The caves with single entrance have a circulation "air bag style" really? The hygrothermal conditions of Andrassa (Ligury, Italy)

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Abstract—**The study illustrates the hygrothermal conditions of a cave (Andrassa) that has the ideal morphology for a circulation "air bag style", where the winter temperature is determined by a convective circulation, which comes from the entrance. We examined the seasonal conditions. Indirectly, the temperature distribution in air and ground indicates the direction of air flow, even when the flows are too slow for direct measurements. The results show that the water in Andrassa cave influences the ground temperature more than air. So, in summer the cave air is colder than on the outside, but the air enters at least at 180 m from the entrance. This condition lasts from spring to autumn: the transitional seasons of the "air bag style", in which "air little circulates, with direction that varies, depending on the temperature variation of the outside air", there are not. During winter, the cave air is a bit hotter (like in the model named "air bag style"), and the thermic gradient is actually negative upwards, but only as far as 60 m from the entrance. It is not there "a short transition zone" between a deep air (cold and homogeneous) and an entrance-zone air (at a temperature that reaches quickly the outside value). The water circulation definitely influences the temperatures of Andrassa. With its weak runoff, and its normal oozing, Andrassa represents the commonest type of cave developed downwards and with single entrance. It seems very probable that the "air bag" model of circulation is not the rule for all caves similar to Andrassa, but is limited to very dry caves.**

Keywords- Temperature distribution, Humidity, Air circulation, Karst, Ponor, Cave, Ligury

I. INTRODUCTION

According to bibliography, every cave developed downwards and with single entrance must have an air circulation in accordance with the model so-called "air bag style" [1]. The air must have only convective movements (due to temperature difference between the cave and outside air), which lead to the following seasonal temperature conditions.

1. During the summer the air in the cave is more cold (i.e., more dense) than outdoor air, so the latter can enter the cave only to a limited extent. Therefore the thermic stratification in the cave is reversed: the deep air is the colder; after a short transition zone, at the entrance the air temperature reach quickly the outside value.

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

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

However, Andrassa (like all active caves) has a water circulation, i.e. an additional source of heat exchanges. Being a ponor, frequently water flows on the bottom. Throughout the year, lots of water dripping falls in largely of the cave. The "air bag" model still applies? If the heat transfer between air, water and rock changes dramatically the air circulation, the "air bag" model (commonly applied to all caves with single entrance) would not be applicable to caves in which, in addition to air, water normally enters (by oozing, or by underground rivers).

II. GEOMORPHOLOGY

The Andrassa entrance (WGS84 44°12'22.8"N, 8°22'42.5"E, 211 m a.s.l.) opens on the bottom of a karst ravine (fig. 1), at the geological boundary between the dolomitic limestone of Middle Trias (medium permeability) and the arenaceous limestone of Middle Miocene (very permeable), just downstream from the western edge of the Manie plateau.

Figure 1. The entrance of Andrassa.

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The latter is a cockpit karst, born in a period of tropical climate, during the Early Pleistocene. During the Pleistocene, the original plateau, much larger, included the area of the cave [2]: this zone was a big cockpit, whose ponor was the Andrassa [3]. Today Manie plateau is greatly reduced, so, only the easternmost part of the cockpit (so-called Andrassa Plains) keeps the original morphology [4]. The western part is a little valley, with a watercourse active only during exceptionally rainy periods [5], the Rian Andrassa.

The Andrassa cave has the typical morphology of a ponor: an initial pit, of 12 m deep, that is followed by several chambers (sometimes flooded), connected by steep, narrow tunnels. The cave is oversized, compared to habitual runoff; because when the cave was the ponor of the entire cockpit, the hydrogeological basin was about double that of today. The accessible part (for a short time, by means of debris removal) of the cave is 400 m long and drops to -60 m [6]. Reference [7] proved that the water of Andrassa arrives at Acquaviva spring (65 m a.s.l., Sciusa Valley), in a time ranging between 80 hours (during a very strong drought), 18 hours (at the first rainy period after the summer drought, with vadose zone saturated) and 15 hours (at last rainy period after the winter period, with epiphreatic zone completely flooded). On the basis of changes in discharge, turbidity, hardness, and tracers concentration, [8] says that the entire path of the water follows the geological boundary between dolomitic limestone (bed) and arenaceous limestone (roof). The inaccessible part of karst system is long at least 1650 m (with a height difference of 85 m). After an initial part with narrow passages and chambers similar to the accessible part, it should be almost horizontal, partially clogged with silt and sand, with large chambers (maybe not completely submerged) at the arrivals of other underground rivers (which come from the Mala Cave, Ingrid Cave, and New Cave of Finalese [9]). In other words, it should be an epiphreatic or phreatic gallery, maybe not completely flooded, but certainly with no real atmospheric circulation.

