DOI: 10.7343/as-2016-197 Special Issue AQUA2015 - Paper

Understanding karst environments by thermo-hygrometric monitoring: preliminary results from the Cesi Mountain karst system (Central Italy)

Comprensione dei sistemi carsici attraverso il monitoraggio termo-igrometrico: risultati preliminari dal sistema carsico della Montagna di Cesi (Italia Centrale)

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Riassunto: La comprensione dei sistemi carsici è di fondamentale importanza per la protezione e la valorizzazione di questi ambienti. Il presente lavoro, tramite un approccio multidisciplinare, contribuisce allo studio delle possibili interconnessioni tra le cavità carsiche presenti nella parte meridionale della dorsale Martana (Montagna di Cesi, Italia centrale), una struttura idrogeologica che alimenta un acquifero regionale drenante verso le sorgenti, ad elevata portata e salinità, di Stifone. Nella parte sud-occidentale della dorsale martana sono state individuate sette cavità, cinque delle quali si impostano nella Formazione del Calcare Massiccio. I dati termo-igrometrici raccolti a partire da novembre 2014 all'interno delle cavità, uniti a quelli provenienti dalle stazioni meteorologiche esterne, hanno permesso di identificare il momento dell'inversione del flusso d'aria che si verifica in tardo inverno/inizio primavera e in fine estate/inizio autunno. Nonostante le complessità morfologiche delle cavità e dei modelli concettuali di flusso d'aria, le variazioni termiche osservate e le misure di flusso d'aria finora disponibili, sembrano indicare che gli ambienti sotterranei - anche se di piccole dimensioni - possono essere interconnessi con un sistema di cavità notevolmente più ampio. In conclusione, le misure in corso, associate alle caratteristiche idrogeologiche e geologico-strutturali del massiccio calcareo, risultano utili per indirizzare le future esplorazioni speleologiche nell'ottica di scoprire cavità più grandi e di comprendere meglio i percorsi di infiltrazione dell'acqua nel massiccio calcareo.

Parole chiave: carsismo, rocce fratturate, monitoraggio termo-igrometrico, Appennino centrale, Montagna di Cesi.

Keywords: *karst, fractured and fissured rocks, thermo-hygrometric monitoring, Central Apennines, Cesi Mountain.*

Abstract: *The understanding of karst systems is of paramount importance for the protection and valorisation of these environments. A multidisciplinary study is presented to investigate the possible interconnection between karst features of a karst area located in the south-western part of the Martani chain (Cesi Mountain, Central Italy). This hydrogeological structure contributes to recharge a deep regional aquifer. The latter feeds the high discharge and salinity Stifone springs. In the south-western part of Martani chain, seven caves have been mapped, five of which are hosted in the Calcare Massiccio Formation. The analysis of thermo-hygrometric data collected since Autumn 2014 into the caves and those from external meteorological stations, showed the timing of the airflow inversion occurring on late winter/early spring and summer/early autumn. Despite the complexity of the morphology of caves and of conceptual models of airflow pattern, these data seem to indicate that the monitored small caves could be interconnected to a considerably wider cave system. Data here presented coupled with the knowledge on hydrogeological and geological-structural setting of the limestone massif are useful to drive future speleological explorations, aiming to discover new large cavities and to better understand the water recharge process.*

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Ricevuto: 26 aprile 2016 / Accettato: 5 maggio 2016
Pubblicato online: 13 maggio 2016

Introduction

It is well known that accessible caves only constitute a small proportion of the total conduit network in a karst system (e.g., Jeannin et al. 2007) and tracer tests in caves are used to identify active conduit networks (e.g., Benischke et al. 2007; Goldscheider et al. 2008). Often, in Central Apennines, karst systems are bounded by fluvial-lacustrine deposits and no springs emerge on the surrounding of the limestone massif. Waters infiltrate along fractures and conduit networks reaching a deep regional aquifer and – after very long time – drain towards high discharge and salinity springs located several kilometres away. In order to improve the knowledge on karts system, the study of the air circulation in caves can be an useful support tool. The understanding of the physics of underground environments are useful in the speleological exploration to identify the existences of cavities interconnection and the presence of unknown high and low entrances to the system. Moreover, this approach – coupled with the hydrogeological and geo-structural surveys – contributes to improve the surface-subsurface conceptual model of the karst system for the purposes of vulnerability assessment and for the understanding of infiltration paths.

