

The climatic study of caves with single entrance:  
temperatures, humidity, thermal exchanges

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**Motta Michele & Motta Luigi**



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## Introduction

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The first mountaineers who climbed the Mont Blanc took the opportunity to measure temperature, pressure, and so on. Almost never the caving exploits has accompanied by similar measures. So, although the man frequented the caves since prehistory, we know better the climate of the higher peaks than that of the caves. Yet, the solar radiation not influence directly the cave climate, so this last is very stable, and potentially it is an excellent climatic indicator. Because of the data variability of climatic stations, these data are true climatic parameters only when there are at least thirty years of observations. It is therefore difficult to use them to study rapid climatic variations, such as the global change induced by greenhouse effect, so much so that it is preferable use other climatic indicators, such as glaciers. On the other hand, the latter are diffused only at high latitudes or on mountain ranges. Because of their progressive reduction, the part of the Earth that requires alternative study methods gradually widens.

In areas with normal geothermal gradient, the internal climate of the karst caves depends mainly on the external climate, in particular by the temperatures of the infiltration water and the air. If the external climate varies, also that of the cave changes (with a delay that depends on the intensity of the exchanges of heat and matter with the outside). In a cave, a few dozen meters from the entrance the stability of climatic parameters is so high that their variability becomes comparable with that of a 30-years climatic series. Therefore we could use the multiannual variations of the caves for know climatic trends. They would be much more representative of the traditional climatic indicators, and above all they would be abundant even in low-altitude areas, free of glaciers.

As is obvious, to use the climatic parameters of the caves, it is necessary to study the dynamics of the caves, in order to:

- clarify what are the external factors that influence the climate of the caves;
- choose the most suitable parameters to describe the cave climate;
- establish data collection procedures;
- identify which types of caves are most useful as climatic indicators.

In this work we have focused the study on single-entrance caves. These caves have neither the marked seasonality (due to the chimney effect) of the caves with two entrances, nor the complexity of the multi-entrance caves, nor the poor relations with the outside of the caves whose entrance is artificially closed. As single entrance is considered here a wide mouth through which can pass air (and the man who studies the cave). These caves are the least known from the climatic and dynamic point of view. In fact, caving has using the internal circulation of multi-entry caves since some decades to see if they are more extensive than it appears and to direct the searches for new galleries. Therefore a vast scientific literature describes the ventilation mechanisms of these caves and the consequent thermal variations. Conversely, the lack of appreciable air circulation is considered by cavers as a clue to not extended cave, i.e. not interesting. However, from the biological point of view, in NW Italy the caves with single entrance are the most interesting: their more protected environment host many more endemic species.

For the purposes of this study are considered a single entry:

- caves in which the water flows (in one direction or another) between entrance and one or several passages that are totally submerged, where can pass only water and not air;

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- caves in which in addition to the entrance there are cracks or holes communicating with the outside, but of a reduced width and with tortuous gait, so the transmissivity of the air through these passages is at least an order of magnitude less than through the main entrance.

The dynamics of each cave have peculiar features, depending on the position, extension and intensity of the factors that influence the climate, in particular by:

- air circulation;
- groundwater circulation;
- oozing.

Also the shape of the cave, especially the general inclination, influences the internal dynamics. In view of this, we have classified the caves studied on the basis of the general trend, which can be toward down (starting from the entrance), horizontal or ascending, and on the basis of the presence or not of water circulation in longitudinal direction (periodic flooding, underground watercourses, emerging water table...). All the caves studied show oozing, at least occasionally.

# 1. The Andrassa (Manie karstic plateau, Liguria, NW Italy): a ponor developed toward down, with water circulation

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## 1. Introduction

A general consensus exists that a major mechanism of ventilation is based on inducing of airflows by pressure gradients, related in turn to gradients in air temperature and density (Faimon *et al.*, 2012 and its references). Few authors (Cigna, 1968; Wigley and Brown, 1971; Bögli, 1978) also cite, as “less usual mechanisms”, the effects of water flowing or wind. In opinion of Faimon *et al.* (2012), the importance of wind “could result from several variables controlling the phenomenon. They are: climatic conditions, altitude, orientation of cave entrance to wind, vegetation in front of cave entrance, cave geometry, and so on.

Melegari (1984) says that every cave with single-entrance and developed downwards must have a ventilation “air bag style”, with three seasonal regimes.

1. In summer the deep air is the coldest, and is denser than outdoor air, so the latter enters the cave only to a limited extent. After a short transition zone, at the entrance the air temperature reach quickly the outside value.

2. In winter, the cave air is the warmest. The outdoor air enters, flows along floor and heats up, then slides along ceiling, before of coming out.

3. In transitional seasons little air circulates, with direction that varies, depending on the temperature changes of outside air.

Faimon *et al.* (2012) say that every single-entrance cave is a “static cave”: its circulation “does not ventilates for one half of season when  $T_{\text{ext}} > T_{\text{cave}}$  or  $T_{\text{ext}} < T_{\text{cave}}$ , depending on whether the cave space is located below the entrance (cold air trap) or above the entrance (warm air trap), respectively”. Kowalczyk and Froelich (2010) define three regimes for a “cold air trap”: permanent winter ventilation (i.e. strong exchange of air), summer stagnation, and diurnal variations. In the stagnant ventilation, the airflow direction changes during the diurnal cycle, and only first part of the cave is vented (Faimon *et al.*, 2012).

However, Andrassa contains groundwater and dripping water, i.e. additional sources of heat exchanges. If the heat transfer between air, water and rock changes dramatically the air circulation, the “air bag” and “static” models (commonly applied to all caves with single entrance) would not be applicable to caves in which, together to air, also water normally enter. On the other hand, almost every cave has a water circulation, often more important than that of Andrassa. Our study contributes to this topic by analyzing short-term and long-term data of temperature and humidity.

## 2. The Study Site

### 2.1. Climate

#### *Precipitations*

The pluviometric station of Le Manie is at 1420 m from cave entrance towards SSW (WGS 84 44.19866 N 8.37656 E, 297 m a.s.l.). The annual precipitation (1943 – 1985 period; Motta, 1987) is 916.6 mm, with 68 rainy days/years. Table 1.1 shows seasonal distribution.

The annual precipitation from 1961 to 2010 is 851 mm (fig. 1.1)

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Tab. 1.1: Seasonal distribution of precipitations at Le Manie, period 1943-1985 (Motta, 1987).

	Winter	Spring	Summer	Autumn
Monthly precipitation	225.5 mm	253.3 mm	114.2 mm	323.2 mm
Rainy days	17	20	11	20
Density of seasonal precipitation	13.3	11.8	10.4	16.2

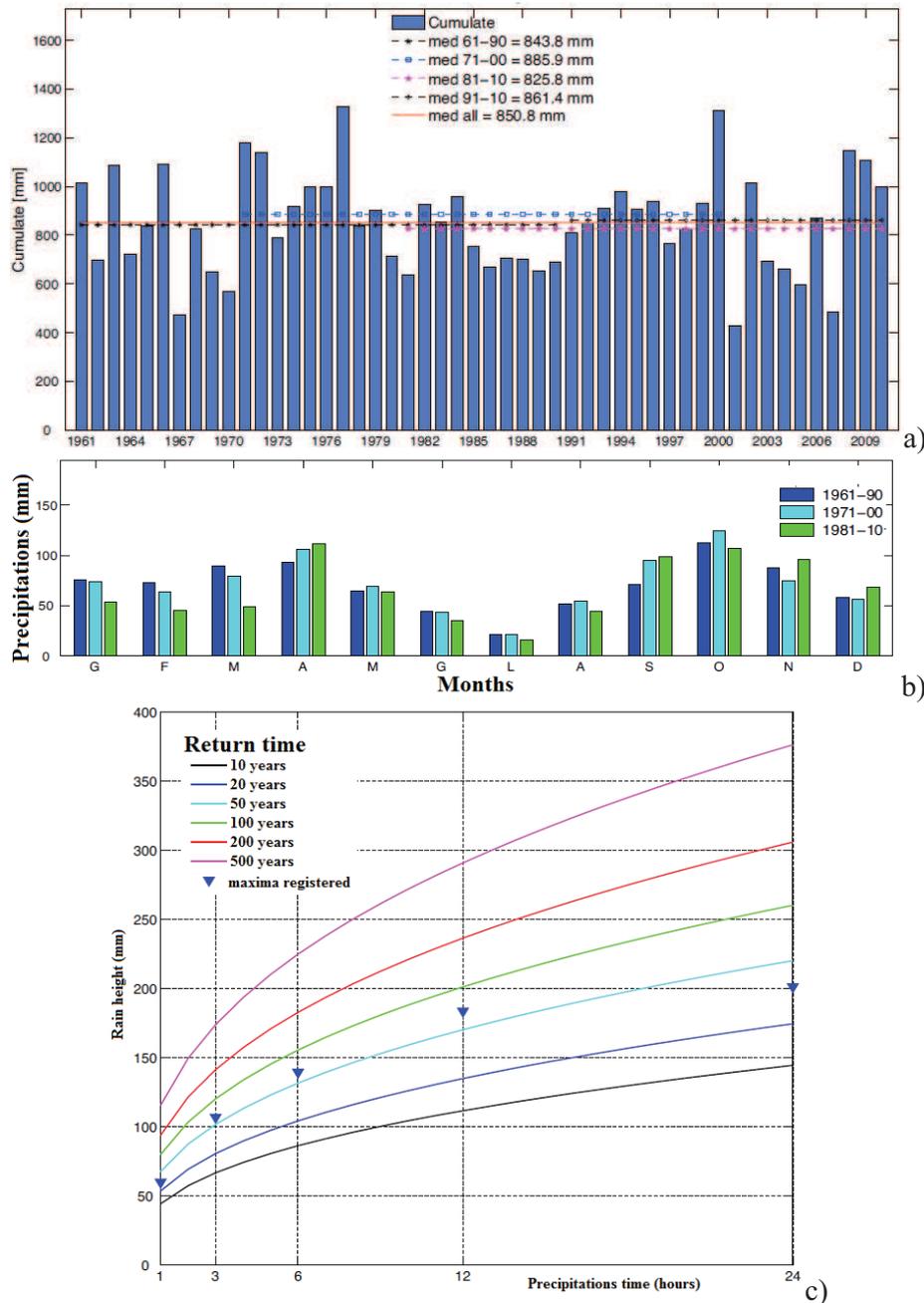


Fig. 1.1: Annual precipitations (a), monthly distribution (b), and curves of rainfall probability (c) at Le Manie station. Redrawn from Agrillo and Bonati (2013).

Towards NNW, the nearest pluviometric station is Vezzi San Giorgio station (tab. 1.2), at 4.5 km from Andrassa and 340 m a.s.l. The annual precipitation is 1109.7 mm, with 52 rainy days/years (Motta, 1987).

Tab. 1.2: Seasonal distribution of precipitations at Vezzi San Giorgio, period 1921-1946 (Motta, 1987).

	Winter	Spring	Summer	Autumn
<b>Monthly precipitation</b>	259.4 mm	330.5 mm	157.8 mm	371.3 mm
<b>Rainy days</b>	12.4	17.6	8.4	14.6
<b>Density of seasonal precipitation</b>	21.0	18.8	18.7	25.4

The rainfall regime is sublitoranean, with main maximum in October and secondary maximum in February – March, main minimum in July, secondary minimum in January. 2015 and 2016, the study years, have relatively low precipitations (fig. 1.2).

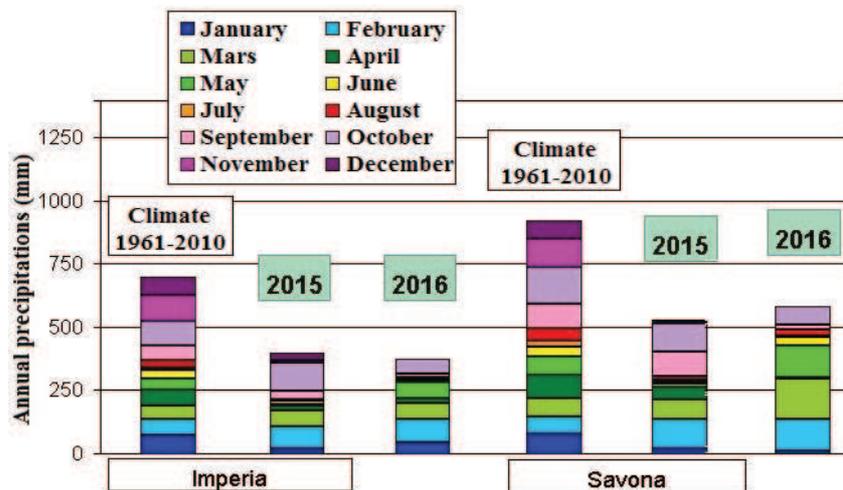


Fig. 1.2: Precipitations of 2015 and 2016 compared with the climate 1961-2010 at Imperia and Savona (towns at W and at E of Andrassa). Redrawn from Agrillo and Bonati (2013).

*External air temperature*

The more representative thermometric station close to Andrassa is Rialto (376 m a.s.l.), at 6 km towards W (tab. 1.3).

Tab. 1.3: Temperatures of Rialto station, period 1951-1974 (Motta, 1987).

Annual means	maxima	minima	mean	Temperature range
	18.85 °C	10.62 °C	14.58 °C	-1.12 / 32.66 °C
Monthly means in the measurements months	January	April	September	November
	6.6 °C	12.6 °C	23.3 °C	11.0 °C

Calice Ligure is the closest station with an over-30 years thermometric series (WGS84 lat. 44.20310, lon. 8.29344. 60 m a.s.l.; fig. 1.3).