We can thus summarize the dynamic of groundwater flow.

1) During ordinary floods, the outer rivulet (Rian Andrassa) collects water overflowing from the Andrassa Plains. This water is intercepted by sinkholes immediately upstream of the entrance to the Andrassa Cave. The narrow tunnels of the 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 enters also through the entrance pit. Sometimes pebbles, sand and twigs enter into the cave. The distal end of the cave remains completely flooded for weeks. Exceptionally, also the Great Chamber remains flooded (fig. 3).

3) After the rains, a large amount of dripping water enters in the cave from the vadose area (particularly at the beginning of Great Chamber). This process has settled several stalactites, travertine dams, and flowstone deposits.

4) During lean periods, the water is only in isolated pools and in areas of persistent oozing, but the floor remains wet everywhere.

III. Data collected

The work presents the data of four surveys in 2016: January 5 (winter), April 13 (spring), July 14 (summer), and November 4 (autumn). We have measured:

1) temperature and relative humidity in air at 1 m from the bottom;

2) temperature of ground;

3) temperature of standing water;

4) temperature of dripping water within of soda-straw (tubular stalactites).

We have measured at 2 m from the body of the operator. The measuring points shape a network with measurement intervals of 10 m. The lighting was only a two-led lamp, in order to avoid unwanted sources of heat. The method and instruments (error of ± 0.1 °C for temperature and ± 1 % for relative humidity) are the same used in Borna Maggiore cave [10]. This method is better for assess the air circulation than a method based only on anemometers [11]. 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.

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

IV. Data analysis

A. Winter

In January the temperatures of air, soil, and standing water (fig. 2 and 3) are near one another, with the exception of a zone of warm air in the Great Chamber. The dripping water is slightly warmer, especially in deepest sector.

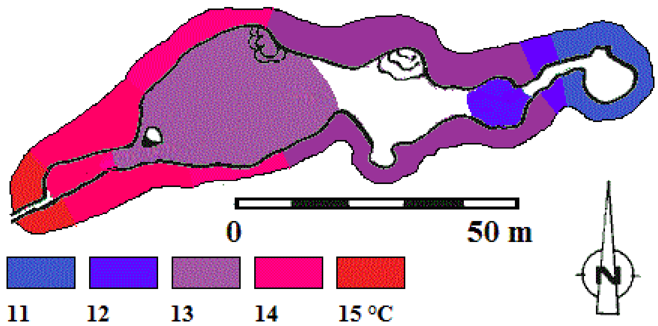

Figure 2. Temperature distribution of the dripping water (colors outside the cave boundary) and of surface water (colors within the cave boundary; the part in white is dry) on January 5, 2016. From [11].

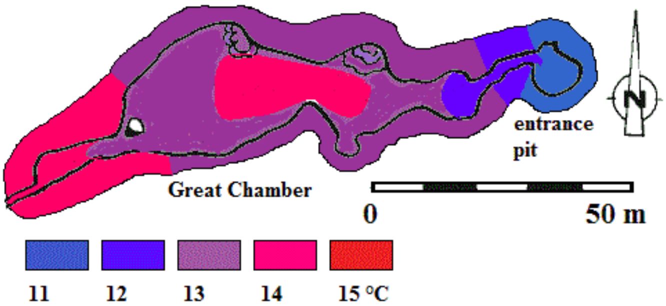

Figure 3. Temperature of air (colors within the cave contours) and of ground (colors outside the cave boundary) on January, 5 2016. Outside, the ground is at 7.0 °C, the air is at 11.0 °C.

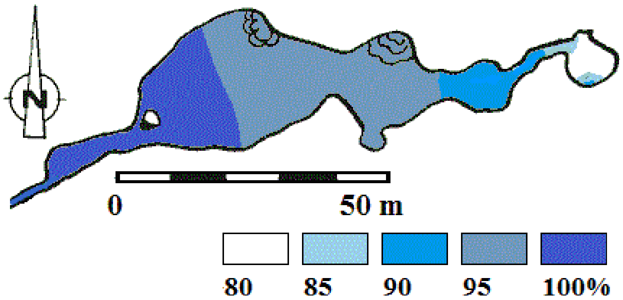

Figure 4. Distribution of relative humidity (%) on January 5, 2016.