Several studies in the literature have investigated the air circulation in the underground, taking into account several parameters such as internal/external air temperature, air density, barometric pressure changes, air flow velocity and its direction, geometry of the karst system, etc (Trombe 1952; Cigna 1971; Lismonde 1981; De Freitas et al. 1982; Atkinson et al. 1983; Villar et al. 1984; Choppy 1986; Cigna and Forti 1986; Smithson 1991; Castellani and Dragoni 1986-1987; Dragoni and Verdacchi 1993; Badino 1995; Cigna 2002; Menichetti and Tosti 2008; Pflitsch et al. 2010).

Subterranean air circulation produces impressive physical effects such as vapour columns coming out from the cave during winter (high entrances) or cold air during summer season (low entrances). The air flow in the south-western part of the Martani chain (Central Italy, Fig. 1) – here named *Cesi Mountain* – has attracted the curiosity of historians in the past: Kircher (1665) documented the existence of a consistent air flow from the *Cesi Mountain* (reported in Badino 2016). In this framework, the present paper aims to improve the knowledge of *Cesi Mountain* karst, by using thermo-hygrometric data and occasional airflow measurements. In detail, the work presents the preliminary results of a monitoring campaign carried out since November 2014 on five of the seven caves mapped along the *Cesi Mountain.* Results are discussed taking into account hydrogeological and geological-structural setting of the limestone massif, which hosts a deep regional aquifer draining towards the high discharge and salinity Stifone springs (Fig. 1).

Geological and hydrogeological characteristics of the study site

The study site is located in the south-western part of the Martani chain (Central Italy - 42.610026; 12.282414), characterized by the outcropping of the Calcare Massiccio Formation: this is a platform limestone (fractured and karstified) - belonging to the Umbria-Marche Sequence - hosting several caves (Figures 2 and 3). In this area the successions are characterized by condensed sequence (Pialli 1976; Colacicchi et al. 1988) - with the presence of stratigraphic gaps and/or condensation - deposited on structural high (horst): in detail, the Jurassic Formations (Corniola, Rosso Ammonitico and Calcari Diasprigni Formations) are replaced by the Bugarone Formation (nodular limestone).

As reported by Brozzetti and Lavecchia (1995), the Martani chain is characterized by an asymmetric east-verging anticline, the western limb of which has been dissected during Pliocene-Pleistocene by an extensional fault zone named *M Martani ‹‹fault››*. As shown in Figure 2 the strike of this *‹‹fault››* changes from NNW-SSE to WNW-ENE in correspondence of the Cesi village. Caves are aligned along the main faults and fractures: for example, the Arnolfi cave (n 3 in figures 2 and 3a) develops along a fault zone having a strike NNW-SSE, while the GIS cave (n 7 in figures 2 and 3c) is roughly

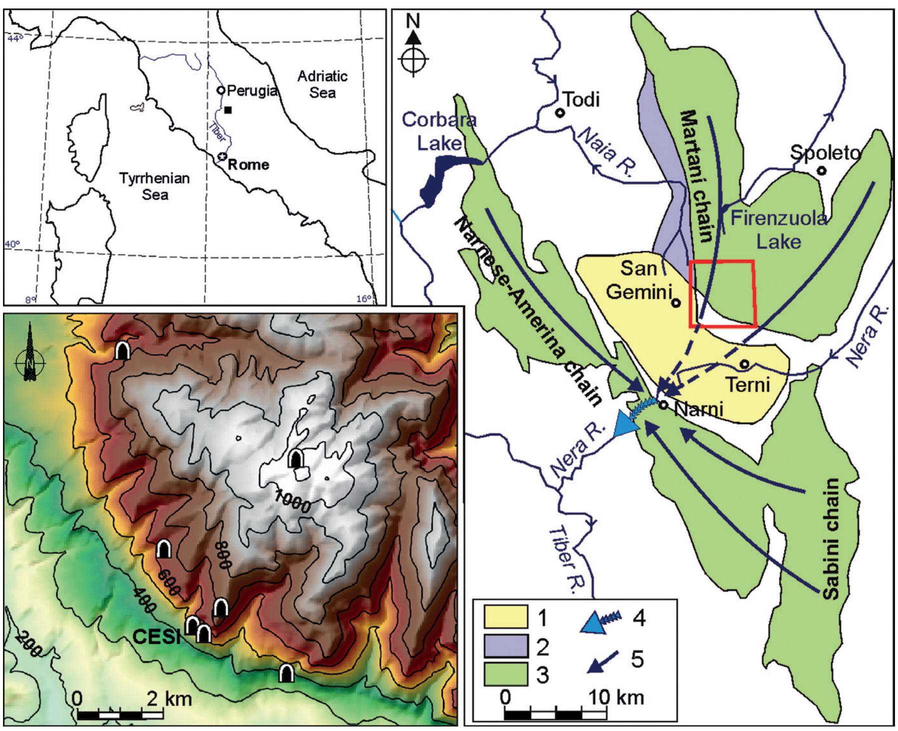

Fig. 1 - Location of the study area (red square) with location of main caves in the southern part of the Martani chain. 1 - Alluvial deposits; 2 - Travertine; 3 - Limestone hydrogeological structures; 4 - Stifone springs; 5 - Regional groundwater flow path.