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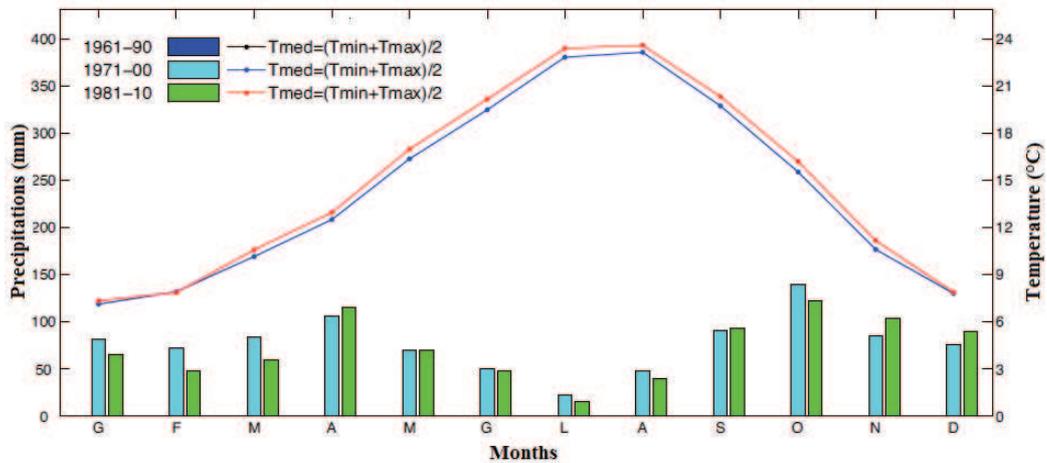


Fig. 1.3: Climatic data of Calice Ligure. The extremes temperatures during 38 years are  $-10.0\text{ }^{\circ}\text{C}$  e  $+40.1\text{ }^{\circ}\text{C}$ . Redrawn from Agrillo and Bonati (2013).

## 2.2. Geomorphology

Andrassa ( $44^{\circ}12'22.8''\text{N}$ ,  $8^{\circ}22'42.5''\text{E}$  WGS84, 211 m a.s.l.) follows the geological boundary between “*Dolomia di San Pietro dei Monti*”, a dolomitic limestone of medium permeability, and “*Pietra di Finale*”, an arenaceous limestone of high permeability. It is just downstream from the edge of Manie plateau, on the bottom of a karstic ravine (fig. 1.4), active after strong rainfalls.



Fig. 1.4: The Andrassa entrance.

The Manie plateau is a cockpit karst, born in a period of tropical climate (Biancotti and Motta, 1989). During Pleistocene, the plateau was much larger, including the area of cave: this zone was a big cockpit, whose ponor was the Andrassa. Today the plateau is greatly

reduced: only the easternmost part of the cockpit (so-called Andrassa Plains) keeps the original morphology (Biancotti et al. 1990). The western part is a little valley, with a watercourse (Rian Andrassa) active only after strong rainfalls (Biancotti et al. 1991), and with several rock walls with shallow caverns (independents from Andrassa).

*Epikarst*

The *Pietra di Finale* has a half-exposed karst, without structural microforms, not having joints. Humus-water grooves, cliff foot recesses, and round karrens are abundant, together to phytokarst microforms: wall pockets, and honeycomb karrens on vertical walls; tube-like holes, and root grooves on flat surfaces (Motta, 2016a). The average inclination of slope is 27.5° (Motta, 1987).

The *Dolomia di San Pietro dei Monti*, instead, is much fissured. Structural microforms, like solution flutes, bedding grooves, and debris karrens, prevail (Motta, 2016a). On the bottom of Rian Andrassa there are some big potholes, frequently full of stagnant water. The average inclination of slope is 21.8° (Motta, 1987).

*Soils and vegetation*

The soils (fig. 1.5) are brown rendzina (USDA: Rendoll and Entic Haploxeroll), brown calcareous soils, and eutrophic brown soils (USDA: Rhodic Eutrochrept) (Ajassa and Motta, 1991), and are thick from 20–30 cm to 1 m into bedrock depressions. A strong erosion hinders the pedogenesis (Brancucci and Motta, 1989).

The plant cover is a wood of evergreens (*Quercus ilex*) and deciduous (*Ostrya carpinifolia*, *Fraxinus ornus*...), with an open underwood (with *Ruscus aculeatus*, *Smilax aspera* )

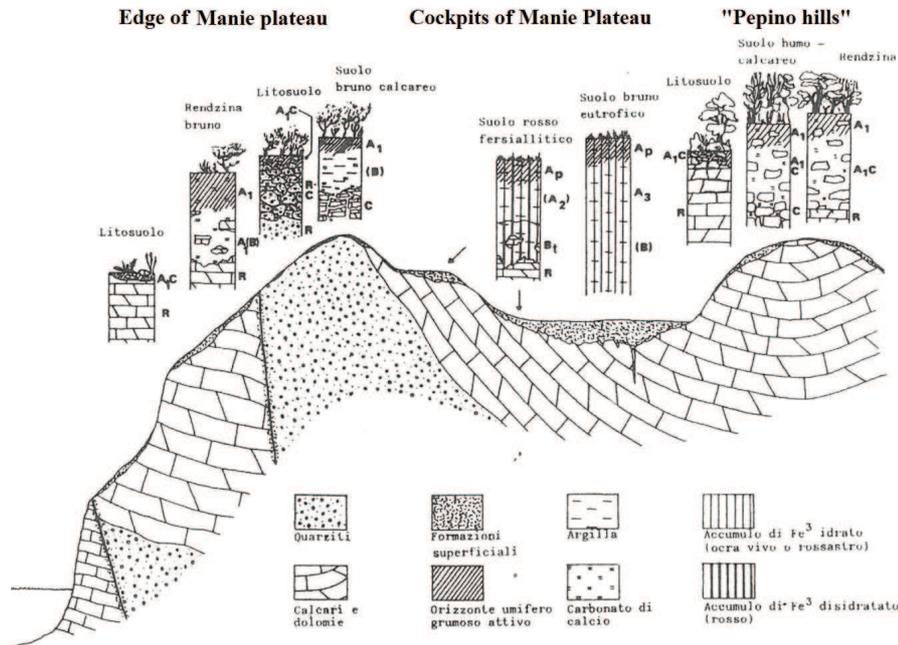


Fig. 1.5: Soils of Manie plateau (Motta, 1987; French classification). The Andrassa is at the edge of plateau.

### 2.3. Evapotranspiration

Estimation of the real and potential evapotranspiration (Thornthwaite method) shows very irregular meteoric influxes, which cause large variations of humidity from one year to the next, especially in winter (fig. 1.6). The winter 2014-15 was very humid, while the next was dry, without any surplus, and finally the 2016-17 was moderately humid. Summers are much more similar in the three years.

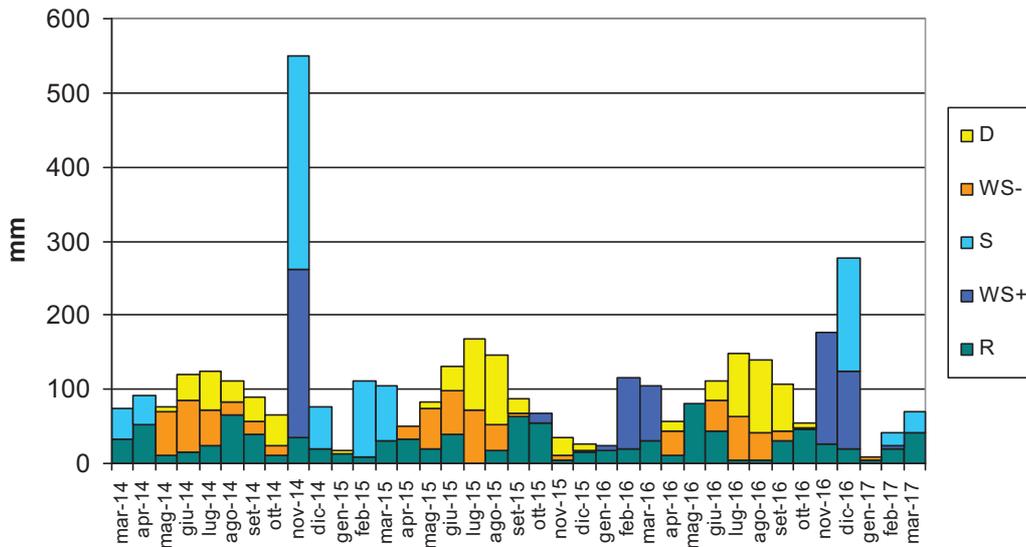


Fig. 1.6: Estimation of the water balance with the Thornthwaite technique (storage = 300). D: deficit; WS- use of water supply; S: surplus; WS+: recharging the water supply; R: residual precipitation water.

### 2.4. Water circulation

#### Hydrology

We have calculated the specific contribution (q) of hydrographic basin upstream of Andrassa (0.875 km<sup>2</sup>) using the empiric equation [1.1], developed by Piedmont Region for a return time of 200 years (Motta, 2016b):

$$q = [255/(S + 6.8)] + 3 \text{ m}^3/\text{s km}^2 \quad [1.1]$$

The result is 36.2 m<sup>3</sup>/ s km<sup>2</sup>, i.e. a water flux (through a section of valley that passing for Andrassa entrance) of 31.7 m<sup>3</sup>/s.

Because of high permeability of basin, this value represents the surface runoff + underground water flux.

#### Hydrogeology

Andrassa is a typical ponor: an initial 12-m pit, followed by several chambers connected by steep, narrow passages. The cave is oversized, compared to habitual runoff, because it was born as ponor of a cockpit, with a hydrogeological basin about double that of today.

The accessible part (for a short time, by means of debris removal) is 400 m long and drops to -60 m (Calandri, 1997). Maifredi and Pastorino (1969) proved that the water of Andrassa arrives to Acquaviva spring (71 m a.s.l., Sciusa Valley). On the basis of changes in discharge, turbidity, hardness, and tracers concentration, Cachia et al. (1974) says that the entire cave follows the geological boundary between dolomitic limestone (bed) and

arenaceous limestone (roof). The inaccessible part of cave is long at least 1650 m, with a height difference of 80 m. After an initial sequence of chambers similar to the accessible part, it should be almost horizontal, partially clogged with silt and sand, with large chambers at arrivals of other underground rivers (coming from Mala Cave, Ingrid Cave, and New Cave of Finalese: Calandri, 2003). In other words, it should be an epiphreatic or phreatic gallery, maybe not completely submerged, but certainly without a true atmospheric circulation.

We can thus summarize the dynamic of groundwater flow.

1) During ordinary floods, the Rian Andrassa rivulet collects waters overflowing from the Andrassa Plains. This water sinks immediately upstream of cave. The narrow tunnels of Andrassa are cluttered with sediment; therefore the water cannot drain completely, so a part the cave is full of water.

2) During exceptional floods, the water (together to pebbles, sand and twigs) enters also through the entrance pit. The floods block the bottlenecks with sediment; therefore the cave end remains completely flooded for several weeks, and the watertable appears extensively. Exceptionally, also the Great Chamber remains flooded.

3) After the rainfalls, a large amount of oozing falls in cave from vadose zone (particularly at the beginning of Great Chamber). This process has settled several stalactites, travertine dams, and flowstone deposits.

4) During lean periods, on the ground the water there is only into some puddles, but the floor remains wet everywhere.

## 2.5. Ventilation

Calandri (1997) has made three CO<sub>2</sub> surveys. In winter, the inner values are slightly bigger of outer ones (200-250 ppm versus 150 ppm); also in summer the inner values aren't very high (max 600 ppm versus 300 ppm in front of the entrance). For Calandri, this "indicates the air movement, at least in the first half of cave".

## 3. Monitoring

### 3.1. Short-Term Data

During five seasonal surveys (January 5, 2016; April 13, 2016; July 14, 2016; November 4, 2016; December 29, 2016) we have measured:

- 1) temperature and relative humidity in air at 1 m above ground level;
- 2) temperature of ground at 0.02 m below surface;
- 3) temperature of groundwater appearing in puddles on the floor;
- 4) temperature of dripping water, within of tubular stalactites.

This method is better for assess the air circulation than a method based only on anemometers (Motta and Motta, 2016b). Indeed, despite a lack of any circulation of air perceptible (with empirical systems commonly employed by cavers as smoke...), the distribution of temperature and humidity allows to easily reconstruct the air flow direction and the thermic imbalances.

We have measured at 2 m from the body of the operator. The lighting was only a two-led lamp, in order to avoid unwanted sources of heat. The measurements form a grid with interval of 10 m as far as 180 m from the entrance. A digital thermohygrometer (HD9216 Delta-Ohm, Italy) has monitored with a penetration probe TP 9AP (A-class DIN 43760/1980) for water and ground, and an air-probe HD 9216S. Resolution: 0.1% relative

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humidity and 0.1 °C; measuring range: temp: – 10 to + 70 °C; RH: 5 to 100%; temperature precision: linearization error (0.04 °C) ± 0.1 °C ± 1 digit; relative humidity precision: ± 2% in the range 5%...90%, +4% - 2% in the range 90%...98%.

In January and April, we have measured as far as 135 m from the entrance, where there it was an obstruction. After that, someone has removed the obstruction, and we have measured as far as 180 m from the entrance.

### 3.2. Long-Term Data

From 01.12.2015 to 02.01.2017, three data-loggers Mylog have collected twice a day the data of two probes Pt100, one into the ground 0.07–0.10 m below surface, and the other on the vault of the cave, in a point without oozing. Position and ground of the stations are:

- bottom of entrance pit, coarse angular pebbles (normally slightly humid) for the A station;
- tunnel between the First and the Great Chamber, muddy sand (normally slightly humid) for the B station;
- Great Chamber, sandy mud (normally soaked) for the C station.

