2007-12-18	2007-01-02	15	0	-0.0006	0.0000	0.0000	0.0000	0.0001	0.0001	-0.0006	0.0000	0.0000	0.0000	0.0001	0.0001
2008-01-02	2008-01-18	16	40	-0.0070	-0.0052	-0.0051	-0.0039	-0.0042	-0.0034	-0.0066	-0.0049	-0.0048	-0.0036	-0.0040	-0.0032
2008-01-18	2008-02-02	15	30	-0.0039	-0.0031	-0.0026	-0.0018	-0.0018	-0.0015	-0.0039	-0.0031	-0.0026	-0.0018	-0.0018	-0.0015
2008-02-02	2008-02-17	15	27	-0.0031	-0.0029	-0.0033	-0.0023	-0.0023	-0.0020	-0.0031	-0.0029	-0.0033	-0.0023	-0.0023	-0.0020
2008-02-17	2008-03-03	15	0	0.0000	-0.0003	0.0000	0.0001	0.0001	0.0000	0.0000	-0.0003	0.0000	0.0001	0.0001	0.0000
2008-03-03	2008-03-19	16	26	-0.0051	-0.0045	-0.0047	-0.0030	-0.0035	-0.0030	-0.0048	-0.0042	-0.0044	-0.0028	-0.0033	-0.0028
2008-03-19	2008-04-18	30	35	-0.0161	-0.0174	-0.0148	-0.0109	-0.0131	-0.0094	-0.0080	-0.0087	-0.0074	-0.0055	-0.0065	-0.0047
2008-04-18	2008-05-03	15	35	-0.0081	-0.0072	-0.0087	-0.0055	-0.0057	-0.0044	-0.0081	-0.0072	-0.0087	-0.0055	-0.0057	-0.0044
2008-05-03	2008-05-18	15	10	-0.0028	-0.0023	-0.0015	-0.0010	-0.0011	-0.0009	-0.0028	-0.0023	-0.0015	-0.0010	-0.0011	-0.0009
2008-05-18	2008-06-02	15	23	-0.0061	-0.0058	-0.0056	-0.0040	-0.0038	-0.0033	-0.0061	-0.0058	-0.0056	-0.0040	-0.0038	-0.0033
2008-06-02	2008-06-17	15	0	-0.0008	-0.0008	0.0002	-0.0001	0.0001	0.0001	-0.0008	-0.0008	0.0002	-0.0001	0.0001	0.0001
2008-06-17	2008-07-02	15	35	-0.0018	-0.0019	-0.0018	-0.0012	-0.0015	-0.0011	-0.0018	-0.0019	-0.0018	-0.0012	-0.0015	-0.0011
2008-07-02	2008-07-17	15	0	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001
2008-07-17	2008-08-18	32	0	0.0002	-0.0014	0.0002	0.0002	0.0001	0.0001	0.0001	-0.0006	0.0001	0.0001	0.0001	0.0000
2008-08-18	2008-09-02	15	3	-0.0002	-0.0018	-0.0002	-0.0002	-0.0001	-0.0002	-0.0002	-0.0018	-0.0002	-0.0002	-0.0001	-0.0002
2008-09-02	2008-09-17	15	0	-0.0006	-0.0007	0.0000	0.0003	0.0003	0.0003	-0.0006	-0.0007	0.0000	0.0003	0.0003	0.0003
2008-09-17	2008-10-02	15	0	0.0001	-0.0006	0.0000	0.0000	0.0000	0.0000	0.0001	-0.0006	0.0000	0.0000	0.0000	0.0000
2008-10-02	2008-10-17	15	5	0.0002	-0.0003	0.0001	-0.0001	0.0001	0.0000	0.0002	-0.0003	0.0001	-0.0001	0.0001	0.0000
2008-10-17	2008-11-05	19	53	-0.0063	-0.0068	-0.0048	-0.0052	-0.0042	-0.0037	-0.0050	-0.0054	-0.0038	-0.0041	-0.0033	-0.0029
2008-11-05	2008-11-20	15	23	-0.0066	-0.0062	-0.0044	-0.0051	-0.0036	-0.0036	-0.0066	-0.0062	-0.0044	-0.0051	-0.0036	-0.0036
2008-11-20	2008-12-09	19	130	-0.0081	-0.0054	-0.0045	-0.0049	-0.0039	-0.0037	-0.0064	-0.0042	-0.0036	-0.0038	-0.0031	-0.0029
2008-12-09	2008-12-24	15	730	-0.0085	-0.0061	-0.0053	-0.0052	-0.0045	-0.0036	-0.0085	-0.0061	-0.0053	-0.0052	-0.0045	-0.0036
2008-12-24	2009-01-08	15	0	-0.0005	-0.0011	-0.0001	-0.0002	-0.0001	-0.0001	-0.0005	-0.0011	-0.0001	-0.0002	-0.0001	-0.0001
2009-01-08	2008-01-23	15	45	-0.0028	-0.0024	-0.0019	-0.0020	-0.0018	-0.0017	-0.0028	-0.0024	-0.0019	-0.0020	-0.0018	-0.0017
2008-01-23	2009-02-17	25	50	-0.0125	-0.0114	-0.0102	-0.0072	-0.0062	-0.0061	-0.0075	-0.0069	-0.0061	-0.0043	-0.0037	-0.0037
2009-02-17	2009-03-04	15	0	-0.0005	-0.0008	-0.0001	-0.0001	0.0000	0.0002	-0.0005	-0.0008	-0.0001	-0.0001	0.0000	0.0002
2009-03-04	2009-03-19	15	23	-0.0036	-0.0040	-0.0034	-0.0021	-0.0025	-0.0015	-0.0036	-0.0040	-0.0034	-0.0021	-0.0025	-0.0015
2009-03-19	2009-04-05	17	150	-0.0071	-0.0052	-0.0058	-0.0036	-0.0037	-0.0040	-0.0062	-0.0046	-0.0051	-0.0032	-0.0032	-0.0035

** values for measurement periods 2007-09-19 - 2007-10-04 and 2007-10-19 - 2007-11-03 are combined*