HYPOGEAN MICROCLIMATOLOGY AND HYDROLOGY OF THE 800-900 m ASL LEVEL IN THE MONTE CORCHIA CAVE (TUSCANY, ITALY): PRELIMINARY CONSIDERATIONS AND IMPLICATIONS FOR PALEOCLIMATOLOGICAL STUDIES

MIKROKLIMA IN HIDROLOGIJA NA NADMORSKI VIŠINI 800-900 m V JAMSKEM SISTEMU MONTE CORCHIA: PRVE UGOTOVITVE IN POMEN ZA PALEOKLIMATOLOŠKE RAZISKAVE

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Abstract   UDC 556.3+551.584(450.52)
Ilaria Baneschi, Leonardo Piccini, Eleonora Regattieri, Ilaria Isola, Massimo Guidi, Licia Lotti, Francesco Mantelli, Marco Menichetti, Russell N. Drysdale & Giovanni Zanchetta: Hypogean microclimatology and hydrogology of the 800-900 m asl level in the Monte Corchia cave (Tuscany, Italy): Preliminary considerations and implications for paleoclimatological studies
The Monte Corchia Cave is one of the most promising sites for studying the paleoclimate of the Mediterranean basin, but its hydrology and hydrogeochemistry are still poorly known. In this paper, we report some meteoclimatic and hydrochemical data for different parts of the cave. Conductivity and water level data from La Gronda channel show that this system reacts rapidly to external meteoric events, indicating the presence of a conductive epikarst. Data on two different drips indicate that the physicochemical parameters, such as conductivity, pH, $\delta^{13}C_{DIC}$ and drip rate depend on the local structural setting and water path length. The data presented show that Galleria delle Stalattiti (the focus of the paleoclimate research) has the most stable conditions in terms of temperature, and the dripwaters show constant pH, electrical conductivity, alkalinity, calcium and magnesium content and $\delta^{18}O$. Drip rate is not affected by rain events and displays long-term trends that require a longer period of monitoring for elucidating their nature. The preliminary data presented here corroborate the hypotheses suggesting Galleria delle Stalattiti as a good example of a "deep" hypogean system of Fairchild *et al.* (2007).
Keywords: karst hydrology, cave meteoclimatology, groundwater, speleothems, Antro del Corchia, Alpi Apuane.

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Ilaria Baneschi, Leonardo Piccini, Eleonora Regattieri, Ilaria Isola, Massimo Guidi1, Licia Lotti, Francesco Mantelli, Marco Menichetti, Russell N. Drysdale & Giovanni Zanchetta: Mikroklima in hidrologija na nadmorski višini 800-900 m v jamskem sistemu Monte Corchia: prve ugotovitve in pomen za paleoklimatološke raziskave
Jamski sistem Monte Corchia je ena najobetavnejših krajev za paleoklimatske raziskave v Sredozemlju. Kljub temu je hidrologija in hidrokemija sistema slabo poznana. V članku predstavimo nekatere klimatsko-meteorološke in hidrokemične podatke iz različnih delov sistema. Meritve prevodnosti in vodnega nivoja v kanalu La Gronda, kažejo hiter odziv sistema na padavine in dobro razvito epikraško cono. Odziv prevodnosti, pH, in $\delta^{13}C_{DIC}$ v curkih kaže na lokalno strukturo in dolžino vodne poti vode skozi vadozno cono. V Geleriji stalaktitov, ki je osrednje območje paleoklimatskih raziskav, smo zabeležili stabilno temperaturo, specifično električno prevodnost, pH, alkalnost ter koncentracijo kalcija, magnezija in $\delta^{18}O$. Hitrost kapljanja se tu ne odziva na padavine, ampak kaže dolgo časovne trende, katerih značilnosti bomo lahko videli šele po daljšem opazovanju. Trenutni podatki podpirajo hipotezo, da je Galerija Stalaktitov dober primer globokega podzemnega sistema v smislu, kot ga definira Fairchild (2007).
Ključne besede: kraška hidrologija, jamska klima, podzemna voda, kapniki, Antro del Corchia, Apuanske Alpe.

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INTRODUCTION

In recent years, the Monte Corchia Cave system (Alpi Apuane, central Italy) has turned out to be one of the most promising archives for reconstructing the paleoclimate and the paleoenvironment in the Mediterranean basin (Drysdale *et al.* 2004, 2005, 2007, 2009; Zanchetta *et al.* 2007), with implications for the chronology of climatic events at the global scale (Drysdale *et al.* 2007, 2009). However, the hydrology of this large, hypogean system is still far from being completely understood, and the information from climate proxy data extracted from Corchia speleothems is far from complete.

Recently, Fairchild *et al.* (2007) suggested a classification of hypogean environments based on the relationship between flow path, drip chemistry and cave climate, which produces different textures and compositions of speleothems. Specifically, they describe a deep environment characterized by stable conditions in terms of temperature and humidity with slow growth of speleothems, free of influence by short-term (seasonal) variations. They suggested that such conditions could be present only in very deep caves far from the surface, but they do not report examples.