Fig. 1 - Localizzazione dell'area di studio (quadrato rosso) con ubicazione delle principali grotte presenti nella parte meridionale della Dorsale Martana. 1 - Depositi alluvionali; 2 - Travertino; 3 - Strutture idrogeologiche calcaree; 4 - Sistema sorgentizio di Stifone; 5 - Principali direttrici di flusso della falda di base.

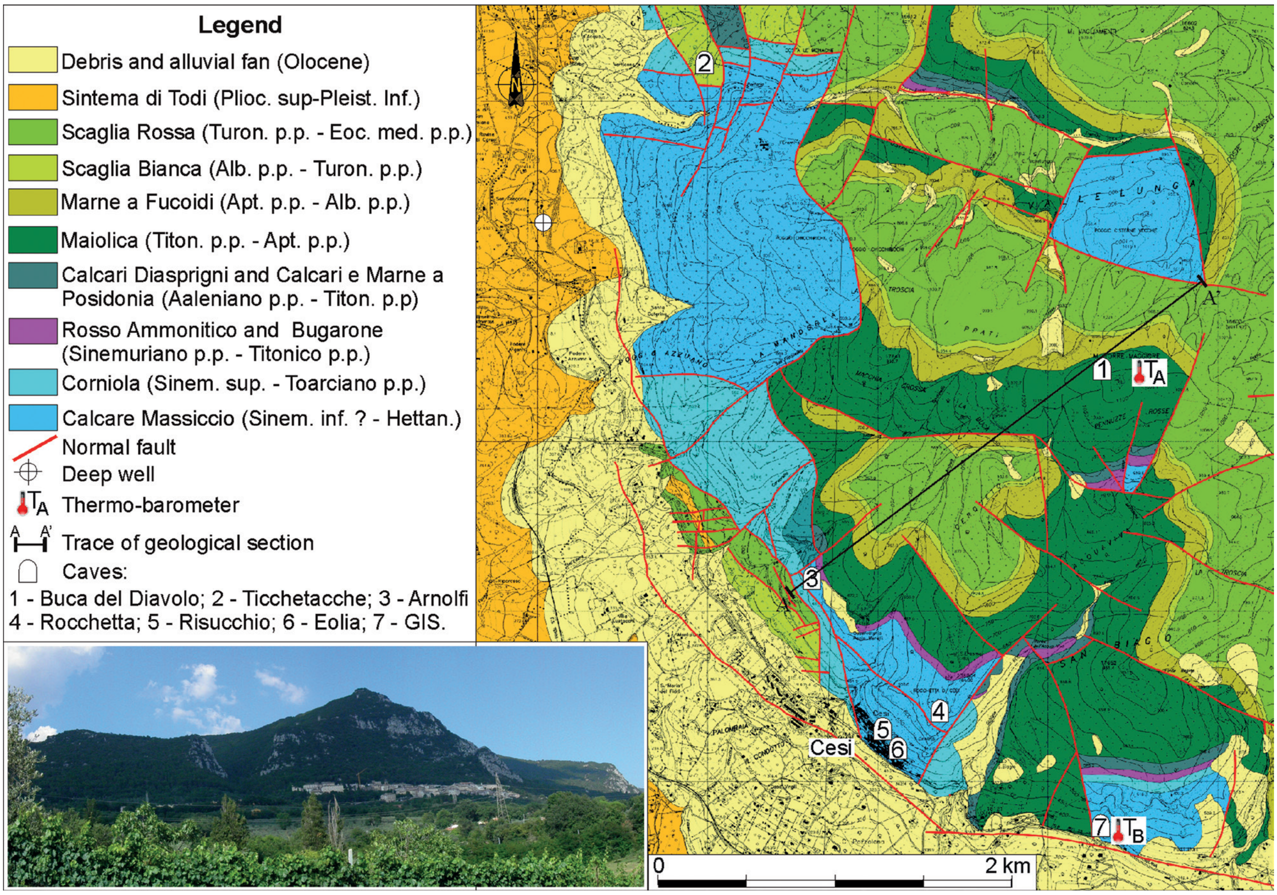

Fig. 2 - Geological map of the southern part of the Martani Chain with a panoramic view of the limestone massif (photo taken from SW) Map has been drafted in GIS environment by using datasets downloaded from, http://umbriageoregioneumbriait/catalogostazioni/catalogoasp). Modified from Di Matteo et al. (2014).