### 3.3. Soil Temperature Data

From November 2016 to June 2017 we measured the soil temperature at 0.25 m depth in 6 stations, which are 20 m from each other starting from the entrance pit and are on the vertical of the cave.

The measurement method and probe are analogous to the ones used for the cave ground.

## 4. Results and Data Analysis

### 4.1. Short-Term Data

#### *Winter*

Air, soil and stagnant water have similar temperatures (Fig. 1.7, 1.8, 1.9), except in Great Chamber, a zone of warm air. The dripping water is slightly warmer, especially in deepest sector. There is a progressive saturation of humidity with the depth (fig. 1.10).

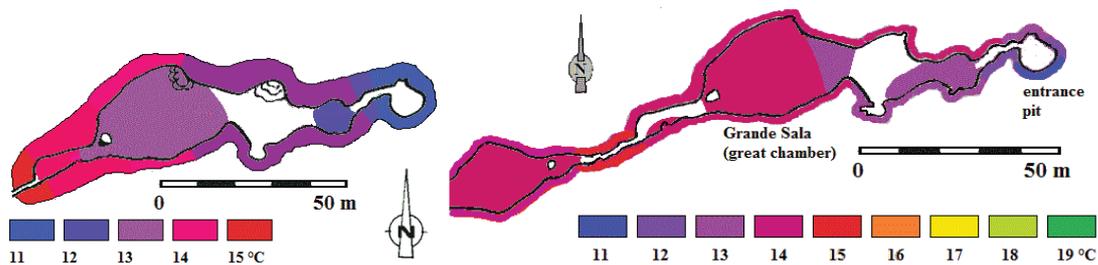


Fig. 1.7: Temperature distribution of the drip water (colors outside the cave boundary) and of surface water (colors within the cave boundary; the white areas are dry) on January 5, 2016 (above), and on December 29, 2016 (below). On January 5, the water into potholes of Rian Andrassa was at 6.5 °C; on December 29, it was at 6.6 °C. Sketch map redrawn from Bixio et al. (1987).

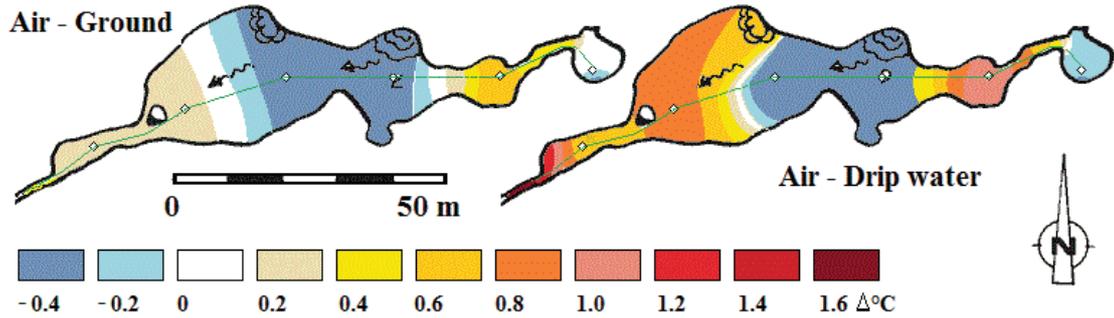


Fig. 1.8: Temperature differences on January 5, 2016.

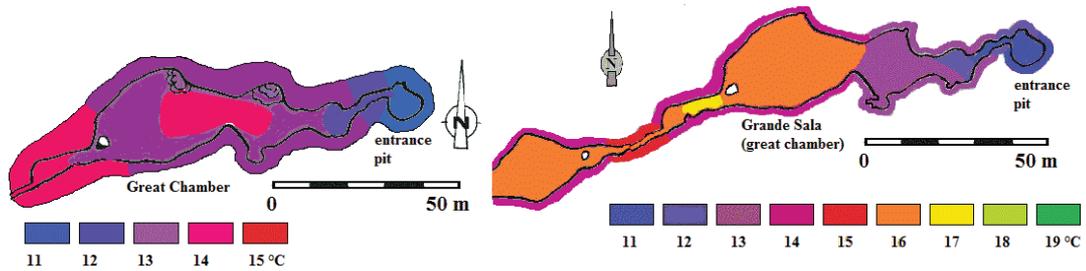


Fig. 1.9: Temperature of air (colors within the cave contours) and ground (colors outside the cave boundary) on January 5, 2016 (above), and on December 29 (below). Outside, on January 5 the soil was at 7.5-7.9 °C, the air is at 11.0 °C (entrance threshold), and 10.2 °C (valley bottom in front of cave); on December 29 the soil was at 6.9 °C (entrance threshold), and 7.4 °C (valley bottom); the air was at 9.4 and 8.6, respectively.

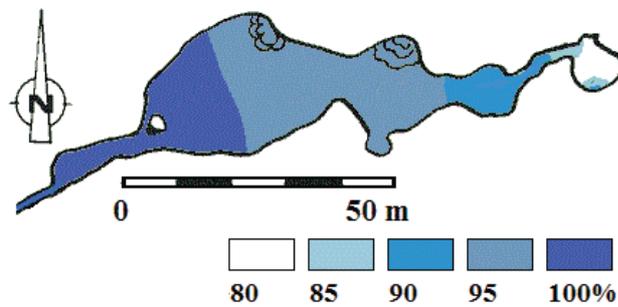


Fig. 1.10: Distribution of relative humidity (%) on January 5, 2016 (map). Outside, the relative humidity varied from 65.2% (entrance threshold) to 70% (valley bottom in front of cave).

### Spring

The dripping water is slightly warmer ( $\Delta T < 1$  °C) than stagnant water (fig. 1.11) and ground (which have similar temperatures; fig. 1.12). The dripping water is coldest into the Great Chamber, and, especially, into the entrance pit. The ground becomes increasingly cold towards entrance. The air is very hot close to entrance; as the dripping water, or slightly more, in deep (fig. 1.12). In the Great Chamber air, standing water, and ground have the same (low) temperature.

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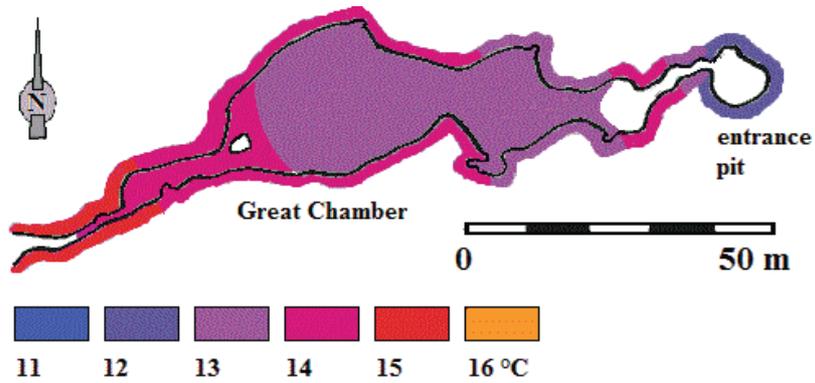


Fig. 1.11: Water temperature (see caption of fig. 1.7) on April 13, 2016. The water temperature of the potholes in Rian Andrassa (the rivulet outside) at the same time is 15.1 °C.

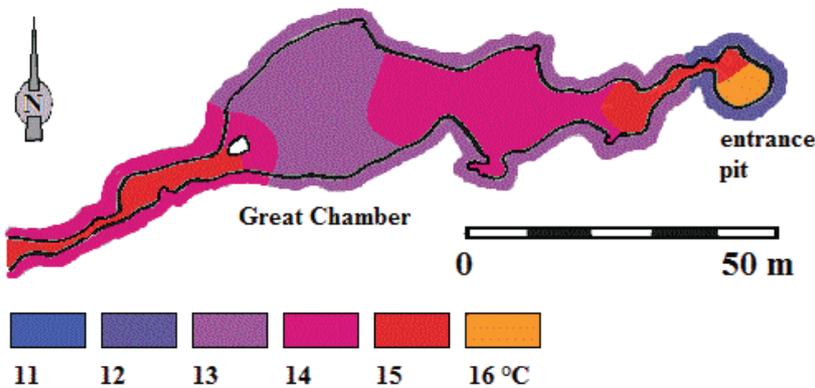


Fig. 1.12: Temperature of air and of ground (see caption of fig. 1.9) on April 13, 2016. Outside, the ground is at 13.0 °C, the air is at 13.1 °C.

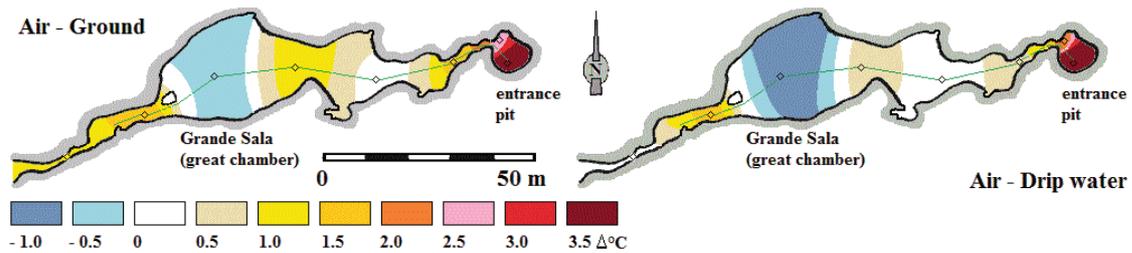


Fig. 1.13: Temperature differences on April 13, 2016.

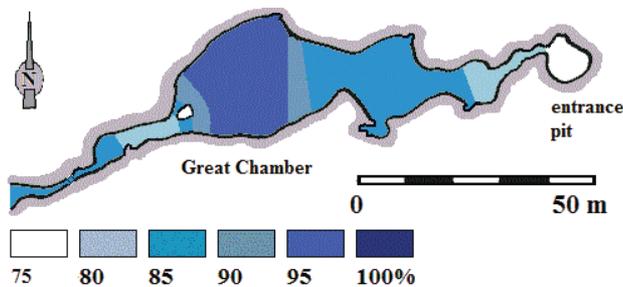


Fig. 1.14: Relative humidity (%) on April 13, 2016. The external air in front of the entrance, at 1.5 m above the ground, had RH = 67.6%

*Summer*

The  $\Delta T$  between dripping and stagnant waters is  $\leq 0.1$  °C. The ground temperature is similar, except in entrance pit that is much colder. In whole cave, especially in entrance pit, the air is much warmer than ground and water ( $\Delta T$  ground–air reaches 6.1 °C!). The deepest chamber and northern side of Great Chamber have the lowest temperatures. The relative humidity is low, except in zones of stronger oozing.

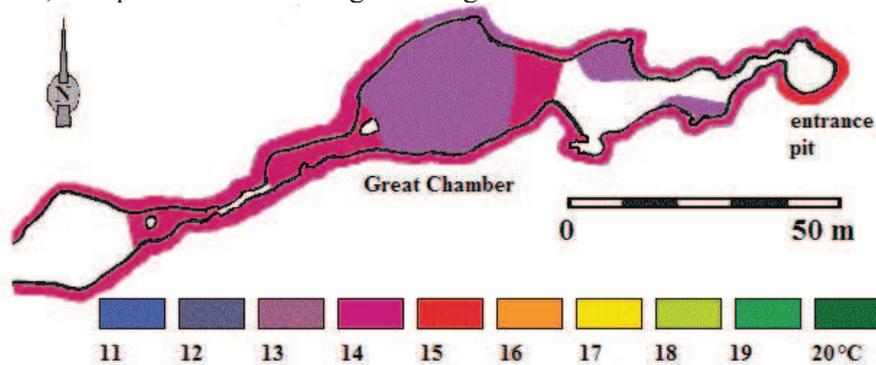


Fig. 1.15: Water temperature (see caption of fig. 1.7) on July 14, 2016. The Rian Andrassa was dry.

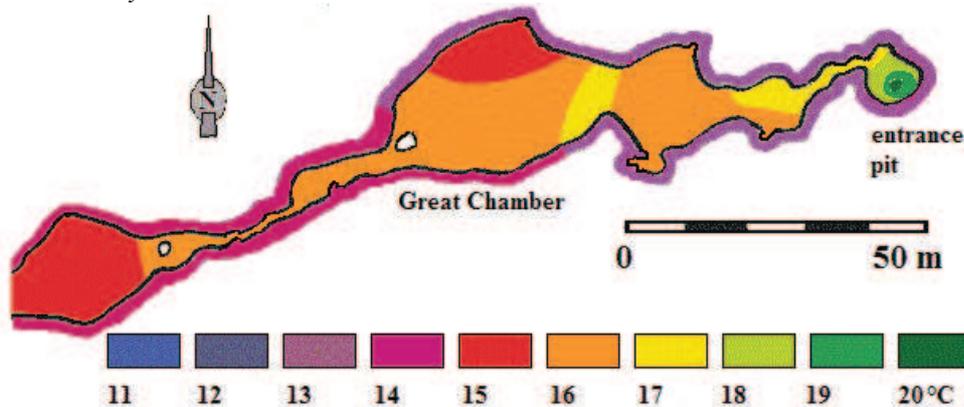


Fig. 1.16: Temperature of air and of ground (see caption of fig. 1.9) on July 14, 2016. Outside, the ground is at 13.0 °C, the air temperature ranged from 23.8 °C (entrance threshold) to 23.5 °C (valley bottom in front of cave).