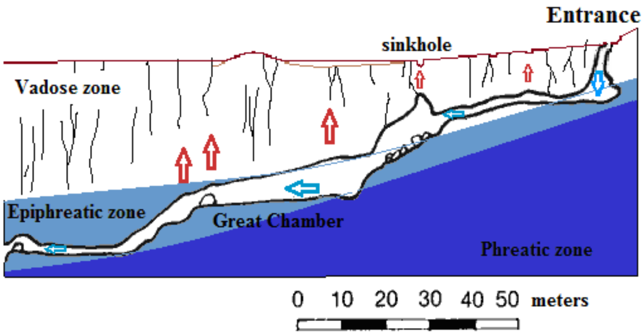

Figure 5. Schematic section of Andrassa (section of cave from [4]; topographic profile from an original GPS survey). The arrows indicate the likely circulation of air in winter (red: hot air; blue: cold air).

The tendency towards saturation with the depth (fig. 4), despite the increased air temperature (fig. 3), indicates a progressive increase of absolute humidity, tied to strong evaporation. The undersaturation near the entrance despite the lowest air temperature, conversely, indicates that the cave, during the measurements, takes in air from the outside. The absence of evidence of exit streams of air indicates that probably the same cracks that carry water of oozing into the cave (together to snails, seeds…) at the time of the measurements aspire warm air from the cave, compensating the entry of cold air in the cave from the entrance (fig. 5).

B. Spring

The dripping water is slightly warmer (Δ°T < 1 °C) than stagnant water and ground (these ones have almost the same temperature; fig. 6 and 7). The temperature of the dripping water is lowest in Great Chamber, and, especially, in the entrance pit. The ground temperature has a more regular distribution: it becomes increasingly low towards the entrance.

Between entrance and Great Chamber, the air is very hot (especially close to entrance). In Great Chamber, the air has the same (lowest) temperature of standing water and ground; below, the air is warm as the dripping water or slightly warmer.

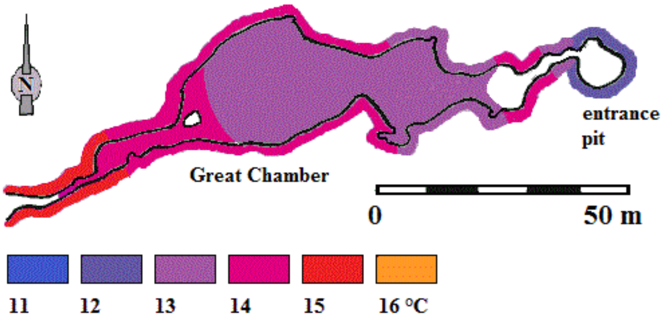

Figure 6. Water temperature (see caption of fig. 2) on April 13, 2016. The water temperature of the Rian of Andrassa (the rivulet outside) at the same time is 15.1 °C.

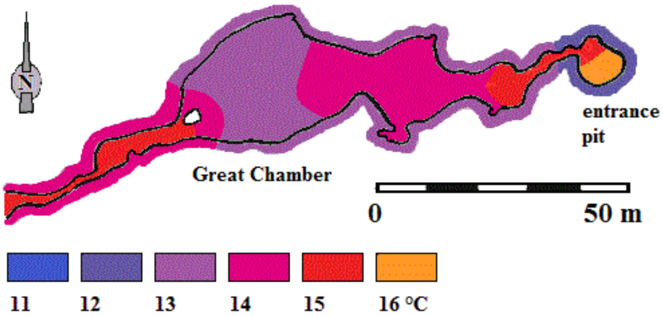

Figure 7. Temperature of air and of ground (see caption of fig. 3) on April 13, 2016. Outside, the ground is at 13.0 °C, the air is at 13.1 °C.

