THE CUEVA DE LOS CRISTALES MICROMETEOROLOGY

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Cueva de los Cristales, Naica, is one of the most interesting caves ever explored. During the Proyecto Naica, led by SpeleoResearch & Film, we undertook a complex series of measurements with the goal of understanding its current physical state. This was mostly carried out by the Department of General Physics of the University of Turin. Its natural state is at a depth of 170 m immersed in 54°C mineralized water. Now it is filled with air, partially surrounded by ventilated galleries at 35–38° C.

All kinds of micrometeorological processes are happening and unfortunately we are rather unprepared to follow the details because it is what in physics is called a "transitional state." It is, in other words, experiencing a "fall" towards a new state of equilibrium that we still have not determined, but that we hope to be able to influence in some way in the future. In the meantime, all the environmental parameters vary far more than expected and in an irreversible way, so the techniques usually used to study caves aren't applicable here.

The climate of a normal cave is in fact substantially static, with minimal oscillations, whether daily or seasonal, around a point of equilibrium. They are oscillations related to the shape of the cave, but which also partly determine it, because they are able to start air currents and condensation processes which, over millennia, can significantly alter the rock. But we are still speaking about systems near equilibrium and which are therefore relatively easy to study. The climate of Cristales is evolving in an irreversible way, as well as quickly.

Our measurements have shown various phenomena. The cave continues cooling by approximately half a degree per year, because it loses heat by conduction towards the nearby mine galleries to the North-West, as well as by irradiation along the access corridor. We have also noticed that in the upper areas the air is stably warmer and more humid than the lower zones and those close to the exit. An unexpected find has been that, while the temperature is very stable, even if in slow decline, the humidity shows strong variations, on both the short and seasonal time scales. This is probably due to meteoric water infiltrations along the fractures created by the mining activity. Finally, there is an air current of about 50 L/s which starts when the access door is opened.

1. Introduction

The Cueva de los Cristales Gigantes, or simply Cueva de los Cristales, is located in Mexico, near the Naica village in the state of Chihuahua, at an altitude of 1100 m asl, is one of the most interesting caves until now explored. It was discovered during the excavation of a tunnel in 2000. Since then it is closed with a steel door (not airtight) and more recently by a transparent veranda which protect the visitors from the exposure to the hostile atmosphere. In fact, at the moment, around 2–3000 people per year are permitted to visit the cave during weekends, but without opening the last, transparent door.

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2. General

The climate of a usual cave is in fact substantially static, with minimal oscillations, whether daily or seasonal, around a point of equilibrium. They are oscillations related to the shape of the cave and its contact with the external environment, but which also partly determine it, because these fluctuations around the equilibrium are able to create "micro-meteora" (transient processes like air currents and condensation) which, over millennia, can significantly alter the rock. But we are still speaking about systems near the equilibrium and which are therefore relatively easy to study.

The main characteristic of the Cristales micro-climate is that it is not stationary or quasi-stationary; it is evolving in an irreversible way, as well as quickly. The Cristales natural state is at a depth of 170 m immersed in 54° C highly mineralized water. Now it is filled with air, partially surrounded by ventilated galleries at 35–38° C. All kinds of micrometeorological processes are happening and unfortunately we are rather unprepared to follow the details because it is what in physics is called a "transitional state." It is then experiencing a "fall" towards a new state of equilibrium that we still have not determined, but that we hope to be able to influence in some way in the future. In the meantime, all the environmental parameters vary far more than expected and in an irreversible way, so the techniques usually used to study caves aren't applicable here.

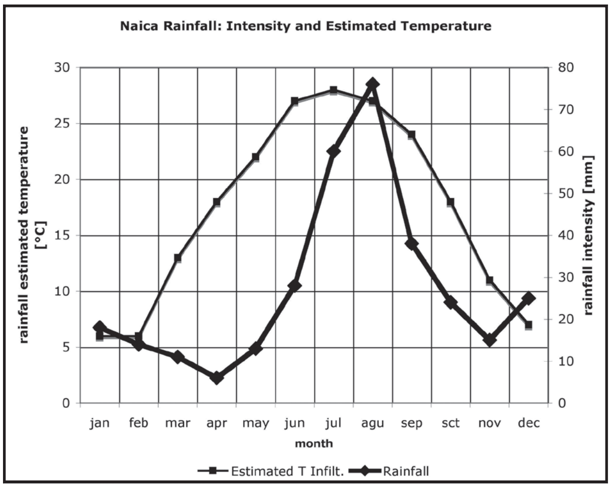

Figure 1: Rainfall intensity and temperature at Naica.