Piccini *et al.* (2008) have recently suggested that the Galleria delle Stalattiti in Corchia Cave might represent an example of the uniform hypogean case of Fairchild *et al.* (2007). However, the data published were relatively sparse and influenced by the fact that the size and remoteness of this cave has prevented the acquisition of accurate and sufficiently long monitoring data from the part of greatest scientific interest before the opening of the cave to tourism. Considering the exceptional characteristics of this site and the relevance of paleoclimatic implications of the research, more detailed monitoring has started recently to better characterize this cave environment. This paper discusses some of the preliminary results from this work. However, differently from Piccini *et al.* (2008), who described the general features of the cave system, in this paper we focus on a preliminary comparison of the basic hydro-geochemical and hydrological characteristics of different sub-systems within Corchia: La Gronda stream and two drips, located at about the same elevation range (from 800 to 900 m asl), but in two different sectors of the cave characterized by different geological and structural (e.g. rock thickness above the cave) contexts. This study points out the complexity of this cave and highlights the particular climatic stability of the Galleria delle Stalattiti. The data presented here support the general idea that Galleria delle Stalattiti could be a good example of a "hypogean cave" *sensu* Fairchild *et al.* (2007).

As a deep environment with low drip rate with continuous flow and constant chemistry in a long time scale, the Galleria delle Stalattiti offers the possibility of a more detailed understanding of the landscape, tectonic and climatic evolution of the region, as introduced by Drysdale *et al.* (2004).

STUDY AREA

The Monte Corchia karst system is located in the southwestern part of the Alpi Apuane (NW Tuscany, Italy) (Fig. 1) and is developed inside the carbonate core of a syncline, almost completely enclosed by a non-karstifiable, low permeability basement. Corchia Cave is about sixty km long and 1197 m deep and it is presently the largest and one of the deepest caves in Italy. The presently known cave consists of a 3D network of passages distributed from 1550 to 450 m asl, having the shape of regular tubes or canyons and with a mainly horizontal pattern. Several high-gradient passages intersect epiphreatic networks along the main fractures and form the present active drainage system from the surface to the main collector (Piccini 1998). The conduit level located between 900 and 800 m asl is still active in the inner part of the system, whereas it forms a relict level of phreatic passages that have been part of the tourist path since 2001. The system now has 14 entrances accessible to humans.

The Alpi Apuane represents a tectonic window that shows the deepest exposed levels (Tuscan Metamorphic Units) of the Northern Apennines (Carmignani & Kligfield 1990; Molli & Vaselli 2006 and references therein). The Mesozoic cover includes Triassic continental to shallow water deposits followed by Upper Triassic-Liassic carbonate platform metasediments ("Grezzoni" dolostones, dolomitic marbles and marbles), which are succeeded by Upper Liassic-Lower Cretaceous cherty metalimestones, cherts and calcschists, and Lower Cretaceous to Lower Oligocene sericitic phyllites and calcschists. The Oligocene-Early Miocene sedimentation of turbiditic metasandstone closes the sedimentary history of the domain.
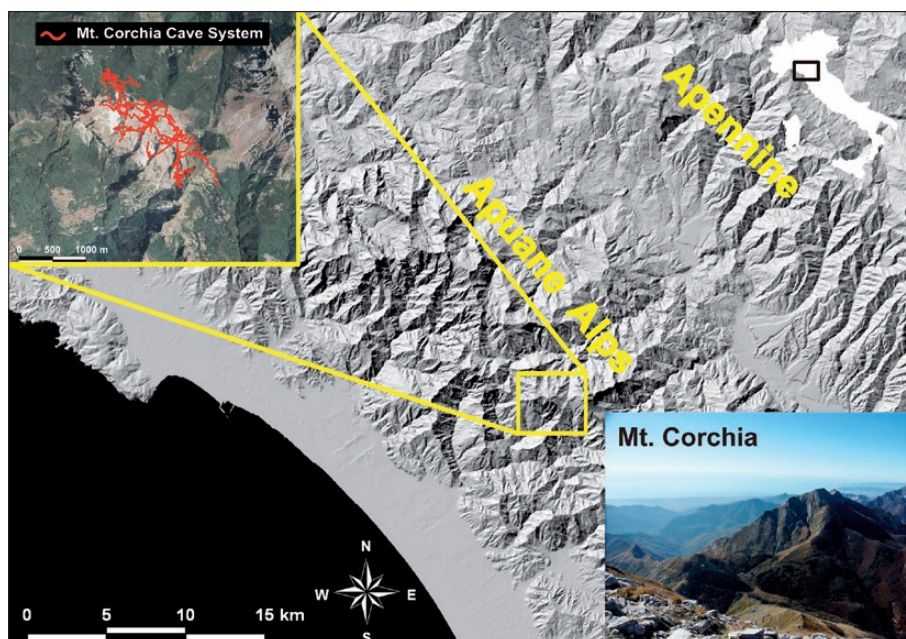
Fig. 1: Location map of Monte Corchia Cave.

very steep bedding and by the tectonic repetition of different rocks (mainly limestone and phyllite), which has enhanced the role of differential erosion. The present topography is the result of heavy fluvial erosion accompanied by rapid tectonic uplift during the Early Pleistocene (Piccini *et al.* 2003). Glacial and periglacial processes reshaped the landscape, emphasizing the "alpine-like" features of this mountain range (Braschi *et al.* 1986). On limestone rock, only a few large-scale karst landforms occur, while medium and small-scale landforms are widely represented. In any case, the most important karst features of this area consist of several cave systems among which Corchia is the largest.

The alpine-like landscape of this peculiar region is due to the complex structural setting, characterized by

METHODS

MICROCLIMATOLOGY

At Corchia Cave, microclimate monitoring by ARPAT (Agenzia Regionale per la Protezione dell'Ambiente, Toscana) started in 1998. Three microclimatic stations were installed along the tourist path (Fig. 2). Station ARPAT-1 is at the intersection of the touristic artificial tunnel and the natural path (870 m asl); station ARPAT-2 is located at Galleria del Venerdì, about 1.4 km from the entrance at 830 m asl; station ARPAT-3 is located at Galleria delle Stalattiti, at 840 m a.s.l. and about 2 km from the artificial entrance, but data for this station are available only from 2002 to 2004. Due to technical problems, only temperature data are validated, and even so, are discontinuously. The sensor for temperature is a Pt-100 type with a measurement range of -50 to +80°C and a digital resolution of 0.1°C. Data are collected hourly and stored in a datalogger. The University of Urbino placed a temperature sensor in the Galleria delle Stalattiti for the period 2005-2008 (here, named URB-2, Fig. 2).