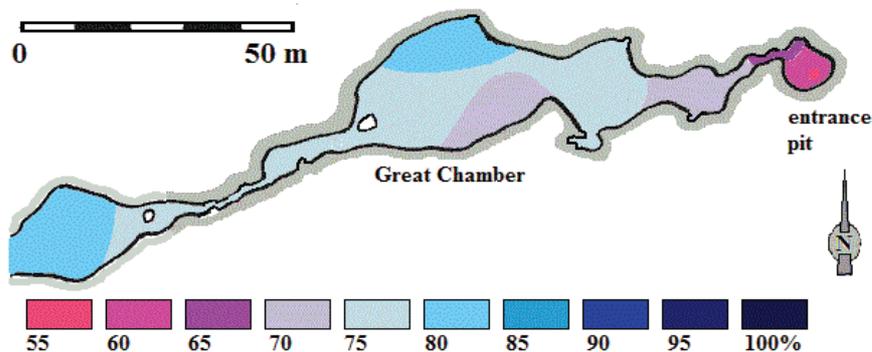


Fig. 1.17: Relative humidity (%) on July 14, 2016. Outside, the air in front of entrance, at 1.5 m above the ground, had RH = 55.7%.

*Autumn*

The puddle water is slightly colder than the ground; the dripping water is slightly warmer than the standing water; the air is much warmer than ground and water. The air of entrance pit has the same temperature of outside, but is more humid. Beyond 32 m from the entrance, the air becomes always colder and more humid up to Great Chamber. Just below this, the air becomes suddenly rather warm, and dry. In deepest sectors, temperature is 4 °C higher than July value (“heat wave” of summer).

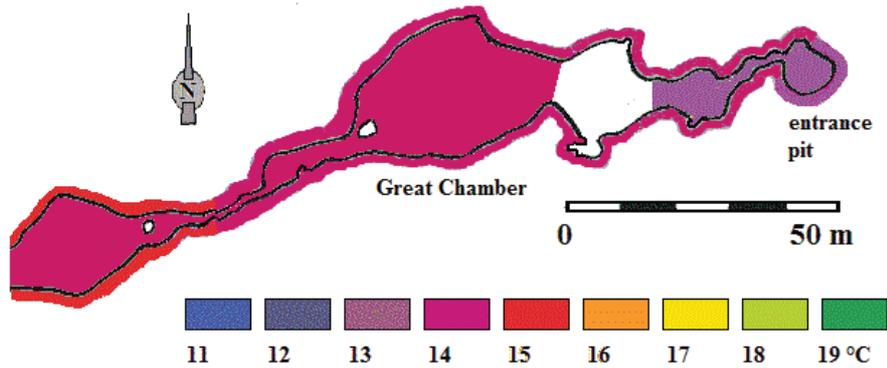


Fig. 1.18: Water temperature (see caption of fig. 1.7) on November 4, 2016.

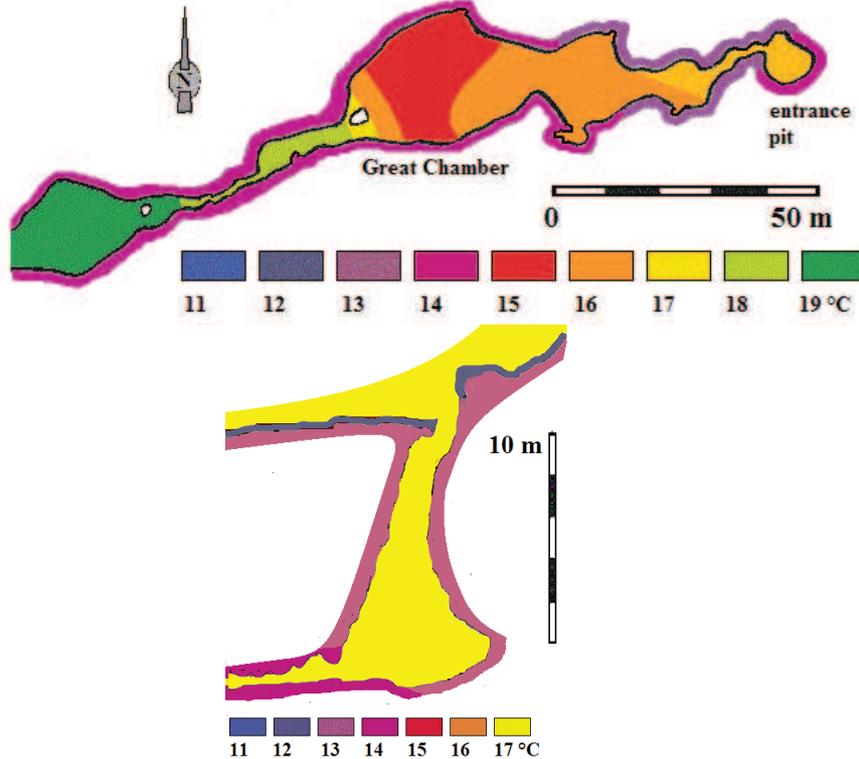


Fig. 1.19: Above: temperature of air and ground (see caption of fig. 1.9) on November 4, 2016 (map). Below: temperature of air and of rock surfaces in entrance pit (cross section).

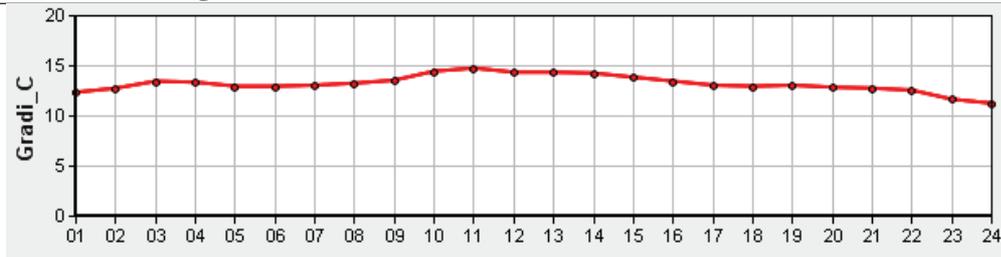


Fig. 1.20: Air temperature of Manie climatic station (average), on November 4, 2016 ([http:// www.arpal.gov.it](http://www.arpal.gov.it)).

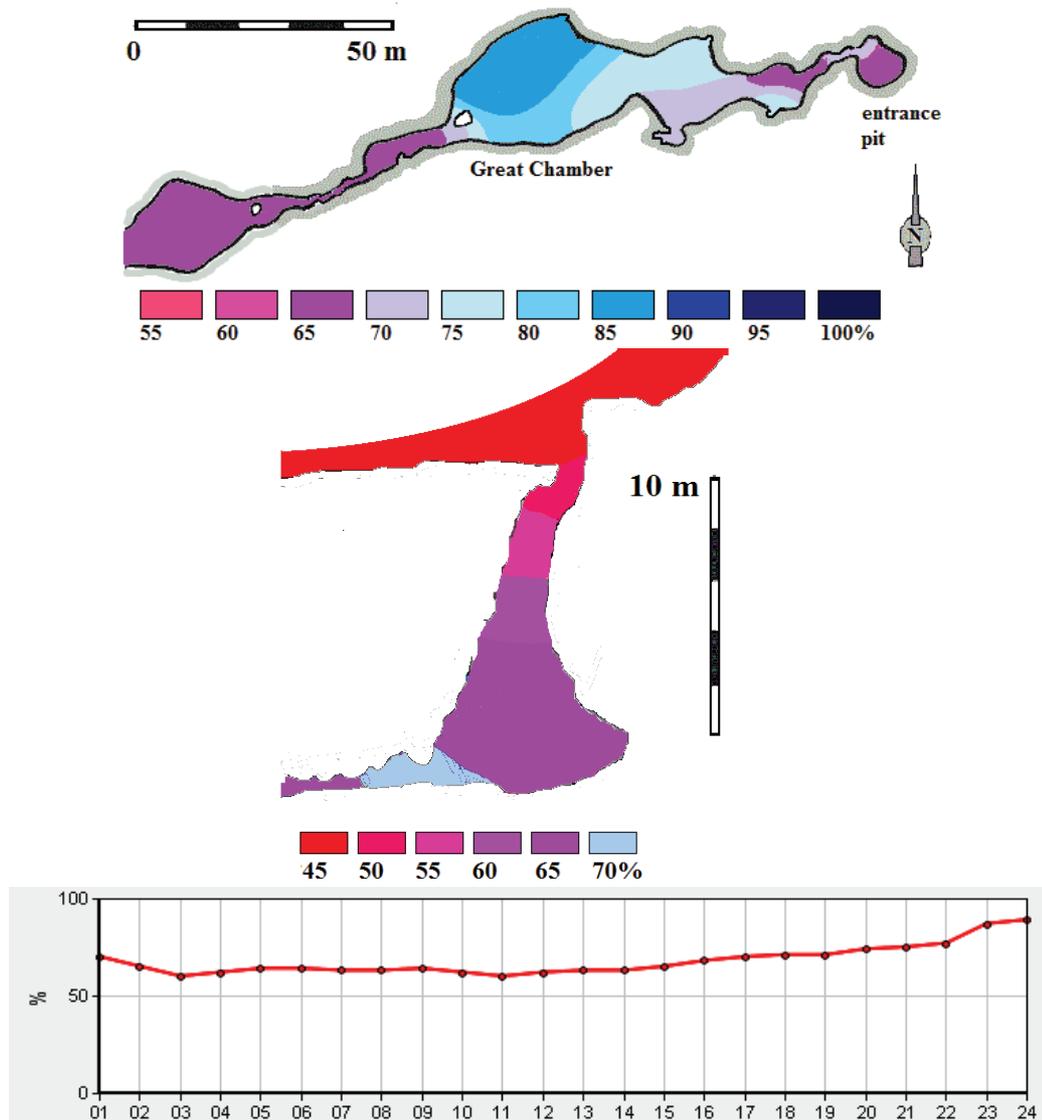


Fig. 1.21: Relative humidity (%) on November 4, 2016. Above: map of cave. Middle: cross section of entrance pit. Below: Manie climatic station (from [http:// www.arpal.gov.it](http://www.arpal.gov.it)).

## 4.2. Discussion of Short-Term Data

### *Seasonal Evolution*

Respect to winter, in spring, in the first thirty meters of Andrassa the air is warmer of 3-5 °C. Between this zone and Great Chamber, instead, the warming of water and ground is  $\leq 1^\circ\text{C}$ . The temperature in Great Chamber is unchanged. In the deep zone, a heat wave keeps high the air temperature. Probably this is due to the oozing, which has the same temperature of 15 °C.

In summer, the temperature of dripping water remains almost unchanged in depth, while it increases near the entrance. The ground temperature remains almost unchanged. In entire cave, the air is hot (particularly within entrance pit), and into Great Chamber the minimum of temperature disappears almost completely. This distribution seems to indicate entry of hot air. To test the hypothesis, we calculated the density with the equation:

$$[2] 1.2929 \cdot 273.13 \cdot [AP - (SVP \cdot RH)] / [760 \cdot (T + 273.13)]$$

where T is the temperature (°C), AP is the absolute pressure (mm Hg), SVP is the saturation of vapor pressure in air at the temperature T, RH is the relative humidity (decimal).

The density distribution (Fig. 1.22) rules out a general convection; however, a flow of heat from outside must influence air temperature, because the air is warmer than soil and water.

This last could take place by diffusion, or (less likely) could be the remnants of a heat wave caused by entry of hot water after a thunderstorm.

The deepest part of cave is warmer in autumn than in summer (normal phenomenon into soils), while near the entrance the cooling begins. The heat wave has travelled through whole cave, and has warmed air up to over 19 °C.

The winter distribution of temperatures is similar to autumn situation, but with cooler temperatures. In deepest part, the summer heat wave decreases slowly. Meanwhile, a weak cold wave, highlighted by air-ground  $\Delta T$ , enters from the entrance. Probably, the lower density of outside air (cold and dry), is the reason of this entrance (fig. 1.23).

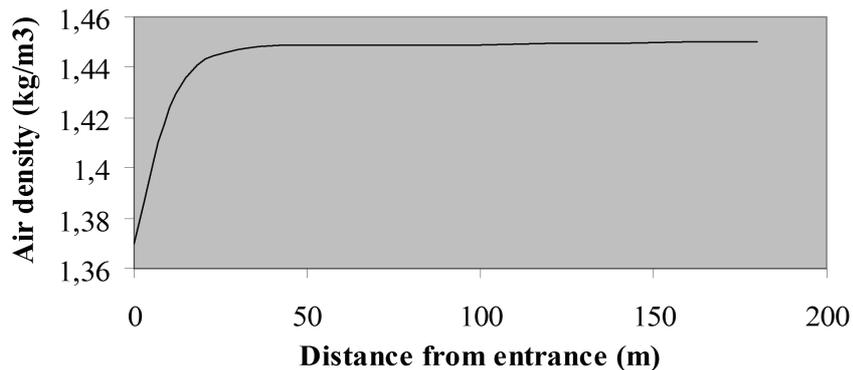


Fig. 1.22. Air density on July 14, 2016.