3. Cristales Environmental Conditions

The equilibrium temperature of cave in the Sierra Naica is given by the average temperature of infiltrating waters (Badino, 2005). In Europe the yearly average temperatures of infitrating waters and air are quite similar, but here they are not because precipitations are concentrated during summer. Corrections due to the Latitude (-4°) and Altitude (+300 m) effects give a Sierra Naica average temperature 1° C higher than El Paso (data from worldclimate.com).

Rainfall average temperature is generally 0.5–1° C less than the air, then we can assume that in Naica infiltration is roughly at the same temperature of El Paso. We obtain then an average yearly temperature of 17.5° C, but an average rain temperature of 21° C if weighted with precipitation intensities. Figure 1 shows precipitations and average monthly temperatures.

In the fall to the aquifer surface altitude (Cueva de las Espadas) the water temperature increases by about 0.75 °C. We can then assume that the equilibrium temperature of a cave at 1250 m asl is 22±1° C. This has to be considered the asymptotic temperature of "external heat source" which drives thermal exchange processes in contact with the Naica caves. Some temperature measurements inside Cristales were first taken in October 2002 (Testo 910, 0.01 °C resolution), giving 47.1° C at the floor and 47.4° C at 2 metres with a Testo 910. We repeated the same measurements with the same instrument in January 2006, obtaining 45.5° C.

The humidity, taken in June 2006 with an Assman psicrometre, was between 92 amd 94 %, then monitoring of relative humidity was possible. We have done this from May 2006 until now with a set of six Testo 175-H. Humidex is an index of the "perceived temperature," which depends on temperature and humidity (Masterton et al., 1979). It is in "degree Humidex;" 35–39: uncomfortable; 40–45: strong and general discomfort, danger; 46-53: highly dangerous; >54: imminent heat shock, death (Fig. 2). Cristales Humidex is around 90-95, twice the lethal, which gives an idea of the technical problems faced during exploration.

Our measurements inside Cristales have shown various phenomena, due to its non-equilibrium state and its

HUMIDEX

temperature [°C] \ relative humidity [%]	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	19	20	20	21	22	22	23	24	24	25	26	26	27	28	29	29
23	19	20	21	21	22	23	24	24	25	26	27	28	28	29	30	31	31	32	33
25	21	22	23	24	25	26	26	27	28	29	30	31	32	33	33	34	35	36	37
27	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
29	26	27	28	29	30	31	32	33	35	36	37	38	39	40	41	42	43	45	46
31	28	29	30	32	33	34	35	37	38	39	40	42	43	44	45	47	48	49	50
33	30	32	33	34	36	37	39	40	41	43	44	46	47	48	50	51	53	54	55
35	33	34	36	37	39	40	42	43	45	47	48	50	51	53	54	56	57	59	61
37	35	37	38	40	42	44	45	47	49	51	52	54	56	58	59	61	63	64	66
39	37	39	41	43	45	47	49	51	53	55	57	59	61	62	64	66	68	70	72
41	40	42	44	46	48	51	53	55	57	59	61	63	66	68	70	72	74	76	79
43	42	45	47	49	52	54	57	59	61	64	66	69	71	73	76	78	81	83	85
45	45	47	50	53	55	58	61	63	66	69	71	74	77	79	82	85	87	90	93
47	47	50	53	56	59	62	65	68	71	74	77	80	83	86	88	91	94	97	100
49	50	53	56	60	63	66	69	73	76	79	82	86	89	92	95	99	102	105	108
51	53	56	60	63	67	71	74	78	81	85	88	92	96	99	103	106	110	114	117
53	55	59	63	67	71	75	79	83	87	91	95	99	103	107	111	115	119	123	127
55	58	63	67	71	76	80	84	89	93	97	102	106	110	115	119	124	128	132	137
57	61	66	71	75	80	85	90	95	99	104	109	114	119	123	128	133	138	142	147
59	64	69	74	80	85	90	96	101	106	111	117	122	127	132	138	143	148	153	159

Figure 2: Perceived temperature.