Two microclimate stations, measuring temperature, precipitation, wind speed and atmospheric pressure, have been installed on the slopes of Mt. Corchia at two different elevations. The stations include a tipping-bucket rain gauge with a resolution of ±0.2 mm/h and accuracy of 0.1 mm/h for events of 10 mm/h and 0.3 mm/h for events of 60 mm/h, an air temperature sensor with a range of measurement of -50 to +80°C and a digital resolution of 0.1°C, an atmospheric pressure sensor with a resolution and accuracy of ±0.5 mbar and a range of measurement of 600 to 1100 mbar, and a wind speed sensor with an accuracy of 0.1 m/s between 0 and 1 m/s and 0.25 m/s between 1 to 10 m/s and a range of measure of 0 to 50 m/s. All stations take hourly readings of the variables and store these data in a datalogger. The first station (MT-1) is at 860 m asl, just at the entrance of the touristic artificial tunnel, the second one (MT-2) at 1480 m asl, near the highest western crest of the mountain. Because of the position of MT-2, there is a loss of rain when the wind blows from west with ascending motion. After comparison with other rain stations around the studied area, rainfall measurements at MT-2 were not considered reliable, and they are not included in this work. Unfortunately, records of MT-1 are not continuous because of technical problems due to the severe microclimatic conditions. For this reason, here we present only significant and validated time series of data. In this work,

Fig. 2: Detailed map of the Monte Corchia, 800-900 m cave level, with drip and microclimatic stations.

we illustrate data monitored in different parts of Corchia system during the period 2005-2009. Tab. 1 summarizes the location and description of the stations.

Air temperature measurements at the CNR-1 station started in September 2009; therefore, these data are preliminary. The data logger (Escort Data Loggers Ltd) records temperature (accuracy 0.3°C) every 10 minutes, and the data are downloaded using ESCORT Console software.

HYDROLOGY

Since December 2008, a hydrological station (named IDRO-1) has been installed along the tourist pathway at La Gronda Channel, the main active streamway close to the Galleria delle Stalattiti (Fig. 2). The instrument consists of a multi-parameter probe provided with a thermometer, a pressure sensor for water level measurements, a conductivity-meter, a dissolved oxygen sensor, a pH-meter and a turbidity sensor. The sensors are connected to a data logger that collects and processes the measurements. The monitoring covers only five months up to April 2009, due to the damaging of the instruments during a strong flood. Nevertheless, the record furnishes a first set of data concerning the hydrological behavior of a stream near the Galleria delle Stalattiti chamber during the winter season.

This sensor set was placed in a small artificial pool, so water level is affected by the threshold effect due to the artificial damming of the water flow. Therefore, water level record needs to be viewed with caution during high discharge events because of turbulence.

Drip rate counters have been placed under a stalactite since October 2007 at station CNR-2 and since May 2009 at station CNR-1 (Fig. 2). Drip counters used in this study are the STALAGMATE recorders (Collis-

ductivity, 0.25% for temperature and 0.1 for pH. All of the sensors are calibrated on each sampling trip. Total alkalinity was measured in the field by HCl titration according to Gran's method (Gran 1952) using methyl-orange as indicator.

Tab. 1: Location and characteristics of monitoring sites.

Station name	Type	Location	Elevation m asl
MT-1	Microclimatic	Tourist cave entrance	850
MT-2	Microclimatic (only temperature is considered in this work)	SW flank of Mt. Corchia	1600
ARPAT-1	Microclimatic	Cave at artificial tunnel end	875
ARPAT-2	Microclimatic	Cave at 1.4 km from entrance	840
CNR-1	Drip and water sampling	Cave at 0.80 km from entrance	860
CNR-2	Drip and water sampling	Cave at 2 km from entrance	870
URB-2	Temperature	Cave at 2 km from entrance	870
IDRO-1	Multiparameter hydrological	Cave at La Gronda channel	830

ter & Mattey 2008) (further information can be found at http://81.174.171.35/Driptych/Stal_folder/Stal_frameset.html) that acoustically generate electrical impulses of drops falling onto the lid of a watertight box, which contains a signal detector board and a Gemini event data logger (http://www.geminidataloggers.com). Each drip rate up to the maximum (5 drips/sec) is recorded, with a storage interval of 30 minutes. Each drip counter was placed on the top of the dripwater sampling device; the dripwaters are collected into a tank by a funnel after contact with the drip counter. Both devices are still recording in the cave.

HYDROPHYSICAL ANALYSIS

In the last twelve years, several physical and chemical analyses of rain, surface and cave waters have been discontinuously collected by ARPAT and the CNR (Pisa) (Mantelli *et al.* 2005; Piccini *et al.* 2008). Most of the cave waters have been collected more recently along the tourist path and the most visited parts of the cave, although some samples have been collected in the upper sections of the karst system.

Monthly monitoring of dripwater chemistry started in April 2009. The results presented here referred to data collected from April to September 2009 from the drips CNR-1 and CNR-2. Dripwaters are collected in a single bottle of eight litres for about one month, and the physical and chemical parameters analyzed on a composite sample.