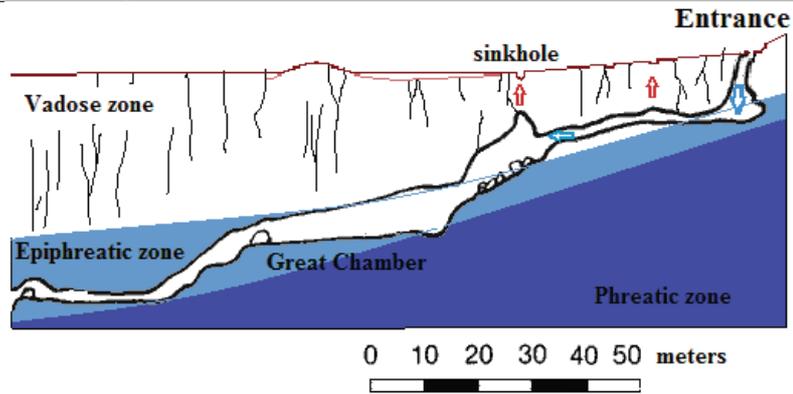


Fig. 1.23: Cross section of Andrassa (cross section of cave from Bixio et al. (1987); topographic profile from an original GPS survey). The arrows indicate the likely circulation of air in winter (red: hot air; blue: cold air).

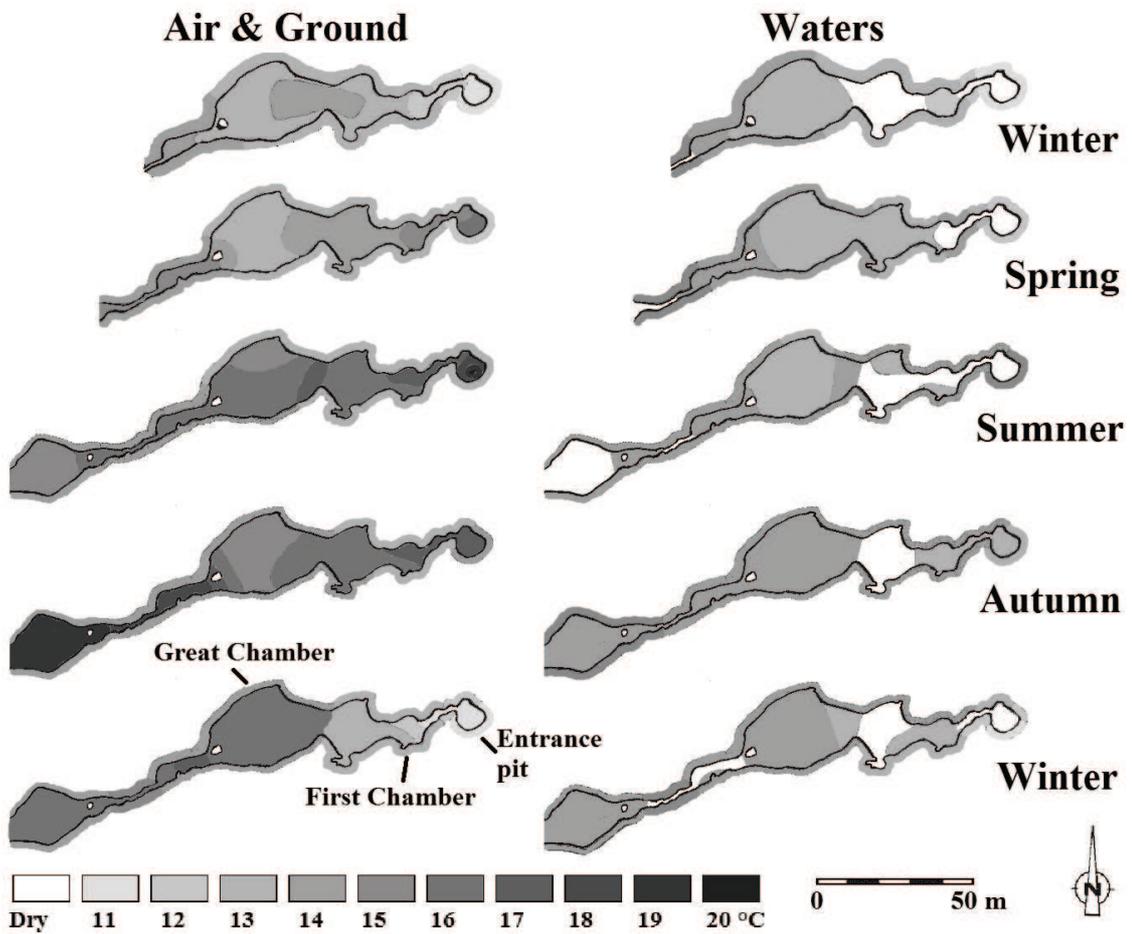


Fig. 1.24: Left maps: seasonal distribution (2016) of temperatures in air (colors within the contour of cave) and ground (colors outside the boundary of cave). Right maps: water temperature (oozing: colors outside the boundary of cave; water in the puddles: colors within the boundary; the white areas are without puddles). Cartographic base: Bixio et al. (1987).

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In winter, the deep air is very humid, even saturated (Fig. 1.25). In spring and summer, this area dries out significantly, while the Great Chamber remains very humid, especially in the N part. The first part of cave is always drier going towards the entrance. In autumn, deepest part becomes as dry as the part near the entrance, while the N side of Great Chamber is still humid. These variations suggest that there are two sources of humidity in the cave, with different seasonal variations:

- oozing, very strong in the N part of the Great Chamber and quite steady in the year;
- water on the ground, which was minimal in November 2016, consequence of a drought period.

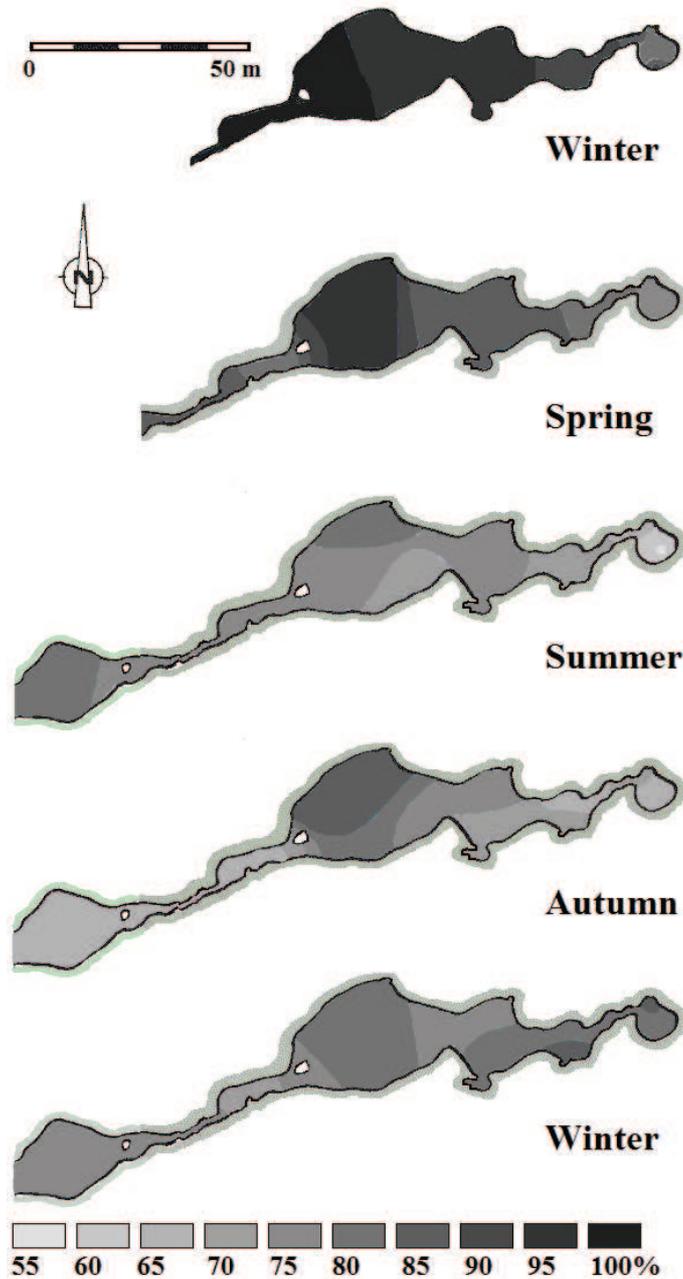


Fig. 1.25: Seasonal distribution (2016) of relative humidity.

In autumn and winter, the air temperature increases with the depth, with the notable exception of a hot area in Great Chamber. In spring and summer, the minimum temperature is in the Great Chamber, and the entrance pit is warmer than the deepest part of cave.

In summer and autumn, the air is in strong imbalance (it is much warmer) with ground and water. In winter, the air takes almost the same temperature of the ground (which is slightly colder). In spring remains at the same temperature of the ground only in the Great Chamber, while in deepest part and especially towards the entrance is warmer.

The air is quite dry and with big fluctuations of relative humidity from point to point. This reveals an air circulation, which prevents from getting to saturated conditions, despite the constant presence of water.

From spring to autumn the absolute humidity beyond 10-30 m from the entrance fluctuates around 11 g/m<sup>3</sup> (fig. 1.26). In summer the oscillations are weak, suggesting a mitigation of variation factors (lowering of groundwater, and perhaps less oozing). The same in winter, but starting from 50 m from the entrance and with a value greater (12 g/m<sup>3</sup>).

Entrance pit (fig. 1.27) is under-saturated always. In winter, this happens despite the lowest air temperature, and indicates that the cave takes air from outside. Likely the air exits through vadose zone above the chambers (fig. 1.23), by the same cracks that carry snails and seeds into the cave (Motta and Motta 2016a, b), balancing the entry of air in cave.

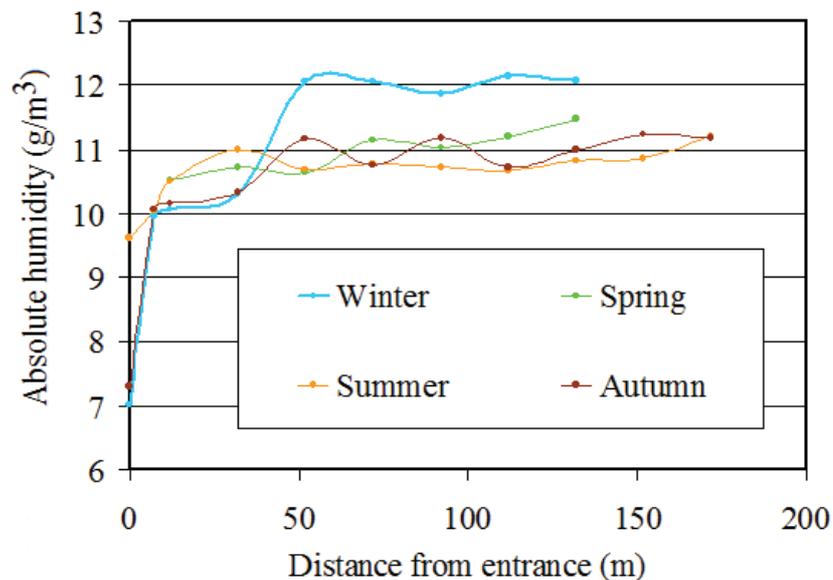


Fig. 1.26: Absolute humidity. Beyond 50 meters from entrance, the absolute humidity is fairly constant, and changes little from spring to autumn. In winter the value is slightly higher.



*Fig. 1.27: The entrance pit.*

From spring to autumn the outdoor air is less dense than air in cave, and cannot enter the cave, but the air transmits heat waves. In spring the heat wave arrives only up to the Great Chamber, where also ends the heat wave of deepest sector, linked with the high temperature of oozing. In summer the heat coming from entrance prevails.

In January, air is slightly colder than walls of cave. In all likelihood, the cooling caused by this air is not enough for to balance the heat flux carried by the air in the rest of the year. In other words, the water circulation (cooling from spring to autumn) is fundamental for the annual thermal balance.

The temperature of ground varies between 11.9 °C and 14.9 °C; that of water between 12.8 °C and 15.5 °C. So, the annual excursion is not more than 3 °C, much lower than that of the air (8.9 °C). Evidently, the ground temperature is very linked with that of water, and independent from air. This shows that the heat flux transported by groundwater prevails on heat flow conveyed by air.

14.1 °C, the average water temperature, is close to temperature of Acquaviva spring (resurgence of the cave), steady around to 14–15 °C during 1990-2002 (Calandri, 2003).

Motta and Motta (2014) have classified many caves of Piedmont and Aosta Valley (regions very close to Manie plateau, with colder climate) in four groups on the basis of their endoclimate (Tab. 4).

Tab. 1.4: Thermal condition groups in Motta and Motta (2014).

Group	Cave	Annual mean	Daily excursion	Annual excursion
A	Bergovei, Caudano, Bossea, Bandito, Arenarie, Dronera, Pugnetto	8.5 - 10.5 °C	Very very weak or absent (< 0.05 °C)	Very weak (< 0.6 °C)
B	Vernante, Diavolo, Partigiano	6 - 9 °C	Very weak (0.02 - 0.10 °C)	Weak (2 - 5 °C)
C	Servais, Argentera, Maestro, Napoleone	7.5 - 10.5 °C	Variable (0.20 - 1.00 °C)	Relatively high (5 - 13 °C)
D	Custretta, Glace, Ghiaccio	3 - 8 °C T < 0 °C in January	Moderate (0.05-0.35 °C)	Relatively high (5 - 13 °C)

A-Group are long caves, with thermal conditions almost stable over time.

The caves of B-Group are small, but well isolated from the external environment: the thermal excursions are very limited.

As well D-Group are small caves. They are at high altitude (on the contrary of C-Group), so in January they normally contain ice. The thermal effect of phase changes of water moderates daily thermal excursions (< C-Group) while the annual thermal excursions remain relatively high.