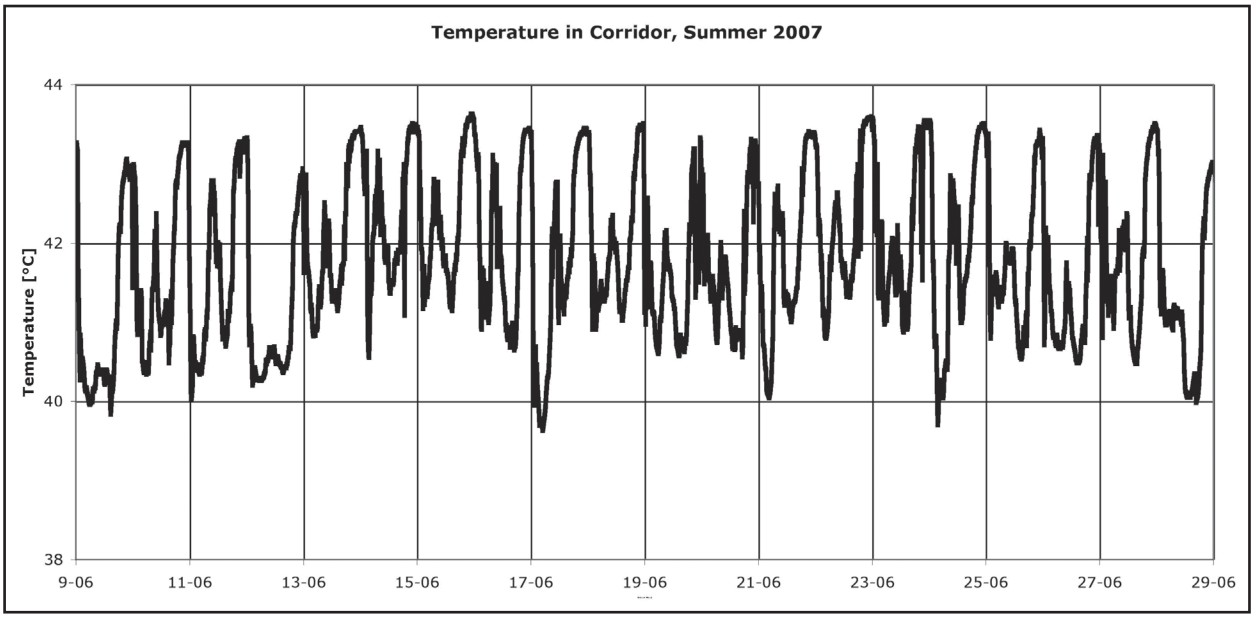

Figure 3: Diurnal temperature variations near the Cristales entrance.

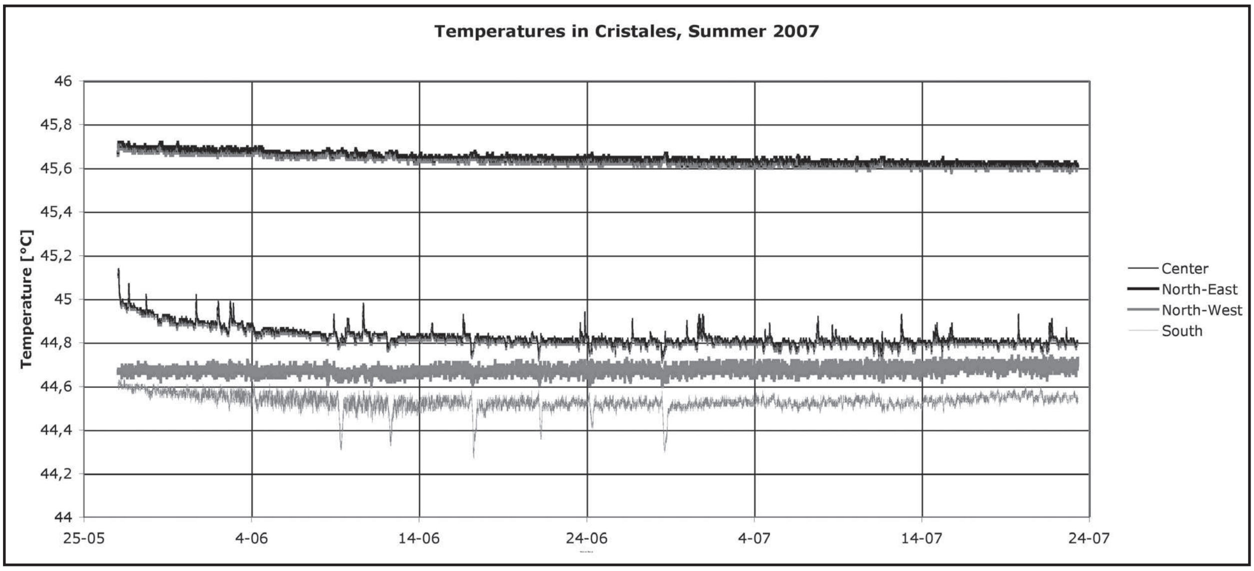

Figure 4: Temperature variations and values in different stations.

probable thermal connection with larger structures in the north-eastern branch.

Main phenomena are:

- Strong thermal sedimentation;
- General temperature decrease;
- Important air draught with open doors;
- Strong relative humidity variations.
- Thermal Sedimentation

In April 2006 we have begun a set of measures with an acquisition system Sigma 3000 (20 PT100, in four groups of four sensors inside the cave) of Lombard&Marozzini, which has given non-continuous data until August 2007 with a relative accuracy <4mK.