Water temperature, conductivity and pH are measured in the field by a portable multi-parameter data logger (DeltaOHM Instruments). Accuracy is 0.5% for con-

Upon collection, each sample was split into two aliquots. One aliquot was filtered and acidified with HCl for cation analysis (Ca, Mg, K and Na) in order to prevent calcite precipitation. The other un-acidified aliquot was analysed for anions and stable isotopes. All solutions were stored in chemically inert plastic bottles and kept in a cool bag until the end of the monitoring period prior to return to the laboratory for analysis. Cations were analysed by Atomic Absorption Spectrometry and anions by ion chromatography (DIONEX-100). The precision for cations and anions were $\leq\pm2\%$. Calcite saturation index (defined as the log of the quotient of ionic activity product and solubility product) and the partial pressure of CO_2 in equilibrium with the solution – expressed as $\log(pCO_2)$ – were determined from measured dripwater chemistry on balanced analyses using the modelling program SOLVEQ (Reed 1982).

The total inorganic carbon (TIC) of the waters was calculated from Total Alkalinity (TAlk), pH, ionic strength and temperature using the stoichiometric approach of inorganic carbon equilibrium (Stumm & Morgan 1981). Because of the low Total Organic Carbon (TOC) concentrations (analyses of different waters from the cave system were between 0.1 mg C/l and 2 mg C/l, Mantelli *et al.* 2005; Piccini *et al.* 2008), the influence of organic anions on alkalinity was considered negligible.

The $\delta^{18}O$ of the water was determined after equilibration with CO_2 (Epstein & Mayeda 1953). The isotopic measurements were made on a ThermoFinnigan MAT-252 mass spectrometer and are given in per mil values (‰) with respect to the V-SMOW standard (Craig 1961). Analytical reproducibility of duplicates measured on different days is better than 0.1‰. The $\delta^{13}C$ of the total dissolved CO_2 in the water (DIC) was measured by adding dry H_3PO_4 to the water sample. The released CO_2 was then collected in a vacuum line, and the $\delta^{13}C$ values were measured with a mass spectrometer as for oxygen and are given in ‰ with respect to the PDB standard (Craig 1957).

RESULTS

AIR TEMPERATURE

Fig. 3 shows the temperature fluctuations of the two external stations (MT-1 and MT-2) and three inner stations (ARPAT-1, 2 and URB-2) during the year 2005. Typical fluctuations emphasize the extreme stability of stations ARPAT-2 and URB-2 compared to ARPAT-1, as expected for the deepest sectors of the cave. Station ARPAT-1 has a mean annual temperature significantly lower than the others two, due to the fact that it is located near two lower entrances through which cold air enters during winter, while ARPAT-2, which is more than 1 km from the entrances, is only marginally influenced by external temperature. In fact, the maximum fluctuation in temperature for station ARPAT-1 is 4°C, from a minimum of 3.6 to a maximum of 9.3°C. For ARPAT-2, the temperature ranges from 7.6 to 9°C.
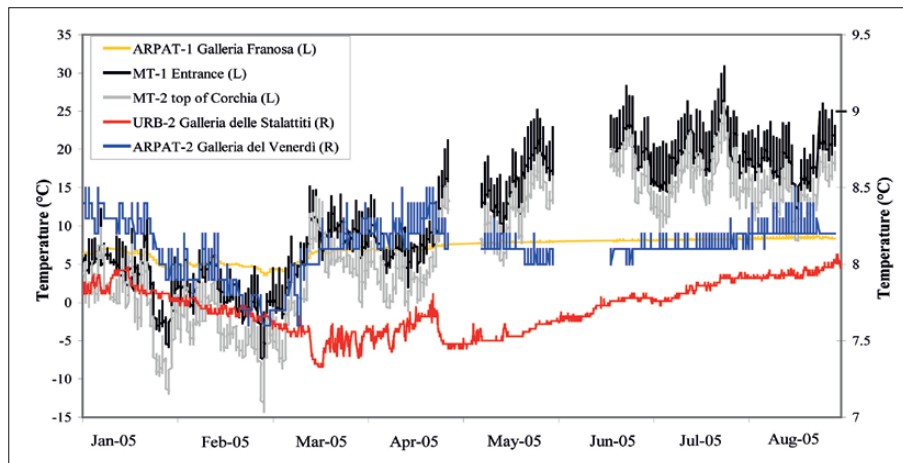
The station URB-2 at Galleria delle Stalattiti is relatively stable in terms of temperature, in agreement with its position nearly 2 km from the nearest natural entrances. Temperature ranges from a minimum of 7.3 °C (in March) to a maximum of 8.1°C (in October and November).

CHANNELLED WATER FLOW

During the period of available measurements, the water level fluctuates between a maximum value of 70.1 cm and a minimum of 52.1 cm; the values of conductivity (EC) range between a maximum of 242 µS/cm and a minimum of 104 µS/cm. The temperature of the water was quite stable with amplitude of 0.8°C in the range of 6.9°C to 7.7°C, and a mean value of 7.3°C. The data recorded by pH probe, as illustrated in Fig. 4, denote the presence of peaks, short in time (about 5 hours) where the signal suddenly increases by ca. 1 pH unit. As these large pH variation events are not associated with variations in water level, conductivity or temperature, they could be considered an artifact of a malfunctioning sensor. Hence, they are not included in the following statistical elaboration and discussion. The maximum value of pH was 7.5 and the minimum 6.