Fig. 2 - Carta geologica della parte meridionale della dorsale martana con una foto panoramica del massiccio calcareo (foto da SW). La carta è stata elaborata in ambiente GIS usando il dataset geologico vettoriale da http://umbriageo.regione.umbria.it/catalogostazioni/catalogo.asp). Modificato da Di Matteo et al. (2014).

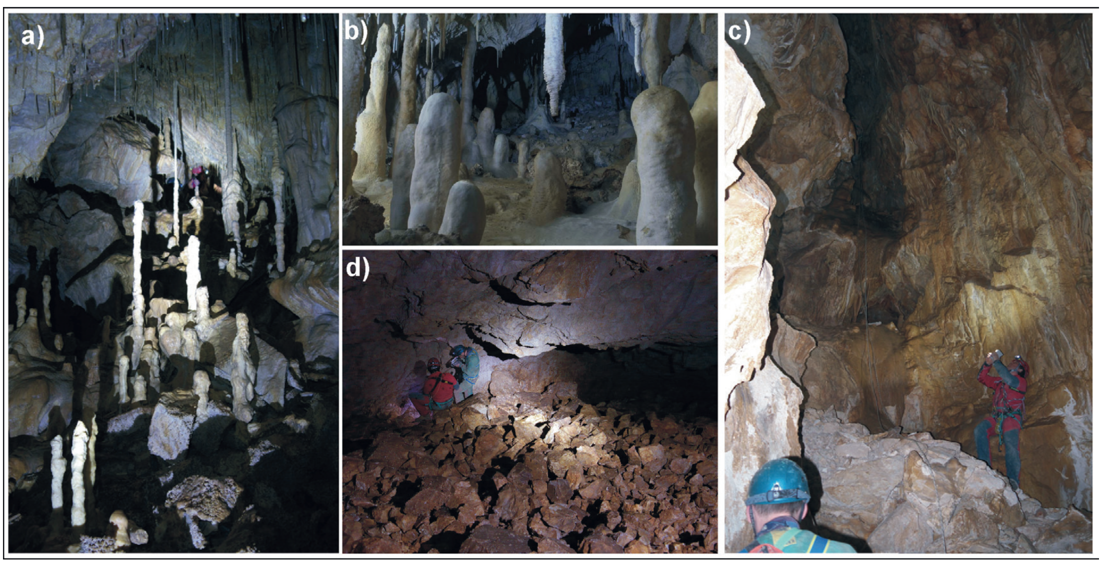

Fig. 3 - Photos of the main caves in Mountain Cesi limestone massif a) Grotta degli Arnolfi (n 3); b) Grotta Eolia (n 6); c) Grotta GIS (n 7); d) Grotta del Ticchetacche (n 2). Modified from Di Matteo et al. (2014).

Fig. 3 - Interno delle principali grotte presenti nel massiccio calcareo di Cesi. a) Grotta degli Arnolfi (n. 3); b) Grotta Eolia (n. 6); c) Grotta GIS (n. 7); d) Grotta del Ticchetacche (n. 2). Modificato da Di Matteo et al. (2014).

oriented WNW-ENE with some sudden change of direction. Five of the seven caves mapped are hosted in the Calcare Massiccio Formation (high permeability) outcropping in the western and southern part of the structure. The Maiolica Formation (stratified and fractured pelagic limestone with high permeability), outcropping along the Martani chain, is also characterized by karstic phenomena, clearly highlighted by the presence of sinkholes (mainly in the north-western part of the chain) and caves (n 1 in figure 2).