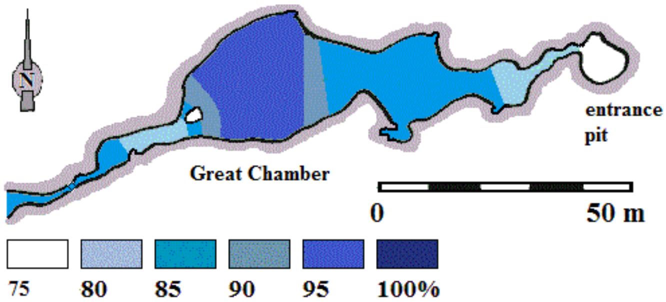

Figure 8. Relative humidity (%) on April 13, 2016. Outside, the air in front of the entrance, at 1.5 m above the ground, had RH = 67.6%

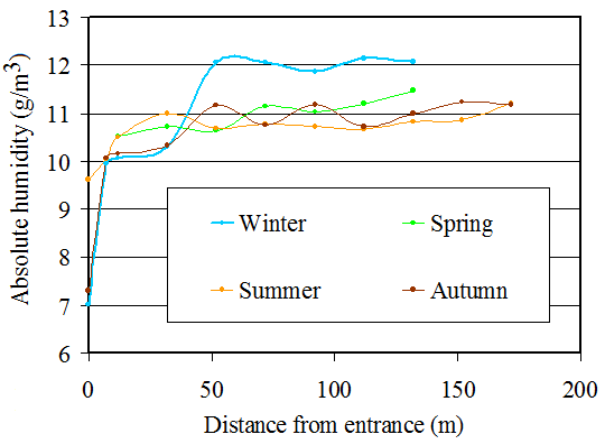

Figure 9. Absolute humidity. Starting from 50 meters away from the entrance, the value is fairly constant, and changes little from spring to autumn. In winter the value is slightly higher.

C. Summer

The temperature of the dripping waters and standing water is almost the same (ΔT ≤ 0.1 °C; fig. 10). The ground temperature is similar (fig. 11), except in the entrance pit that is much colder. In the whole cave, especially in the entrance pit, the air is much warmer than ground and water (ΔT ground – air = 6.1 °C!). The deepest chamber and the N side of the Great Chamber have the lowest temperatures.

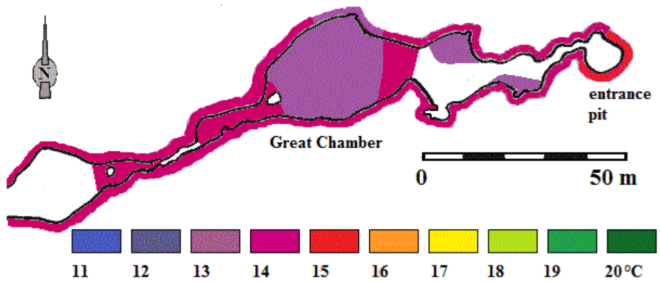

Figure 10. Water temperature (see caption of fig. 2) on July 14, 2016. The Rian of Andrassa was dry. Map of the cave redrawn from [12].

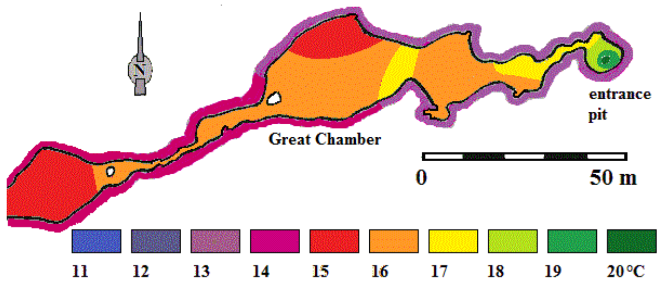

Figure 11. Temperature of air and of ground (see caption of fig. 3) on July 14, 2016. Outside, the ground is at 13.0 °C, the air is at 23.8 °C (top of entrance pit) and 23.5 °C (in front of the entrance).

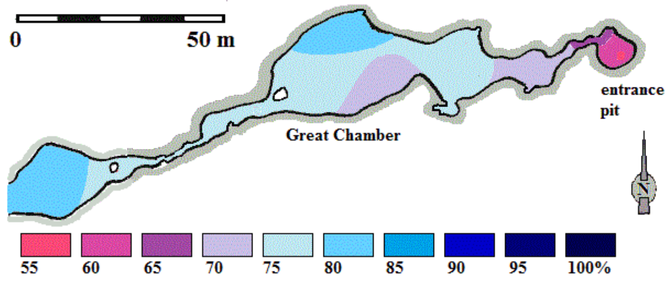

Figure 12. Relative humidity (%) on July 14, 2016. Outside, the air in front of the entrance, at 1.5 m above the ground, had RH = 55.7%

D. Autumn

- The standing water is always slightly colder than ground;

- The dripping water is slightly warmer than standing water (fig. 13);

- The air is much warmer than ground and water (fig. 14). The air temperature changes a lot. In entrance pit, the air temperature is the same of outside, but it has more humidity (fig. 15). After 32 m from the entrance, the air becomes always colder. The air within the Great Chamber is the coldest, and with more humidity. Just below the Great Chamber, the air becomes suddenly rather warm, and dry. In deep sectors the temperature arrives at the greatest value ("heat wave" of summer), 4 °C above the July value.