Water level is rapidly influenced by rain events, as illustrated in Fig. 4 where the behavior of the water flow regime was compared to rainfall. This behavior reveals the occurrence of an epikarst with a very good permeability. The negative correlation between electrical conductivity and water level, during the main storm events, suggests that the cave stream is fed by infiltration through vadose passages with rapid flow rate. The pH decreases in correspondence to the rainfall events, indicating water with a lower pH.

Fig. 3: Temperature at the station ARPAT-1, ARPAT-2, URB-2, MT-1 and MT-2 during winter-summer 2005. The temperature data of ARPAT-1, MT-1 and MT-2 are plotted on the left y-axis (L); while URB-2 and ARPAT-2 are on the right y-axis (R).

Fig. 4: Water level, electrical conductivity and pH of Gronda stream (IDRO-1) compared with rainfall.

DRIP RATES

The discharge at the CNR-1 and CNR-2 stations did not cease during the studied period. The Fig. 5 underlines the different behavior of the two drips and their
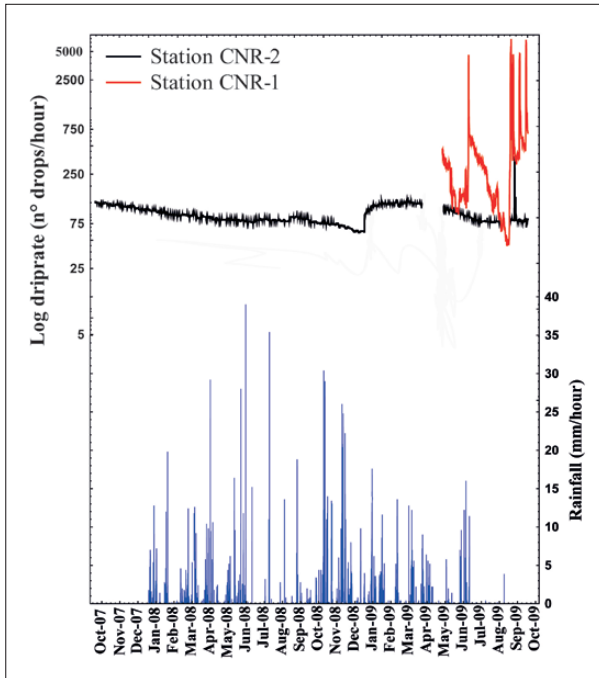

Fig. 5: Drip rate at the stations CNR-1 and CNR-2 and hourly rainfall at the station ARPAT-1, near the tourist entrance.

different sensitivities to rain events. CNR-1 is fed by a fracture characterized by a rapid response to infiltration. Drip rate ranges from about 60 drips/h to more than 7000 drips/h. The short period for monitoring does not yet allow us to resolve significant correlations and time periodicity. CNR-2 shows a different behavior: drip counting ranges from 60 to 130 drips/h, except for a short period (from 23 and 24 September 2009) when it reached about 450 drips/h. This exceptional event lasted about 12 h. However, as the event happened only once during the monitoring period, we cannot say if it is due to a genuine behavior of the system or was caused by an electrical disturbance.

In the CNR-2 drip record, there is not a simple and direct correlation with rainfall events as recorded at the entrance. It is clear, in fact, that there is no rapid response of drip rate to rain events, because the relative maxima of the drip rate in August and October are not coeval with rainy periods. Fig. 6 shows a change in the drip rate during the monitoring period. In particular, for the year 2008, a descending trend is recorded up to 3 September 2008, when the drip rate increased in a few hours from 80 to 90 counts/h and then started to

reduce again. On 8 January 2009 the drip rate reached 125 counts/h and descended slowly.

The period of the monitoring is short to allow meaningful time series analyses. Nonetheless, as a first
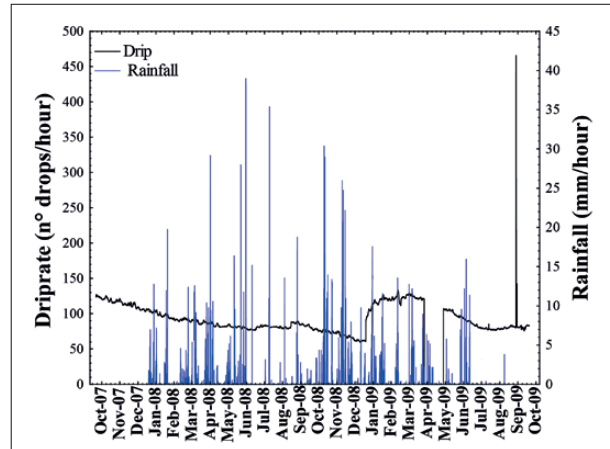

Fig. 6: Drip rate at the station CNR-2 in relation to rainfall. Data are hourly.

attempt, seasonal fluctuations are clearly not evident. Further, the first long descending trend up to 3 September 2008 is reproduced by an exponential curve, whereas the second and thirds events are better described by a parabolic curve. This suggests that the behavior of the system during these two events can be reproduced by an equation simulating a piston flow-discharging system. A longer monitoring period is needed to model the hydrology of the drip.

HYDROPHYSICS AND HYDROCHEMISTRY

Water chemistry of dripwaters at the CNR-1 and CNR-2 sites from April to September 2009 is illustrated in Fig. 7. The two stations show differences in the hydrochemical composition and in the variance of a number of parameters. Tab. 2 shows the mean and the standard deviation (SD) for the measured parameters. Hydrochemical parameters that do not show variability throughout the monitoring period at the station CNR-2 include Ca, Mg, alkalinity and conductivity. The pH varies at least from a maximum of 8.41 to a minimum of 8.10, but irregularly, without any significant correlation with drip rate. Also water temperature increases in a non-monotonous way from 7.6 to 8.0°C. The partial pressure of CO_2 is mainly invariant with a peak in July; in addition saturation index for calcite is constant with a mean value of 0.4 and a minimum in July. The Ca, Mg and alkalinity content is mainly invariant also at the station CNR-1. The differences between CNR-1 and CNR-2 are evident, not only in the Ca and Mg content of the two dripwaters

Tab. 2: Statistics (mean and standard deviation, SD) for chemical composition of the dripwaters collected for one year (2009-2010) for a total of 10 samples.