As reported by Di Matteo and Dragoni (2006), the water budget carried out on a river catchment located a few kilometres north (Firenzuola catchment, figure 1) indicates that about 63% of the total yield produced by the catchment feeds the regional groundwater flow, which has its main outflow trough the high discharge and salinity Stifone Springs (Q_m = 13 m^3/s; TDS = 3 g/L). The water salinization of these springs occurs when the groundwater reaches the anhydrides, below the Umbria-Marche Sequence (Di Matteo et al. 2009). It is interesting to point out that no springs emerge on the surrounding of the limestone massif of the *Cesi Mountain* that is bounded by talus and alluvial fans which are interdigitated with fluvial-lacustrine deposits (Cattuto et al. 2002). Moreover, the information coming from a deep borehole in the western part of the Cesi Mountain (Fig 2) indicates that about 330 m of dry rocks were drilled, the latest 270 m of which are in the Calcare Massiccio Formation (ISPRA 2010). No water has been found at the well bottom (136 m a.s.l.) confirming that the base aquifer, draining towards the Stifone springs (80 m a.s.l.), has a low hydraulic gradient (a few meters/km) - which is considered common for base regional flow in karst-fractured aquifers (Castany 1967; Boni et al. 1986; Boni and Petitta 1994; Di Matteo et al. 2009). The borehole encountered two main cavities 376 and 176 m a.s.l. (personal communication of the geologist in charge of the borehole drilling). The karst here studied represents the highest part of a complex paleokarst system made up by hidden cavities and conduit networks.

Methodological approach

Monitoring

After a previous campaign of air temperature monitoring inside the Arnolfi cave carried out by Di Matteo et al. (2014), an intensive new monitoring program was implemented since November 2014. In detail, the following measurements were carried out inside and outside five of the seven caves investigated (ns 1, 3, 4, 5, and 7 in figure 2):

- continuous thermo-hygrometric measurements inside the caves by USB PCE-HT71 data logger (1015 x 30 mm, 25 g, range of measures: 0-100% Ur, -40/+70 °C, resolution 0.1 % Ur, 0.1 °C, four readings per day);
- occasional air flow velocity acquisition by hot wire anemometer (SENTRY ST-732, air velocity: 0~40m/s, accuracy ±0.03 m/s);
- continuous outside air temperature, air pressure and air humidity by two thermo-barometers LUTRON MHB-382SD and VOLTCRAFT DL-181THP (four readings per day): one located at the bottom (T_B, close to cave n7, about 350 m a.s.l.) and one at the top (T_A, close to cave n1, about 1100 m a.s.l.) of the limestone massif (figure 2).

Figure 4 shows the used instruments, together with the particular of the sections used for airflow measurements in caves ns 1 and 3: USB data logger for air temperature were placed approximately in the middle of the cave length.

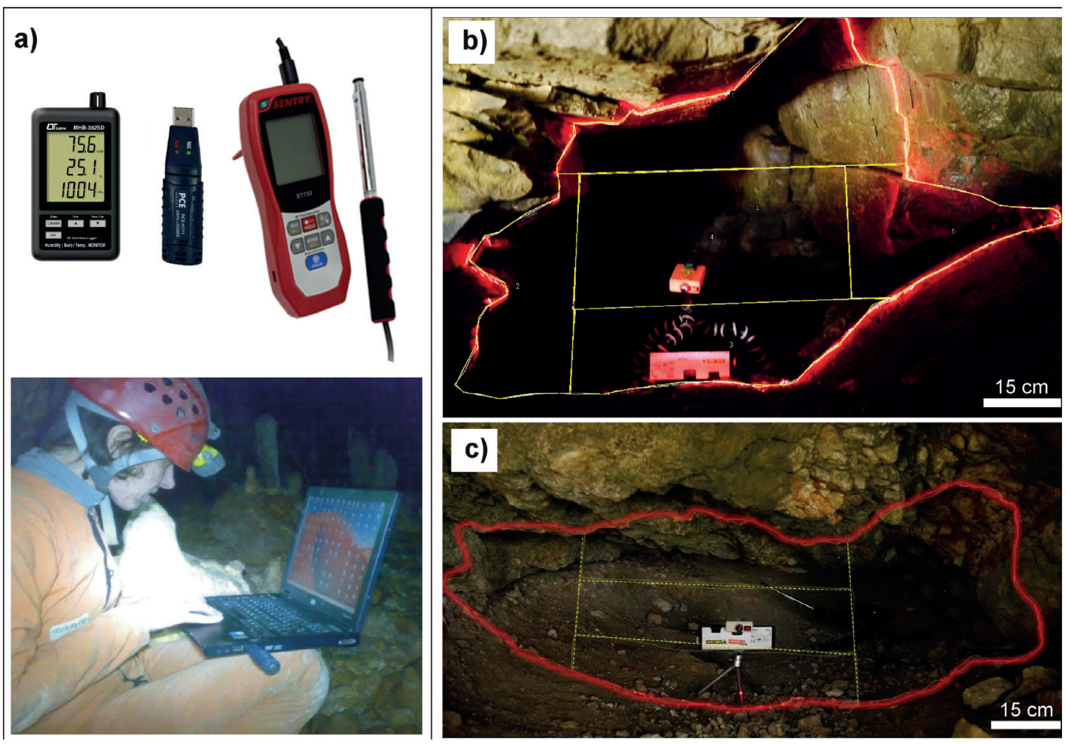

Fig. 4 - Details of USB thermo-hygrometer (PCE-HT71) and hot wire anemometer ST-732 a), and survey of sections for air flow measurement by laser level tripod for cave n 1 – Buca del Diavolo (b) and cave n 3 – Arnolfi (c).