The C-group are very little caves: therefore, temperatures are quite similar to those at the entrance of larger caves (variable-temperature zone). It is for this that the daily excursion is bigger, from moderate (for a cave environment, i.e. 0.2 °C) to high (~1 °C), and the annual thermal excursions are relatively high. Being at low altitude, there is not any phenomenon of freezing / melting, which is a factor of temperature stabilization. Andrassa, despite its big size and daily excursion like to the A-group, has the annual excursion of C-group (~8.9 °C). Instead, the average is bigger, because of warmer Ligurian climate.

### 4.3. The effect of event of November 24-25, 2016 and the heat waves

On November 24-25, 2016, a 60-mm rain has given in 16 hours 52,500 m<sup>3</sup> of water at hydrographic basin upstream of Andrassa. The estimate of flow rate (Giandotti equation) at the height of cave entrance is 0.9 m<sup>3</sup>/s (average), swinging between 0.2 and 2.1 m<sup>3</sup>/s (on 24/11, peak between 13.00 and 14.00).

The rain water is fell with air temperature of 10-15 °C (see figure 1.28), close to water (and ground) temperature within the cave (13-15 °C), but much cooler than the air in cave (15-19° C). Even assuming that only 10% of the water flows on the floor of the cave, since the water has a specific heat capacity per unit volume 4,000 times higher than that of air, it is obvious that the rain caused a strong cooling. The event of November 24-25 is not exceptional (the 2016 is even drier than normal, see fig. 1.2), therefore testifies the importance of the heat flow associated with rainfall, although the cave ventilation studies consider this flow little or nothing. This event in all probability originated a "cold wave", whose effects persist for some time, overlapped to effects of other events with temperature higher or lower than cave temperature:

- heat waves in summer, caused by entry of hot air, or from average increase of infiltration water temperature (which arrives to the cave as groundwater, mingling to stagnant water);

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- heat waves during dry periods of winter months, caused by heating of dripping waters during the passage through vadose zone (which maintains a temperature close to the annual average);
- weak cold waves can coming from entrance in winter, perhaps for convective processes, like in "static cave" model;
- in all seasons, rainfalls can cause heating, or cooling, when their temperature differs from that of cave.

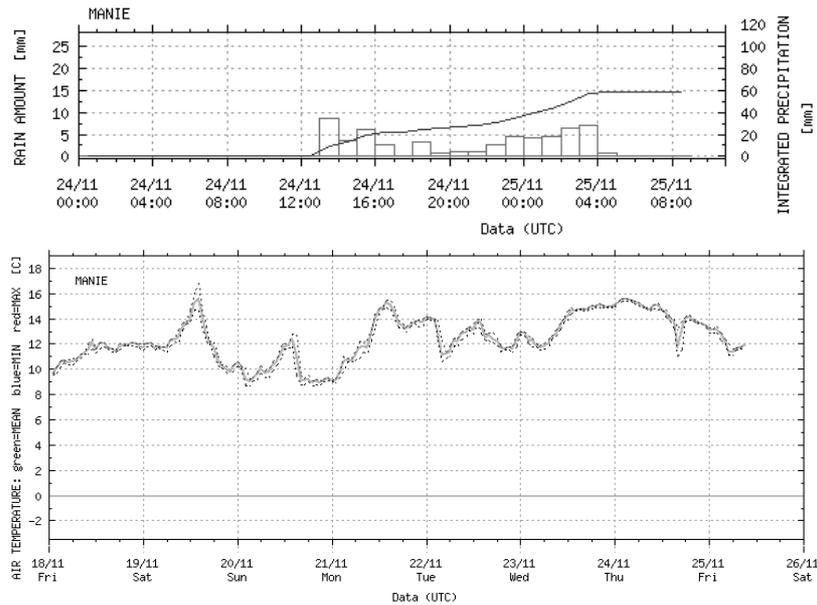


Fig. 1.28: The event of 24-25 November 2016 (Arpal 2016): above rainfall, below air temperature.

It is therefore obvious that summer temperature within Andrassa is not uniform as in the stagnant air of a "static cave", but has fluctuations caused by thermal waves, as several authors have observed in soils.

In other words, the model of "static cave", considered applicable to any single-entrance cave, appears inapplicable to Andrassa and, likely, to all active caves, even in times of drought. Given the complexity and heterogeneity of factors at play, it is unlikely a modeling of the entire cave based on mathematical formulas, even complex. In active caves with single entrance should be applied case by case (and sector by sector) a more complex model, in which the air flow depends substantially by:

- position of water fluxes and seasonal variations (Motta and Motta, 2015a);
- heat waves;
- thermal and barometric imbalances with the outside air (Badino, 2010).

#### 4.4. Results of Long-Term Data Analysis

##### *Time Variations*

The long-term data are in Fig. 1.29, 1.30 and Tab. 1.5. The average calculated on all available data (mean \* in table 4) is almost identical to the average of the monthly data (mean).

The standard deviation is higher near to entrance, less in middle and deep part of the cave.

The ground don't has daily thermal excursion: the difference between the temperature measured at 12:00 and 24:00 is  $< 0.05$  °C in all the months (only exception is the difference of  $0.06$  °C in B in March).

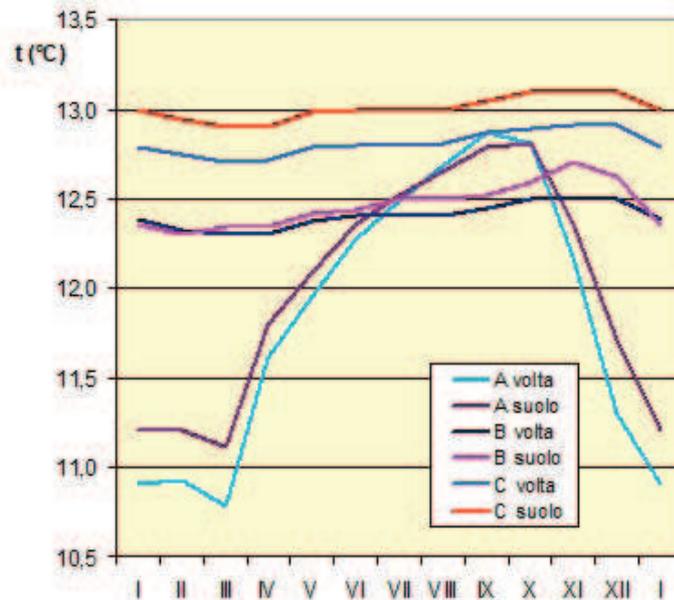


Fig. 1.29: Distribution of monthly temperatures. Volta: vault; suolo: ground.

Tab. 1.5: Monthly temperatures of roof (interface air-rock) and ground.

Station	A		B		C	
	Vault	Ground	Vault	Ground	Vault	Ground
Probe	N.A.	10 cm	N.A.	7 cm	N.A.	8 cm
Depth	N.A.	10 cm	N.A.	7 cm	N.A.	8 cm
January	10.91	11.20	12.39	12.35	12.79	12.99
February	10.93	11.20	12.32	12.30	12.74	12.94
March	10.78	11.11	12.30	12.34	12.70	12.90
April	11.61	11.79	12.30	12.34	12.72	12.91
May	11.95	12.08	12.37	12.41	12.79	12.98
June	12.27	12.36	12.40	12.43	12.80	13.00
July	12.49	12.52	12.40	12.50	12.80	13.00
August	12.69	12.66	12.40	12.50	12.81	13.00
September	12.87	12.79	12.44	12.52	12.86	13.04
October	12.81	12.80	12.50	12.60	12.89	13.10
November	12.18	12.36	12.51	12.70	12.91	13.10
December	11.30	11.72	12.49	12.62	12.91	13.09
Mean	11.90	12.05	12.40	12.47	12.81	13.00
Mean*	11.89	12.05	12.40	12.46	12.81	13.00
Standard deviation	0.75	0.61	0.08	0.16	0.07	0.07

Note: N.A. means not applicable. The mean\* is calculated on all available data.

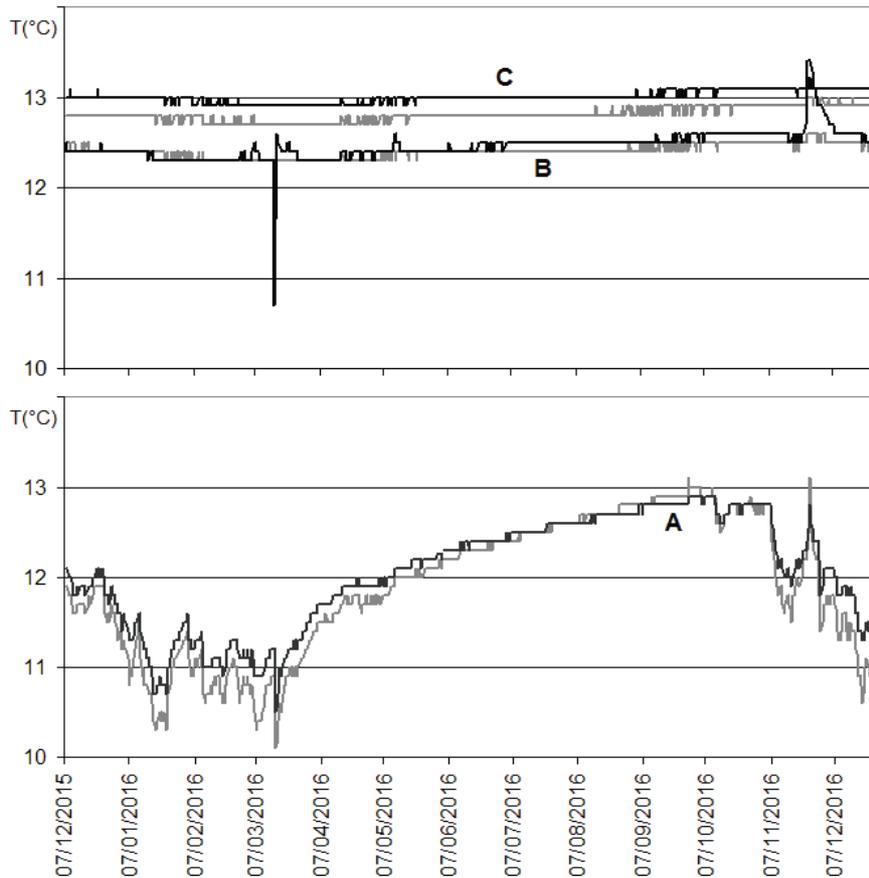


Fig. 1.30: Long-term data of A, B, and C station. Black line: roof probe; grey line: ground probe).

The annual oscillations of the two probes are analogous in each station.

The station A has a long minimum (11 °C) from January to March, then a heating, first fast (April - May), then slower, up to a maximum of 12.8 °C in September - October. It follows a fast cooling that brings back the temperature to 11 °C in January. The cave vault is colder (of about 0.3 °C) than ground from December to March, while during the warmest months the difference decreases, and in September the vault becomes 0.08 °C hotter than the ground. The annual thermal excursion is 2.1 °C for the vault, 1.7 °C for the ground.

The B station has almost steady temperature. The minimum, 12.3 °C, is from February to April, the maximum, 12.5 °C, is from October to December. The vault is colder than the ground for almost all the year except January and February. However the temperature difference is always < 0.1 °C, except in November-December, where it climbs to 0.19 °C, certainly due to the rainfall of November 24-25, 2016. The annual thermal excursion of the vault is only 0.2 °C; the one of the ground, as a result of the exceptional cooling resulting from the rainfall of November 24-25, 2016, was double, 0.4 °C.

The C station is warmer than B, but the months of minimum and maximum are the same. The temperature oscillations of vault and ground are identical. Both have 0.2 °C of annual excursion. The vault is always colder than ground of 0.2 °C. Obviously this rule out a

thermal stratification of the air, and suggests that the temperature of the vault is more influenced by the percolating water, that of the ground from the air.

*Thermal Characteristics of the Different Parts of the Cave*

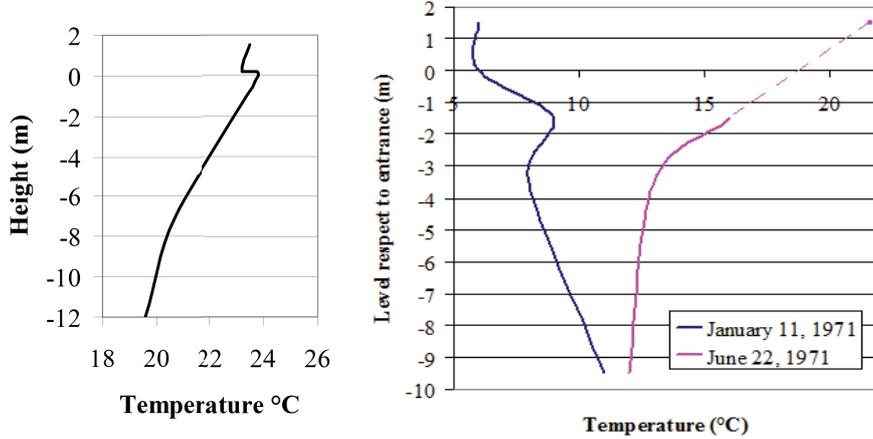


Fig. 1.31: Air temperature (°C) vs. altitude (m) within the entrance pit, on July 14, 2016 (left), and in 1971 (Massa, 1971). The height 0 is the entrance level (211 m a.s.l.).