	CNR-2		CNR-1	
	Mean	*SD*	*Mean*	*SD*
Water Temperature (°C)	7.8	0.2	7.9	0.4
Conductivity (µS/cm, 25 °C)	342.6	8.5	228.6	7.9
pH	8.28	0.11	8.16	0.11
Alkalinity mmol/l	2.74	0.08	2.15	0.09
HCO_3 (mmol/l)	2.74	0.09	2.15	0.07
Ca mmol/l	0.78	0.01	0.80	0.02
Mg mmol/l	0.94	0.01	0.29	0.01

Fig. 7: Water chemistry of CNR-1 and CNR-2 stations from April to September 2009.

equilibration with the cave atmosphere and calcite precipitation. The CO_2 degassing of dripwater causes an increase of the pH with a consequent rise in carbonate species (as CO_3^{--}) dissolved in waters. In these conditions calcite precipitation should be thermodynamically favoured although the kinetics of precipitation is slow (Dreybrodt *et al.* 1997). Moreover, low Ca concentration in dripwater would severely dampen calcite precipitation rates (Genty *et al.* 2001). As highlighted by Drysdale *et al.* (2004), it was not possible to collect fresh calcite for both the CNR-1 and CNR-2 dripwater sites. In this condition a potential increase of pH due to CO_2 degassing and the oversaturation state should take place in a condition of constant alkalinity and Ca. To investigate whether a chemical-physical reaction happens, we have started monitoring the pH of the drip "instantaneously" and collecting aliquots of water for some hours, in order to evaluate differences due to 1 month of storage.

Extensive literature (Baker *et al.* 1997, 2000; Musgrove & Banner 2004; Spötl *et al.* 2005; Baldini *et al.* 2006; McDonald *et al.* 2007) indicates that, **within the** same cave chamber, highly conductive flow and slow, constant flow can co-exist, and these different drips can have substantially different chemical and physical properties. However, this is probably not the case at the Galleria delle Stalattiti, which is under ca. 400 m of rock and is located just below the impermeable basement (see also Piccini *et al.* 2008), making it difficult to imagine significant differences among drips. The selected site resulted from a preliminary selection of other sites (even if there are relatively few drips in the chamber), showing a very similar behaviour (obtained only by scattered observation), and it was selected considering accessibility and to avoid disturbing the tourist path.
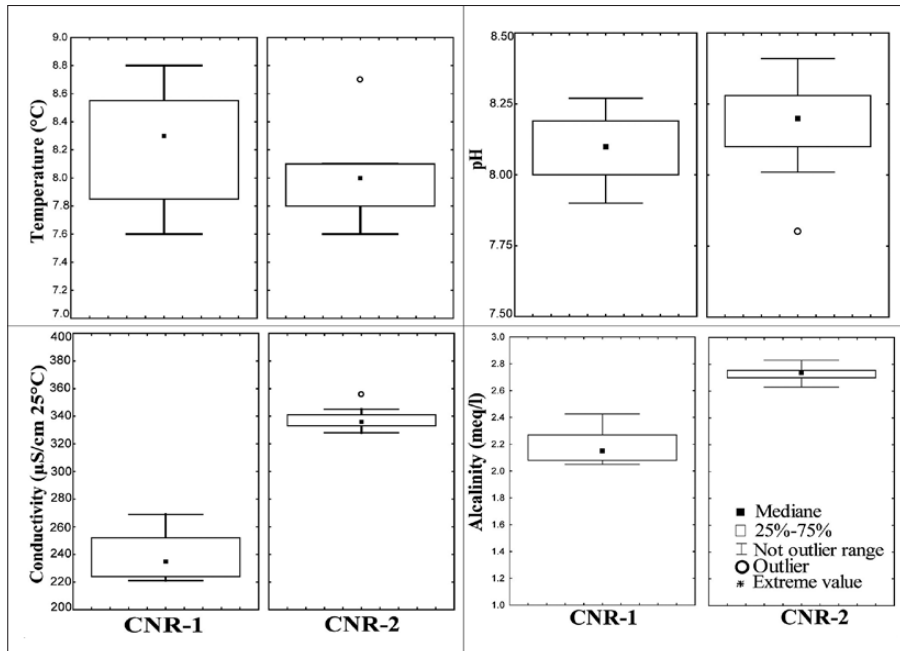
but also in Mg/Ca molar ratio that is 1.21 for CNR-2 and 0.36 for CNR-1.

CNR-1 is characterized by a lower conductivity and alkalinity than CNR-2 (Tab. 2 and Fig. 8). Water temperature at CNR-1 has a higher variability, with a relative minimum in April and June and an increase from June to September. Indeed, the interquartile range for the temperature is 0.3°C and 0.7°C for CNR-2 and CNR-1, respectively. Drip site CNR-1 shows a quite regular variation of the pH with a minimum during July. Consequently saturation index (SI) for calcite in this dripwater is lowest during late July. Hence, both pH and SI show a trend that mirror the calculated pCO_2 of the waters.