Fig. 4 - Particolare del termo-igrometro USB (PCE-HT71) e dell'anemometro a filo caldo (ST-732) a), e della ricostruzione della sezione per la misura della velocità del flusso d'aria mediante livella laser per la grotta n. 1 – Buca del Diavolo b) e di quella n. 3 – Arnolfi c).

Air flow circulation in karst system

Air circulation inside cave systems and/or between the interior of caves and external environment is an omnipresent phenomenon, although it is not always noticeable. There are various mechanisms that can cause air circulation, mostly (but not only) linked to difference of density of air masses, which move according to Archimede's law:

a. at constant temperature and pressure, the density of air decreases with increasing humidity; this phenomena is important for the development of karst by condensation (Trombe 1954; Bögli 1978; Castellani and Dragoni 1982);
b. if the barometric pressure outside a cave is higher than inside, or viceversa, air moves towards the place with lower pressure. This effect is often rapid and it is hardly measurable in most cave systems (Pflitsch et al. 2010);
c. usually, the air temperature in a cave is fairly constant and approximately equal to the yearly average air temperature outside the cave. This means that the internal and the external air temperatures are different: this corresponds to different air densities. Airflows produced by differences of air densities are also named *density-driven flows*.

Point c) is the key factor for the generation of air currents (Trombe 1954; Bögli 1978; Castellani and Dragoni 1982; De Freitas et al. 1982; Badino 1995; Pflitsch and Piasecki 2003). In the following we shall focus on this last process. The effect of density on the movement of air masses in major karst systems, connected with the surface by at least two entrances at different elevation (e.g., two cavities interconnected each other and located at different altitude), can be approximated by eq. 1 (Trombe 1952; Castellani and Dragoni 1982; Lismonde 2002; Luetscher and Jeannin 2004).

$$\Delta P_m \approx \frac{\rho_0 \cdot g \cdot h}{T_0}\left(T_i - \frac{T_A + T_B}{2}\right) \quad (1)$$

ΔP_m = driving pressure (Pa);
ρ_0 = mean air density inside the cave (kg/m^3);
g = acceleration due to gravity (m/s^2);
h = altitude difference of the system (m);
T_0 = 273 °K;
T_i = mean air temperature of the system (°K);
T_A = is the outside temperature at the top of the system (°K);
T_B = is the outside temperature at the bottom of the system (°K)

The terms *driving pressure* ΔP_m (eq. 1, from Luetscher and Jeannin 2004) indicates the pressure produced by density gradients between cave air and atmospheric air. According to eq. 1, the airflow into the caves moves upward (upward airflow ventilation mode, UAF) or downward (downward airflow ventilation mode, DAF) during the seasons (Faimon and Lang 2013): in Central Apennines the UAF mode occurs during winter/early spring while the DAF mode during spring/early autumn. When $T_i = T_A = T_B$ or $T_i = [(T_A+T_B)/2]$ no ventilation is present into the cave: this situation can be observed when the system passes from UAF to DAF mode, or viceversa.

Due to wall roughness and sudden changes in cross-section of karst conduits, in general the air flow through the system (q_m) is turbulent. As eq. 2 shows (from Luetscher and Jeannin 2004), q_m is expressed by the Darcy–Weisbach equation, where R is the *aeraulic resistance* of the conduit which reflects the headlosses occurring in a natural conduit (kg^{-1} m^{-1}). In other words if ΔP_m increases, the flow through the system (q_m, kg/s) not necessarily increase due to the shape and complexity of conduits affecting the headlosses.

$$q_m = \sqrt{\frac{|\Delta P_m|}{R}} \quad (2)$$

In next sections the results of continuous thermo-hygrometric monitoring and occasional air flow measurements are presented and discussed taking into account also the geological-structural setting of the Cesi Mountain.

Results and data analysis

As illustrated in section 3.1, two thermo-barometers were placed at the bottom (T_B) and the top (T_A) of the limestone massif to monitor the external air temperatures (cfr eq 1). As shown in figure 5, during the observation period (November 2014 – December 2015), the mean external air temperature at the top (10.8 °C) was of about 4.7 °C lower than that at the bottom (about 15.5 °C). The mean annual air temperature registered at the bottom of the system is close to data registered by the thermometer of San Gemini (309 m a.s.l., about T = 15.7), which is the official meteorological station of the *Servizio Idrografico della Regione Umbria,* located about 3 km west to Cesi village. The maximum temperatures were recorded in middle July 2015, the minimum one at the end of December 2014.