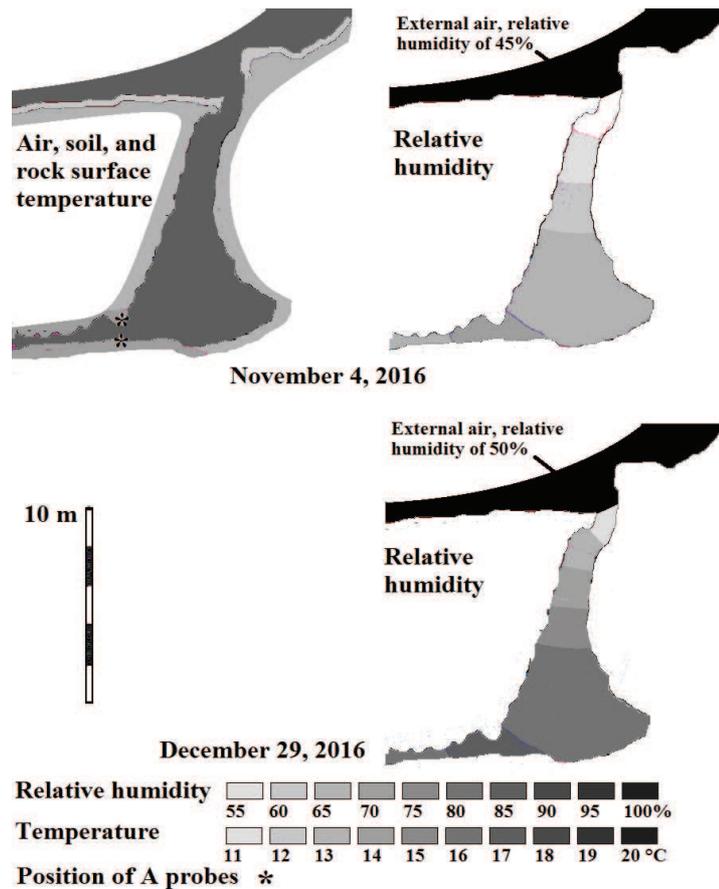


Fig. 1.32: Temperature of air, outer soil, and rock surface (left), relative humidity (right) within the entrance pit (cross sections). The external air is represented in full black.

The temperature within the entrance pit changes regularly from bottom to entrance, where the temperature adapts to external temperature quickly (Fig. 1.31). Station A has the typical features of variable-temperature zone (Fig. 1.32). B and C are very similar to each other, despite the strong morphological differences, and have the almost constant temperature typical of the caves with poor ventilation (Motta and Motta, 2014).

#### 4.5. Short-Term and Long-Term Data Comparison

The long-term data of the ground are more stable and less close to air temperature measured during the short-term surveys. The reason is obvious: the probe measures at a depth of 0.07 - 0.10 m, while the one of short-term data works at a depth of 0.02 m.

It is less obvious the reason that the long-term data of the vault aren't directly comparable with the short-term data measured in air 1 m above ground level: the first are much more stable, less sensitive to heat waves, and closer to ground temperature. Evidently the sensor fixed on the vault represents better the roof rock than air.

#### 4.6. Relations Between the Temperatures of the Different Components of Cave

Since the temperature of air (T), ground (Tg), dripping water (Td) and puddle water (Tw) are very stable over time, we can hypothesize that a temperature difference between two neighboring components corresponds to a thermal exchange.

14% of cases examined:  $T_d \geq T_g > T$ . This happens throughout the cave, typically in winter and only rarely in spring. Where there is, puddle water is colder than the ground. Tw can be higher than T ( $T_d \geq T_g > T_w > T$ ), or less commonly lower ( $T_d \geq T_g > T > T_w$ ).

Tab. 1.6: Characteristic examples of conditions  $T_d > T_g > T/T_w$

Day	Station	T (air)	Tg (ground)	Td (dripping water)	Tw (almost stagnant water)
05/01/2016	1	12.5	13.5	13.5	12.8
05/01/2016	4	13.7	14.0	14.6	13.9
05/01/2016	5	14.1	14.4	14.7	14.1
29/12/2016	1	13.4	13.5	14.6	13.3

73% of cases:  $T > T_d > T_g$ . This occurs throughout the cave and throughout the year, especially in the intermediate seasons. Tw is very close to Tg: equal or 0.1 °C higher. It is generally less than Td; sometimes equal ( $T > T_d \geq T_w \geq T_g$ ).

Tab. 1.7: Characteristic examples of conditions  $T > T_d > T_w \geq T_g$

Day	Station	T (air)	Tg (ground)	Td (dripping water)	Tw (almost stagnant water)
05/01/2016	3	14.2	13.8	13.9	13.8
13/04/2016	2	14.0	13.6	13.9	13.6
13/04/2016	3	14.9	13.8	14.2	13.8
13/04/2016	5	15.8	14.0	14.1	14.0
14/07/2016	Chamber beside 1	16.6	13.7	14.0	13.8
14/07/2016	B	16.0	13.8	13.9	13.8
14/07/2016	3	17.0	13.9	14.0	14.0
14/07/2016	C	15.2	13.9	14.1	13.9
04/11/2016	3	16.4	14.0	14.2	14.1
04/11/2016	C	15.3	14.0	14.6	14.0
04/11/2016	5	14.7	14.2	14.2	14.2
04/11/2016	6	18.8	14.5	14.9	14.5
04/11/2016	7	19.1	14.4	15.0	14.4
04/11/2016	8	19.1	14.4	15.1	14.5
29/12/2016	Chamber beside 1	13.7	13.5	13.6	13.6
29/12/2016	4	16.0	14.0	14.1	14.0

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29/12/2016	7	16.6	14.4	14.5	14.5
29/12/2016	8	16.6	14.4	14.8	14.5

Only in November and December,  $T > T_d > T_g > T_w$ ; the puddle water is colder than ground of 1 - 7 °C.

*Tab. 1.8: Characteristic examples of conditions  $T > T_d > T_g > T_w$*

Day	Station	T (air)	Tg (ground)	Td (dripping water)	Tw (almost stagnant water)
04/11/2016	1	17.5	13.9	14.5	13.8
04/11/2016	Chamber beside 1	16.1	13.9	14.4	13.7
04/11/2016	4	15.0	14.2	14.6	14.0
29/12/2016	2	14.6	13.7	13.8	13.6
29/12/2016	3	16.1	14.0	14.3	13.9
29/12/2016	C	16.1	14.2	14.3	13.9
29/12/2016	6	16.9	15.0	15.2	14.3

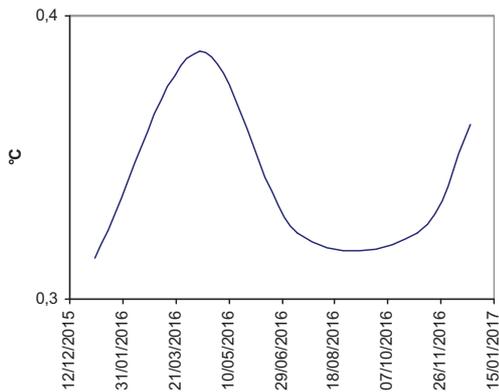
11% of cases:  $T > T_g > T_d > T_w$ . This occurs mainly in the summer, not close to the entrance. The puddle water is colder than the ground of about 2 °C, and colder than the dripping water of 1 °C.

*Tab. 1.9: Characteristic examples of conditions  $T > T_g > T_d > T_w$*

Day	Station	T (air)	Tg (ground)	Td (dripping water)	Tw (almost stagnant water)
14/07/2016	4	16.0	14.1	14.0	13.9
14/07/2016	5	16.4	14.5	14.2	14.1
14/07/2016	7	16.2	14.6	14.4	14.3

Only in a 2% of the cases, in winter, and at the entrance of the cave (where there isn't puddle water),  $T_g > T > T_d$ .

Generally, the dripping water is warmer than the ground. The average of difference between  $T_d$  and  $T_g$  remains positive ( $> 0.3$  °C) throughout the year throughout the cave, and is a bit higher in early spring (Fig. 1.33).



*Fig. 1.33:  $\Delta T_d - T_g$  (average of all stations).*

## 4.7. Results of Soil Data Analysis

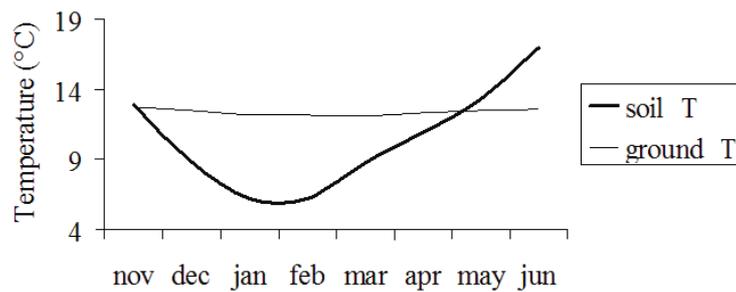
Correlations between the temperature of soil, cave roof, cave floor and climatic station, and analysis of the correlation with the water balance of the soil were performed by Olmo (unpub.) and Colosio (unpub.). Respect to temperatures in cave, soil temperatures are less stable (fig. 1.34), less influenced by the water balance, and more correlated to temperature

The climatic study of caves with single entrance

of external air (fig. 1.35). The thermal gradient between the ground and the underlying cave is very irregular (tab. 1.10). This testifies that the water influences the cave temperature much more than the soil temperature, and the heat conduction from the surface is not important.

*Tab. 1.10: Thermal gradient between cave and surface (from Colosio, unpublished).*

Station	04/11/2016	12/12/2016	13/01/2017
soil/dripping water (cave vault)			
O	0,037	0,225	0,35
B	- 0,022	0,445	0,744
C	0,005	0,247	0,391
A	0,221	0,7	1
D	0,033	0,177	0,295
E	0,038	0,194	0,228
soil/cave ground (cave floor)			
0	0,027	0,189	0,279
B	- 0,008	0,336	0,528
C	0,011	0,185	0,289
A	0,117	0,468	0,711
D	0,013	0,141	0,237
E	0,048	0,171	0,256



*Fig. 1.34: Monthly average of temperature into soil above the cave and into cave ground.*

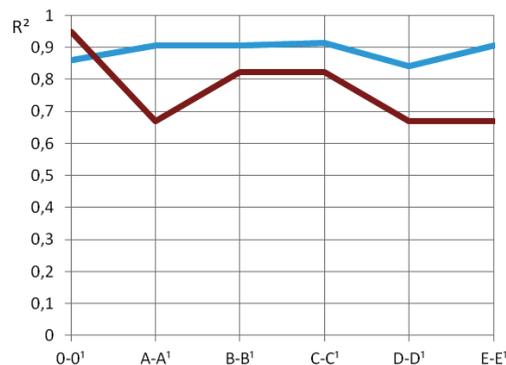


Fig. 1.35: Blue line: determination coefficient soil °T – average of external air °T; red line: determination coefficient dripping water °T - average of external air °T. O-E: soil stations.

## 5. Implications

### 5.1. Andrassa (and similar caves) is a good indicator of climate?

It is clear that an active cave like Andrassa has temperature tied to several factors, each of which has its own special relationship with the weather:

- the temperature of the groundwater is mainly determined by the average water temperature of rain in area of infiltration;
- the temperature of oozing water is determined both by temperature of rain water on area of cave, both by temperature of soil and of vadose zone;
- the air temperature is linked both to temperature of surfaces with which it is in contact (water, cave walls, ground), both to temperature of outside air and to ventilation mechanisms (convective circulation, input or output of air because of changes in air pressure).

The cave ground is thermally more stable to air and water, but, for the above reasons, we cannot share the opinion, expressed by older literature (e.g. White 1988), that the ground temperature reflects the external mean annual temperatures. For example, changes in rainfall can vary the temperature of the cave ground even with outside temperature unchanged (see for other possible situations Faimon et al. 2012). Simply put, an active cave like Andrassa is not the best climate indicator, especially when there are better alternatives, like fossil caves.

### 5.2. What is the influence of temperature and humidity on the habitat of Andrassa?

The habitat of Andrassa (and of Underground Compartment Superficial *sensu* Motta & Motta 2015b) has substantially equal average temperature than the outside but offers:

- daily and annual excursions very low (compare temperature maps with figure and table 3);
- humidity quite constant (tab. 1.5), always > 50% within entrance pit and > 65% elsewhere; values that are high in this Mediterranean climate, with frequently days of dry and strong wind.

The widest humidity range is in deepest part, not in entrance pit, and the narrowest humidity range is in Great Chamber, which is also the most humid zone.

Tab. 1.11: Humidity distribution in Andrassa Cave.

Position		135 m from entrance	Great Chamber	Entrance pit
Relative humidity	<i>Winter</i>	100 %	95 %	80 %
	<i>Spring</i>	85 %	95 %	75 %
	<i>Summer</i>	75 %	75-85 %	55 %
	<i>Autumn</i>	65 %	75-85 %	65 %
$\Delta$ RH max		35 %	20 %	25 %
Absolute humidity		10.7-11.2 g/m <sup>3</sup>	10.8-11.9 g/m <sup>3</sup>	7.0-9.8 g/m <sup>3</sup>

## 6. Conclusions

This work presents the distribution and oscillations of temperatures, and the humidity distribution in Andrassa, an active ponor with a single entrance. In addition to the specific results, which depend on this specific cave (as thickness of vadose zone, sequence of narrow passages and chambers, etc.), and by weather, and measurement moment, many conclusions/approaches are universal.

It is evident the total difference from the "air bag style". Is true that in summer the air in cave is colder than the outside, but this does not prevent the formation of warm zones even very far from the entrance. In autumn the deep air can be warmer than outer air (and even of the air within cave during July), while the cave should behave as "cold air trap"! The period of air always warmer towards the entrance (from spring to autumn) is much longer than the one predicted by the "air bag" model.

During winter, the air in cave is really a bit hotter than outdoor (like in "air bag style"). The air in cave is really always colder towards entrance, but only between the Great Chamber and entrance. It is not there "a short transition zone" between a deep zone with cold and homogeneous air, and an entrance zone with air that reaches quickly the outside temperature.