We are aware that a one month-aggregate sample should undergo compositional changes as a result of

Fig. 8: Box-whisker for temperature, pH, conductivity and alcalinity of the dripwater collected at the stations CNR-1 and CNR-2. For the elaboration 15 samples were processed for CNR-2 and 11 for CNR-1.
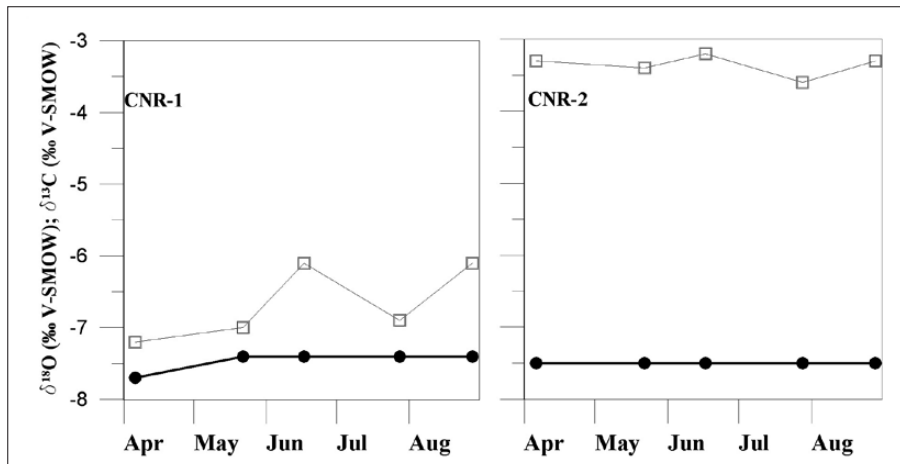

Fig. 9: Oxygen and carbon isotope composition of dripwaters at the stations CNR-1 and CNR-2.

The oxygen isotope composition at the drip station CNR-2 was significantly constant during the monitoring period as illustrated in Fig. 9, confirming the data discussed by Piccini *et al.* (2008). The drip station CNR-1 shows relatively more variability with a lower value measured in April. Piccini *et al.* (2008) also measured the most negative value in April. This could confirm that CNR-1 is likely influenced by seasonal effects and in this case by infiltration of snow melt characterized by more negative isotopic values. The carbon isotope composition of the dissolved inorganic carbon (DIC) is quite different for the two stations, and CNR-1 ($\delta^{13}C$ = -6.66±0.52) shows more variability than CNR-2 ($\delta^{13}C$ = -3.36±0.15), with low values in April and July.

DISCUSSION

The hydrological and hydrophysical monitoring of the 800-900 m asl cave level in Mt. Corchia shows very different conditions for the two sectors of the cave considered.

The karst system has, in general, a very conductive epikarst as indicated by the response of the La Gronda channel to storms. An inverse correlation between EC and discharge indicates that this streamway is fed by infiltration through vadose passages with rapid flow rate during storm events. However, not all the rain events produce appreciable changes in water level or EC. This could suggest that parts of the rapidly draining fractures are not directly involved in feeding the channel. It could also be evidence of the occurrence of solid precipitation (snow) during this period that, therefore, does not give infiltration.

The temperature in the cave is determined by the strong airflow. This influence is particularly evident in the sector of the cave close to the artificial entrance during winter, when cold and dry air enters from lower entrances.

During summer, the airflow is downward and both the stations record the temperature of the air coming from upper entrances, which here is already in thermal equilibrium with the cave walls. Fig. 3 clearly shows that when the external temperature rises systematically above the mean cave temperature, the two stations soon reach almost the same temperature, indicating that the airflow changes direction.

It should be noted that the minimum of temperature at URB-2 is shifted later in time with respect to station ARPAT-2. This behavior could be explained in this way. We hypothesize that in April there is a downward flow of air, which runs in galleries with flowing waters before arriving in the Galleria delle Stalattiti. In this period, the infiltration water still derives from snow melting and so is relatively colder than during the summer season. Conversely, the Galleria del Venerdì, where the station ARPAT-2 is placed, is a dry passage, and in this situation the air tends toward a thermal equilibrium with the rock (Badino 2004), which here is warmer than flowing waters.

Deep sectors of the cave, such as the Galleria delle Stalattiti, are characterized by more stable thermal conditions with maximum annual oscillations of less than 1°C.

The two monitored sectors of the cave also display different hydrodynamic and physicochemical characteristics of the dripwater. CNR-1 seems to reply rapidly to

events and there is more variation in the data for drip-water temperature, conductivity, pH, and $\delta^{13}C$ than at CNR-2. At CNR-1, the rock is a well karstified marble with persistent interconnected fractures that allow efficient flow of infiltration water. The high variability of drip rate suggests the system responds quickly to hydrostatic pressure variations related to rainfall events. We measured a low oxygen isotope composition of the drip-water in April, in correspondence with rainfall events and melting of snow. Indeed, as suggested by Piccini *et al.* (2008), CNR-1 is fed by waters with lower residence time as indicated by few tritium measurements.

Despite the small difference between the pH of CNR-1 and CNR-2 during the monitored period, the CNR-1 median value is lower than CNR-2 denoting a possible influence of rainwater, as recorded for La Gronda channel. Station CNR-2, in Galleria delle Stalattiti, is geometrically overlain at the surface by an impermeable basement of phyllites and metavolcanics (Fig. 10), which are only superficially fractured (Piccini *et al.* 2008). Furthermore, alteration processes of silicates produce clay minerals that prevent the vertical infiltration of recharging meteoric water. Therefore, we presume that water travel is partially developed along the contact zone of "Grezzoni" and this basement. Such structural conditions could explain the different behavior and the long residence time of the waters in the feeding system. In fact, CNR-2 is a higher conductivity site, indicating a higher content of dissolved solids, compared to CNR-1.