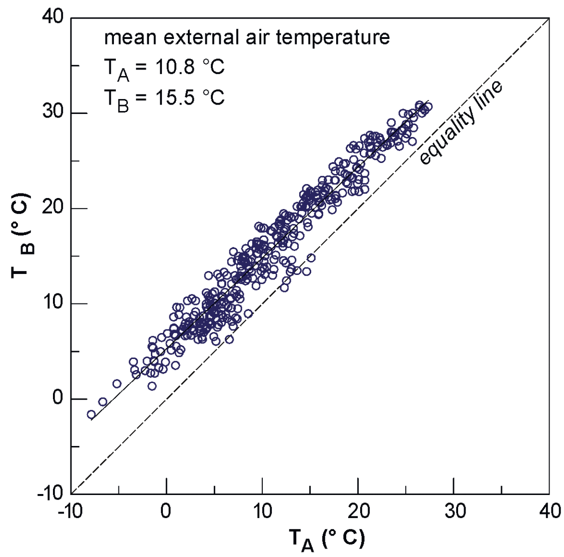

Fig. 5 - Comparison between external daily air temperature at the bottom (TB) and at the top (TA) of the limestone massif (location of thermometers is in figure 2).

Fig. 5 - Comparazione delle temperature giornaliere dell'aria registrate alla base (T_B) e al top del massiccio calcareo (T_A). La localizzazione dei termometri è in figura 2.

Figure 6a and b shows the air temperature recorded inside and outside two caves located respectively at the bottom and at the top of the system, n 3 (Arnolfi cave) and n 1 (Buca del Diavolo). During winter/early spring a large quantity of cold air enters into the Arnolfi cave (Figure 6a), but as soon as the external temperature rises above the internal one, the air flow definitively inverts (the air is expelled from the cave). The air inside the cave gradually reaches a temperature of 11.5° C. A new air flow inversion is registered at the middle of November 2015. On the contrary, the highest cave shows an outflow of warm air during winter with temperature ranging from 11.4° C to about 9.0 °C. Measurements of air flow velocity were carried out in August 2015 in Arnolfi cave and at the end of February 2015 in Buca del Diavolo cave (Figure 6a and b). In detail, the air flow discharge (Q) was of 0.50 m^3/s in Buca del Diavolo cave and 1.85 m^3/s in Arnolfi cave. Measurements carried out during the summer 2015 on

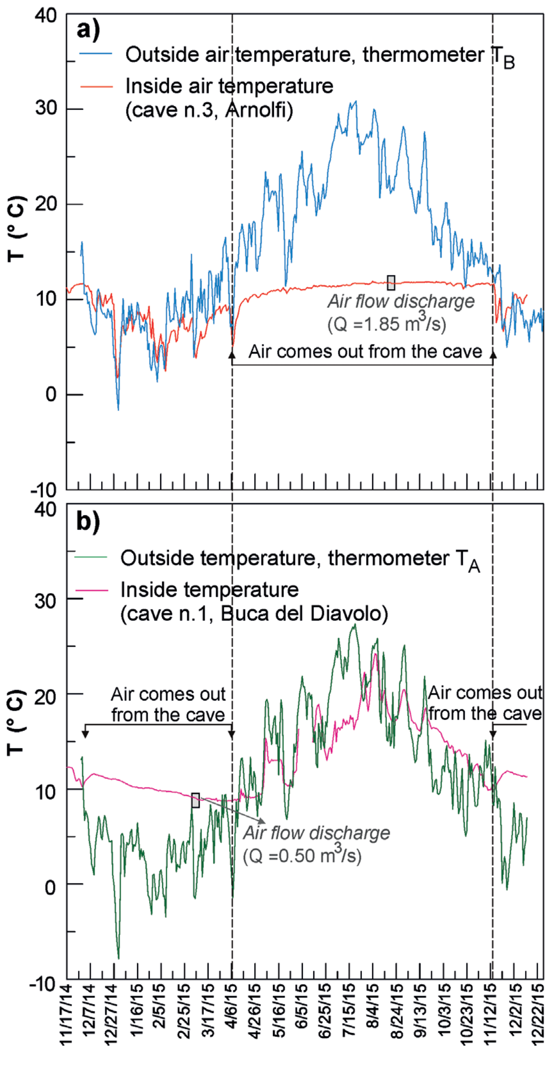

Fig. 6 - Air temperature inside and outside the cave n 3 (a) and n 1 (b) for 2014-2105 period. Q = air flow discharge.