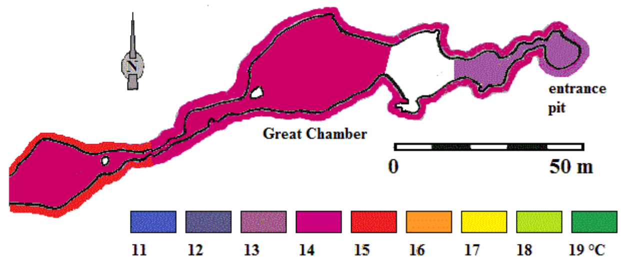

Figure 13. Water temperature (see caption of fig. 2) on November 4, 2016.

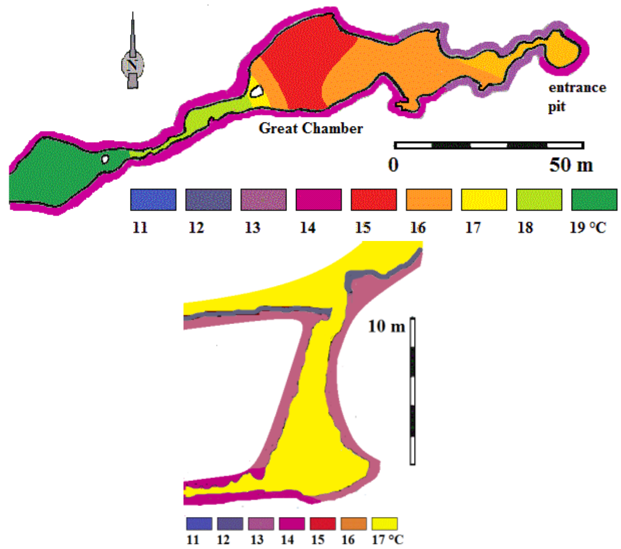

Figure 14. Above: temperature of air and of ground (see caption of fig. 3) on November 4, 2016 (map). Below: temperature of air and of rock surfaces in entrance pit (section).

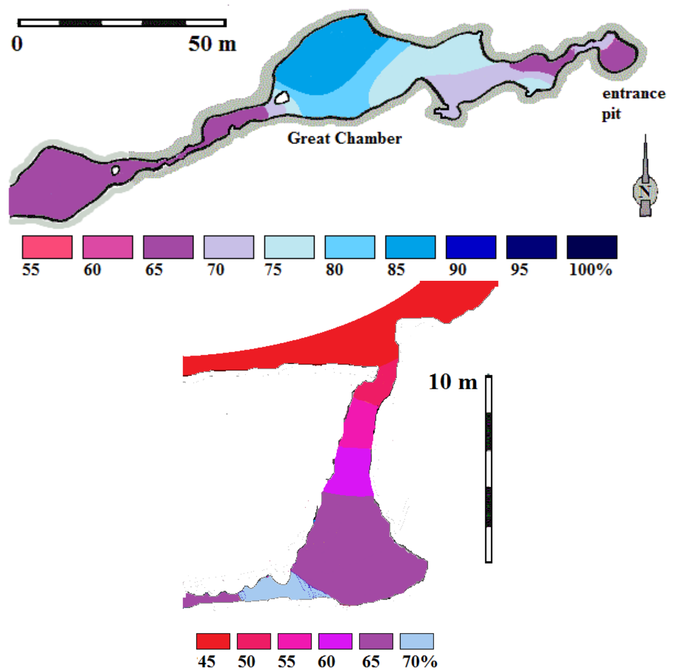

Figure 15. Above: relative humidity (%) on November 4, 2016 (map). Below: relative humidity in entrance pit (section).

V. Discussion

A. Seasonal evolution

Respect to winter, in spring, near the entrance, the water becomes slightly warmer ($\Delta T < 1°C$). Also the soil and the air of deeper areas have a modest warming. The air at the entrance, instead, gets very hot.

In summer, the water temperature by dripping remains almost unchanged in depth, while it increases near the entrance. The ground temperature remains almost unchanged. In the entire cave, the air temperature increases (particularly within the entrance pit), and in the Great Chamber the minimum of temperature is almost completely disappeared.