TIC is higher for CNR-2 waters (2.76±0.09 mmole) than CNR-1 (2.17±0.07 mmole). This result probably indicates that the infiltrating waters at CNR-2 become enriched with carbonate along their flow path. This could be related to the higher residence time, as supported by tritium data (Doveri *et al.* 2005; Piccini *et al.* 2008), in the system and the rock type. As illustrated in the Fig. 7 the alkalinity and Ca at both stations are constant. This supports the notion that precipitation of carbonate does not happen in the one-month sample (as empirically observed), even if a CO_2 degassing is probably occurring.

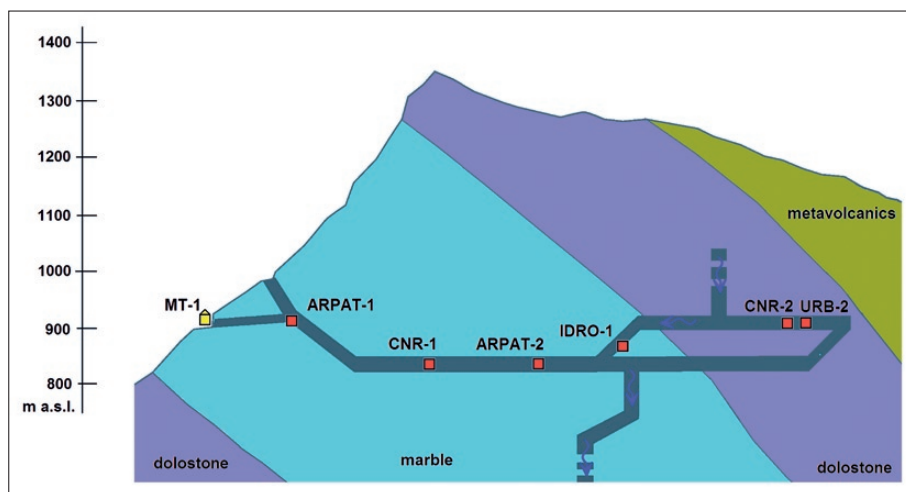Although only one drip point was monitored in the Galleria delle Stalattiti preliminary data indicated

Fig. 10: Geological sketch of the 800-900 m asl level of Corchia cave (tourist path), showing the hydro-structural position of monitoring sites. Note that stations CNR-2 and URB-2 are below the overturned basement.

that most of the characteristics of the drip are reasonably constant over a long period. This indicates that any concretions originated by this kind of flow will mainly reflect long term changes in drip conditions over the recharge above the cave, rather than changes driven by seasonal/yearly variability. This seems to closely match the "hypogean cave" *sensu* Fairchild *et al.* (2007). It is probable that this condition is principally present in the Galleria delle Stalattiti for its deep position and the presence of the impermeable basement on top. Otherwise, CNR-1 drips show a more (although limited) variable behaviour as an effect of less rock cover and absence of the basement. This implies that not all the deep cave sector can have the same behaviour. Moreover, this indicates that potentially the speleothems growing within the Galleria delle Stalattiti can have a high paleoclimatic signal/noise ratio reflecting long-term, persistent changes in climate conditions. In this view these speleothems are not able to detect short term (yearly/decadal) environmental changes.

CONCLUSION

The present strong airflow influences the air temperature in the sector of the cave close to the artificial entrance particularly during winter, when cold and dry air enters from lower entrances. Deep sectors of the cave, like the Galleria delle Stalattiti, are in any case characterized by sufficiently stable thermal conditions with maximum annual oscillations of less than 1°C.

Hydrological and hydro-geochemical data from La Gronda channel indicate that the epikarst above Corchia Cave is highly conductive and give a general idea of the speed with which rain enters the system. Monitoring highlights the different behaviour of the system at each station investigated, due to position with respect to the entrances and depth with respect to the surface. Hydrogeochemical data and drip counts indicate a significant difference between stations CNR-1 and CNR-2, with the latter characterised by more stable conditions. The thicker rock mass and, moreover, the peculiar geological conditions of the Galleria delle Stalattiti, explain these differences. This is also in agreement with isotopic and tritium data. As already stated in Piccini *et al.* (2008), the isotopic composition of the water (δD, $\delta^{18}O$ and tritium content) at the CNR-2 drip indicates a stable and well-mixed plumbing system characterized by a relatively long (ca. 50 yr) residence time. This implies that only persistent and relatively long-term (decadal?) variations in the isotopic composition of local precipitation are capable of forcing a significant change in the isotopic composition of dripwaters and, therefore, of the speleothem calcite.

The hydrodynamic and hydro-physical behavior of the drip at station CNR-2 and of drip sampling in the same sector of the cave show constant chemical and physical values, in agreement with the presence of a regular plumbing system, as suggested by stable isotopes.

Although the monitoring of the cave was largely discontinuous and only for the recent period, data are collected systematically, so the data presented here corroborate the hypotheses suggesting Galleria delle Stalattiti as a good example of a "deep" hypogean system of Fairchild *et al.* (2007). In fact, the physical chemistry (such as pH, conductivity and temperature) at CNR-2 suggests a uniform composition of the water and, since there is no correlation with rainfall events, the component from fracture-fed flow seems to be negligible. Moreover, the air temperature in that sector shows oscillation less than 0.8°C. This can explain the high quality of the Galleria delle Stalattiti in recording centennial to millennial climatic change, whereas it is probably not suitable for recording environmental changes at higher frequency.

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