Fig. 6 - Temperatura dell'aria all'interno e all'esterno delle grotte n. 3 (a) e n. 1 (b) per il periodo 2014-2015. Q = portata del flusso d'aria.

the main caves located at the bottom of the system (except Eolia cave n 6) showed a total discharge not less than 6 m^3/s. The measurements carried out in February 2015 on the two high entrances (caves n 1 and n 4) showed a total discharge of about 1.3 m^3/s.

Discussion and conclusions

The results of the monitoring campaign, analyzed taking into account the geological-structural setting of the Cesi Mountain, provide some interesting remarks. Figure 7 shows a geologic cross section roughly oriented NE-SW (trace is reported in figure 2) passing through the caves ns 1 and 3, the air temperatures of which have been analyzed in the previous section (Figure 6).

As can be observed in Figure 7, the limestone sequence in the highest part of the massif is characterized by a set of extensional fold-related fracturing, representing the preferential pathway for the underground air circulation and for the infiltration of water. Currently a new targeted speleological survey (February 2016) allowed to map a conduit in a high fractured zone in the Maiolica Formation (partially clogged by sediments, Figure 8). This conduit is similar to Buca del Diavolo cave, in terms of overall geometry, air temperature and ventilation mode: at the end of February 2016 the air temperature (T = 10.8 °C) and the air flow discharge (about 0.56 m^3/s) were practically similar to those obtained for Buca del Diavolo in February 2015 (during UAF ventilation mode).

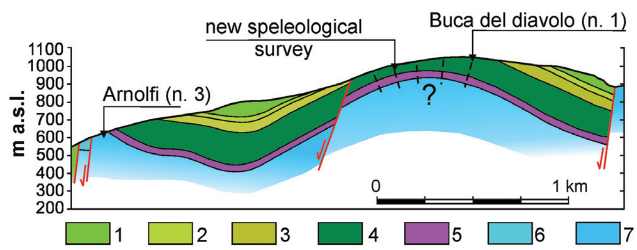

Fig. 7 - Geologic cross section oriented NE-SW (trace is in Fig 2) 1 – Scaglia Rossa; 2 – Scaglia Bianca; 3 – Marne a Fucoidi; 4 – Maiolica; 5 – Bugarone, Rosso Ammonitico, Calcari Diasprigni/Calcari e Marne a Posidonia; 6 – Corniola; 7 – Calcare Massiccio.

Fig. 7 - Sezione geologica orientata NE-SW (la traccia è in Fig. 2). 1 – Scaglia Rossa; 2 – Scaglia Bianca; 3 – Marne a Fucoidi; 4 – Maiolica; 5 – Bugarone, Rosso Ammonitico e Calcari Diasprigni/Marne a Posidonia; 6 – Corniola; 7 – Calcare Massiccio.

The results here obtained indicate that the underground environments – although small in size – seem to be interconnected with a considerably wider cave system in the underlying Calcare Massiccio (?) by means open fractures or conduits. Thermal and air flow velocity data available up to now do not provide a definitive response on the interconnections between high and low caves. The present study has to be considered as a first step in the understanding of this complex karst system and the findings are useful to perform further investigations aiming to setup a continuous air flow monitoring network on some selected cave. This monitoring will provide new information about underground

Fig. 8 - Photos of the ongoing speleological survey in a small cavity along a high fractured zone in the Maiolica Formation (the location is in Figure 7).

Fig. 8 - Particolare della nuova esplorazione speleologica in corso in una piccola cavità impostata all'interno di un zona fortemente fratturata nella Formazione della Maiolica (la localizzazione è in Fig. 7).

environments, not easily accessible for exploration, by analyzing the frequencies of airflow oscillations (eg, Cigna 1968; Plummer 1969; Badino 2010; Faimon et al. 2012; Lang and Faimon 2013).

In conclusion results here discussed, together with the presented conceptual scheme, improve the knowledge on the karst system, necessary to protect and valorise the entire limestone massif. Moreover, the approach contributes to improve the surface-subsurface conceptual model of the karst system for the purposes of vulnerability assessment and for the understanding of infiltration paths.

Acknowledgments: The study was funded by Fondazione Cassa di Risparmio di Terni e Narni (CARIT), Project DIM14FCRTR. The authors wish to thank the Servizio Idrografico della Regione Umbria for meteorological data.

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