In autumn, the deepest part of the cave is even warmer than in summer, while near the entrance begins the cooling.

In winter the distribution of temperatures is similar, but with cooler temperatures, to situation in the autumn.

In winter, the air more humid is that of the deep zone, which get to saturation (fig. 4). In spring and summer, this area dries out significantly (fig. 8 and 12), while it remains very humid the Great Chamber, especially in the side N. The first part of the cave is always drier going towards the entrance. In autumn, the deepest part becomes as dry as the part near the entrance, while the N side of the Great Chamber is still humid (fig. 15). These variations suggest that there are two sources of humidity in the cave, with different seasonal variations: the dripping, which is very strong on the N side of the Great Chamber and is quite steady in the year; the standing water, which was minimal in November 2016, consequence of a long period of few precipitations.

B. The distribution of temperature and humidity

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

In summer and autumn, the air has a strong imbalance (it is much warmer) with air 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 the deep part and especially towards the entrance is warmer.

The air is quite dry and with large fluctuations in relative humidity from point to point. This reveals the presence of a circulation of air, which prevents from getting to saturated conditions, despite the constant presence of water. From spring to autumn this air is warmer than the walls of the cave, so that tends to get cold and to gain humidity. In spring the thermic flow arrives only up to the Great Chamber, where also comes the thermic flow coming from the deep part of the cave (which no goes toward the entrance, but likely comes out towards the outside through some cracks that are at the beginning of the Great Chamber). In summer the thermic flow penetrates up to the deepest sector.

In January the air is instead colder (very little) of the walls of the cave. In all likelihood, the cooling caused by this air, is not enough for to balance the heat flux associated with the warm air in the rest of the year. In other words, the water, not the air, carries out the heat carried by the air in the cave from spring to autumn.

The entering of air in the cave is likely balanced by the exit of air through the vadose zone above the cave, especially above the chambers (fig. 5).

The temperature of ground varies between 11.9 °C and 14.9 °C; that of water between 12.8 °C and 15.5 °C. Then, the annual excursion is not more than 3 °C, much lower than that of air (8.9 °C). Evidently ground temperature is closely connected with that of water, and independent of that of the air. This shows that the heat flux transported by water is predominant compared to heat flow conveyed by air.

The average temperature of the water (14.1 °C) as, probably, that of the ground, is close to temperature of resurgence (Acquaviva source, in Sciusa Valley). This temperature has been steady around 14 – 15 °C over the period 1990-2002 [11].

VI. Conclusions

It is clear the total difference from model named "air bag style". Is true that in summer the air in the cave is colder than the outside, but this does not prevent the entry of a thermic flow at least up to 180 m from the entrance. The water circulation definitely determines the dynamics of Andrassa. The morphology of Andrassa is not particularly conducive to the entry of air, as it has long narrow tunnels with < 2 m² section! So, there conditions are probably presents in many, if not all, the caves with a single entrance (e.g. the caves described in [13]). The period of air always warmer towards

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the entrance (from spring to autumn) is much longer than period predicted by the model named "air bag style".

During the winter, the air within the cave is really a bit hotter (like in the model named "air bag style"; see also fig. 4 of [12]). The air within the cave is actually always colder towards the entrance, but only between Great Chamber and entrance. It is not there “a short transition zone” between deep air (cold and homogeneous) and air within entrance (at temperature that reaches quickly the outside value). See also fig. 5 of [12].

There is no trace of "transitional seasons", during which, "little air circulates, with direction that varies, depending on the temperature variation of the outside air." In conclusion, although the Andrassa has the typical morphology for a circulation "air bag", not has this kind of dynamic, due to factors that commonly found in many caves:

- there is a large amount of dripping water from the vadose zone;

- there is standing water or outflow of water in the bottom;

- the cracks are air permeable.

This leads to suspect that in reality:

- a substantial portion of the air circulation occurs through small cracks (i.e. inaccessible to cavers);

Figure 16. The entrance pit.

- thermic imbalances of 1-2 °C are possible even very far from the entrance, without any relation with the arrival of air coming from the entrance;

- the air has frequently humidity < 100 % (due to thermic imbalances) 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 water).

Andrassa has a weak water runoff and an amount of dripping normal: we can safely say that this cave is within the most common type of cave with single entrance and directed downward. In all likelihood, the "air bag" model of circulation is not the rule for every cave directed downward and with single entrance, but it is limited to very dry caves, and perhaps in practice is found only in single and almost vertical pits.

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