There is no sign of "transitional seasons", during whose, "little air circulates, with direction that varies, depending on temperature variation of outside air." There is no sign of convective draughts: the vault is averagely colder than the ground. The propagation of heat waves in the air suggest, however, that a part of the heat exchanges takes place through the internal atmosphere (for possible mechanisms see Badino, 2010). Therefore, the air entrance is one of the causes of the thermal variations of the cave, albeit not the only. In particular, the circulation of water (dripping, water table) is the other great factor of the thermal dynamics in Andrassa. The morphology of Andrassa is not particularly conducive to entry of air, as it has long narrow tunnels with  $< 2 \text{ m}^2$  section! So, these conditions there are probably in many active caves with single entrance (e.g. the caves described in Motta & Motta 2014). In conclusion, although the Andrassa has the typical morphology for an "air bag" circulation, does not has this kind of dynamic, due to factors that commonly found in many caves. This leads to suspect that in reality a thermal imbalance of 1-2 °C is possible in any cave, also very far from the entrance, without any relation with an arrival of air from the entrance; consequently, the humidity is frequently  $< 100\%$  even in caves with abundant water (on the other hand, several authors believe that the genesis of stalactites is linked to a partial evaporation of dripping waters).

The distributions of temperature and relative humidity within Andrassa are also incompatible with the “static cave” model. The researches on CO<sub>2</sub> of Calandri (1997), and the low relative humidity suggest a continuous, albeit slow, renewal of air. This can happen, as it seems to indicate the temperature distribution, by diffusion. Thermal imbalances between air, soil and water probably cause local, convective motions of air that contribute to facilitate the propagation of heat waves. Although lacking a strong ventilation, we can't properly speak, as Kowalczk and Froelich (2010), of a "summer stagnation" versus a "winter ventilation", especially for the deepest sector. Besides, the cave is not a cold air trap, and in autumn the cave air is warmer than the outside air, because of persistence of heat waves, and the "winter ventilation" doesn't arrive in depth.

Andrassa has a weak water runoff and an amount of oozing normal: we can safely say that this cave belongs to the most common type of cave with single entrance and directed downward. In all likelihood, both the "air bag" model, both the “static cave” model, are not the rule for all caves directed downward and with single entrance, but they are valid to very dry caves only.

The relationships between the temperatures of air, water, rock, and ground are very interesting. First of all, among all the mathematically possible relations between T, T<sub>g</sub> and T<sub>d</sub>, in the cases examined there are not those in which T<sub>g</sub> > T<sub>d</sub> > T or T<sub>d</sub> > T > T<sub>g</sub>.

The puddle water is never the warmest component, besides is always colder than dripping water. This suggests different origin (groundwater coming from upstream). If we consider also the puddle water, only five of the 24 cases mathematically possible exist. So, certainly the relations between the temperatures of neighboring materials aren't casual, but they derive from the processes with which the external air and the circulating water influence the temperature of the cave ground (Badino, 1995; Tab. 1.12).

Normally, in winter the outside air cools the cave ground. At the entrance, the circulating water and the oozing can cool the ground even more than the air. Already at the start of the spring, the outside air and water tend to be hotter than the ground and they heat it. In the summer in the middle and deep part of the cave, the air heats the ground (by propagation of heat waves), but the circulating water is colder, and it tends rather to cool it. Autumn is like spring.

The most representative temperature of the average temperature of the cave is that of its ground T<sub>g</sub>, which has a considerable stability in the face of disturbances such as heat waves and heavy rainfall. Therefore this is the temperature that better describes the climate of a cave.

*Tab. 1.12: Probable causes of the thermal relations in Andrassa.*

Relations	Processes	Presence
T <sub>d</sub> ≥ T <sub>g</sub> > T <sub>w</sub> > T	Outdoor air cools the cave.	Prevailing in winter.
T <sub>d</sub> ≥ T <sub>g</sub> > T > T <sub>w</sub>		
T > T <sub>d</sub> ≥ T <sub>w</sub> ≥ T <sub>g</sub>	Outdoor air and dripping water heat the cave.	Prevailing especially in the intermediate seasons.
T > T <sub>d</sub> > T <sub>g</sub> > T <sub>w</sub>	Dripping water and groundwater cool the cave.	Entrance, in autumn and winter.
T > T <sub>g</sub> > T <sub>d</sub> > T <sub>w</sub>	Outdoor air heats the cave, while circulating water cools the cave.	Middle and deep part of the cave, especially in summer.
T <sub>g</sub> > T > T <sub>d</sub>	The dripping cools the cave.	Entrance, in winter.

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This is even truer from the ecological point of view, since most of the cave organisms live in contact with the ground (Motta and Motta, 2014; Isaia et al., 2013).

The temperature of Andrassa ground is 2-3 °C lower than annual temperature of closest climatic stations, despite a difference in height between average altitude of hydrographic basin and cave entrance of only 50 m. 2 °C is the normal  $\Delta T$  between the rainfall water and local air (Badino, 2010). Also the position in the shade of Andrassa (because of trees and of canyon morphology) is a considerable reason (but on 4 November the air near to entrance appears warmer and dryer of climatic station: see fig. 1.21).

Finally, the stability of  $T_g$  makes this parameter useful to check for medium to long-term changes resulting from global change, particularly in poor areas of other environmental indicators such as glaciers.

## 2. The Cento Corde cave (Rocce dell'Orera karstic plateau, Liguria, NW Italy): a fossil ponor developed toward down, without water circulation

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### 1. Introduction

The water is the bigger factor influencing the temperature distribution within Andrassa. Still, some special features, as the fact that in autumn the air is much warmer than water in summer (i.e. the heat waves), aren't possible to explain neither with the influence of water circulation nor with the ventilation models that some authors offer for the single-entrance caves. Therefore it is mandatory to check caves similar to Andrassa, but dries. For this comparison the Cento Corde cave is almost perfect. This cave is a ponor developed toward down, at the edge of a cockpit karst; the altitude, rock, and morphology (an entrance pit and a sequence of chambers and steep, narrow tunnels) are very similar to Andrassa. The differences are a shorter length and a very sunny position of the entrance.

### 2. The study site

#### 2.1. Geomorphology

The Cento Corde pit (44°9'47.023" N, 8°19'5.602" E WGS84, 230 m a.s.l.) is just downstream from edge of Rocce dell'Orera karstic plateau, at the foot of a suspended cliff. The rock is *Pietra di Verazzi*, an arenaceous limestone of high permeability. Length: 36 m Depth: -24. The cave has a narrow entrance of about 1x 1.5 m, followed by a pit of 10 meters that leads to a chamber of 10x10x4 m; it follows a jump of 4 m from which a tunnel with inclination of 30-40°, and average height of the vault 6-4 m, leads to the muddy-stony bottom.

Rocce dell'Orera plateau is the western sector of a cockpit karst, born in a period of tropical climate (Biancotti and Motta, 1989). During Pleistocene, the plateau was much larger, and included the Manie plateau; it is probable that the Cento Corde pit was the ponor of a cockpit, as Andrassa. Today the cave is totally inactive, partially filled by speleothems, and the water enters only by dripping ([www.catastogrotte.net](http://www.catastogrotte.net)).



Fig. 2.1: The entrance (from [www.catastogrotte.net](http://www.catastogrotte.net)).

The morphology of Rocce dell'Orera is a half-exposed karst, without structural microforms, not having joints. Humus-water grooves, cliff foot recesses, and round karrens are abundant,

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together phytokarst microforms: wall pockets and honeycomb karrens on vertical walls; tube-like holes and root grooves on flat surfaces (Motta, 2016).

## 2.2. Climate

Calice Ligure is the closest climatic station (WGS84 lat. 44.20310, lon. 8.29344. 60 m a.s.l.; fig. 1.3).

The 2017 was the warmest of 2011-2017 period, with an annual mean of 15.2 °C (average of 2011-2017: 14.8 °C).

## 3. Monitoring

### 3.1. Short-Term Data

During a survey (January 5, 2016; April 13, 2016; July 14, 2016; November 4, 2016; December 29, 2016) we have measured:

- 1) temperature and relative humidity in air at 1 m above ground level;
- 2) temperature of ground at 0.02 m below surface;
- 3) temperature of groundwater appearing in puddles on the floor;
- 4) temperature of dripping water, within of tubular stalactites.

Method and instruments are the same used into Andrassa.

## 4. Results and Discussion

### 4.1. Winter

On January 3, 2017, air, ground and stagnant water have similar temperatures. Figure 2.2 shows the condition of air temperature near ground (temperature and humidity). On measurement day, a strong wind (tramontana) kept homogeneous the external temperature near to cave entrance.

In theory, winter ventilation should make the outside air enter the cave. Given the morphology of the cave, short and with narrow entrance, it would be logical to expect that at the ground the temperature in January is constant throughout the cave and, at least during the daylight hours, is considerably colder than the outside air (cold air trap). The temperature distribution looks instead like a heat wave. The temperature at the inlet rises abruptly by 3.6 °C compared to the outside air, while on the cave bottom the air is colder than outside air. The cliff on which the cave opens is very sunny and warm during daylight hours (see fig. 2.3). The most probable hypothesis is that the violent thermal and barometric changes outside (during a sunny day the outside temperature of the rock surface easily exceeds 20 °C even in the middle of winter) cause the entry of heat waves, bringing the temperature within the cave to values also much higher than the annual average.

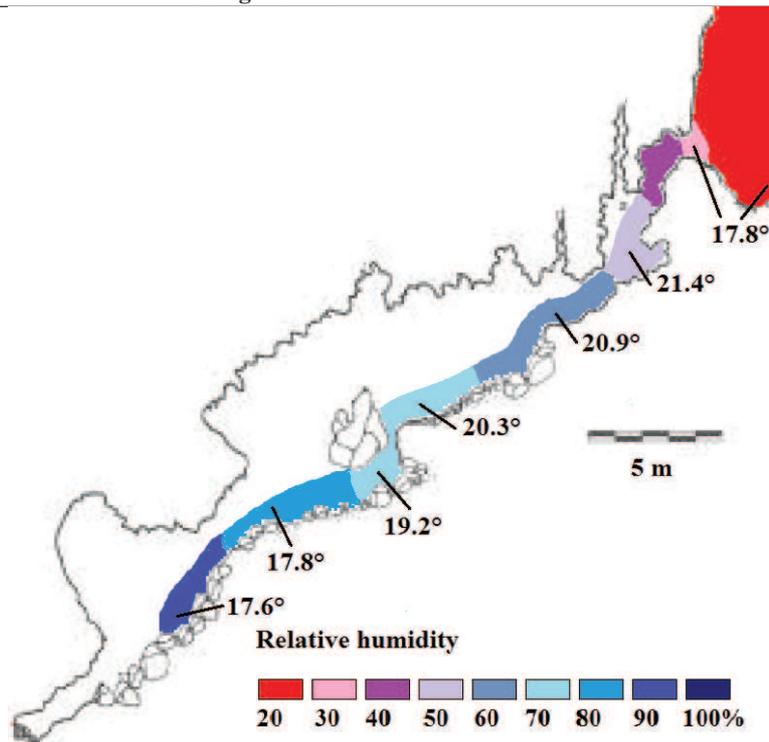


Fig. 2.2: Air temperature at 0.8 m on the ground level, survey of January 3, 2017 by M. Motta. Drawn on an original cross section of Daniele Vinai, Rosalinda Farinazzo, Simone Baglietto, Mauro Rossi, Simona Mordeglia (*Gestionale speleologico ligure*, 2017).

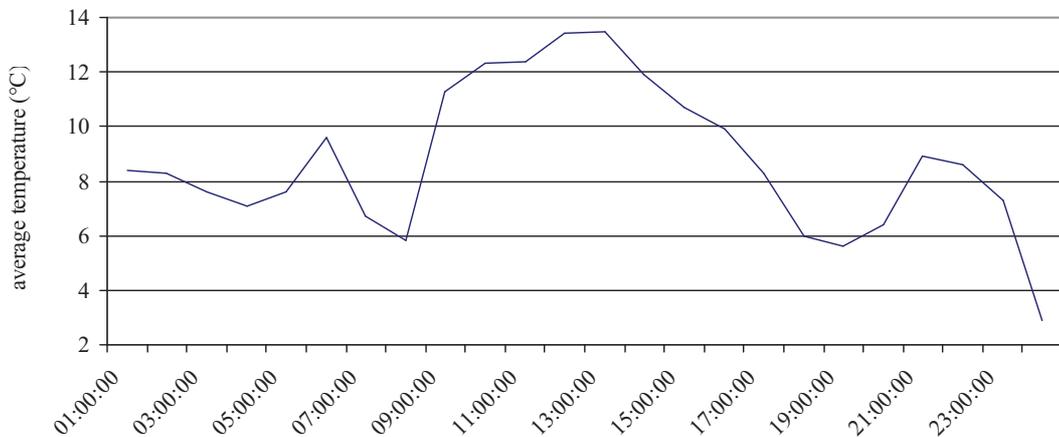


Fig. 2.3: Average of air temperature at Calice Ligure station on January 3, 2017 (processed from data of Arpal, 2017).

## 5. Conclusions

The few available data are sufficient to show that even a dry cave developed toward down does not follow the "traditional" models of ventilation (e.g. Cigna, 1968; Faimon et al., 2012), and probably also in this case the diffusion of heat occurs by propagation of heat waves.

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Since the cave is not a cold air trap, it is potentially a good climatic indicator. However, because of the heat waves, for climatic uses it is better to use the temperature of the soil rather than that of the air, too influenced by heat waves.