The thermal sedimentation in Cristales is extremely strong and shows diurnal variation. In fact, the highest part of the cave is quite stable, at a temperature around 45.5 °C, highly humid; also the "cold trap" at the bottom of the cave is quite stable at 44.6 °C (Fig. 4). The intermediate region shows important variations. It looks like a hot bubble that fills the highest part of the cave (and surrounding regions) has a diurnal variation and fills or empties the cave, leaving the highest and lowest parts undisturbed, but filling the intermediate area with hot air, including the access corridor (Fig. 3).

It shows a strong, regular daily effect, not depending on direct intervention on the doors. The maximum is at 00.00 UTC (16.00 LT), with often a sudden, very short drop. After that, the temperature falls down in few hours.

There is a secondary, less regular maximum around 09-10 UTC (01-02 LT). It seems due to temperature daily variations, maybe with some trapping effects, or pressure variations inside the mine due to regular actions on the ventilation.

There is a vertical sedimentation with an average gradient of 1.4/10° C/m at the end of 2006, reduced to 0.9/10° C/m at the end of 2007; there was also a N-S gradient of 0.6/25° C/m (Fig. 4). The downward hot bubble drift causes condensation on crystals surface in the highest part of cave.

5. Temperature variations

In the period 2002-2008 the cave has cooled by approximately half a degree per year, because it was losing heat by conduction towards the nearby mine galleries to the North-West, as well as by irradiation along the access corridor (Fig. 5). The estimated heat losses (the two of around 100 W each), as compared with the temperature decrease allow to calculate in 6×10^9 J/K the total thermal capacity of the “Cristales thermal system”, roughly 30-50 times larger than the thermal capacity of known crystals.

At the end of 2007 the mine conduits surrounding the cave have been closed to airflow and their temperature quickly increased to approximately 40° C. This fact, accompanied

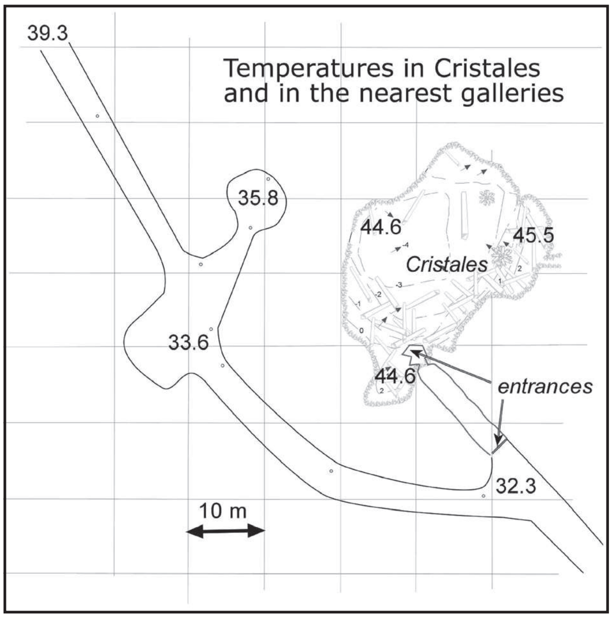

Figure 5: T-field in Cristales and surroundings.

probably with a careful management of internal door, which is now always kept closed, has almost stopped the temperature decrease of Cristales. The temperature at the top (North-East) has become stable around 45.5° C, whereas the temperature near the door, where there was a strong heat loss, has increased by 0.7° C to 45.2° C in January 2009 (Fig. 6). Condensation onto crystals in the upper parts of the cave is now virtually stopped.

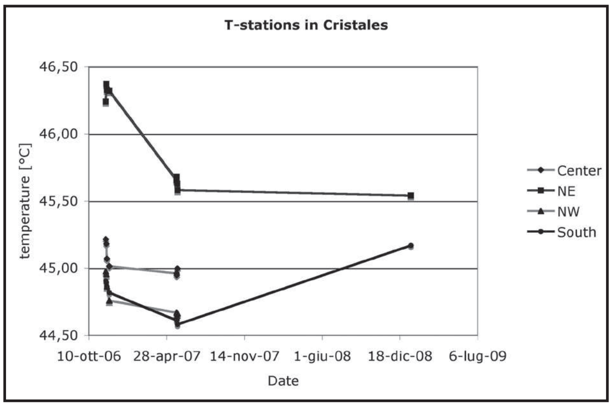

Figure 6: Temperatures in Cristales stations.

Fig. 5 shows the general temperature trend since the beginning of operations, in the region South, near the entrance. Geochemical data suggest that the Cristales temperature when drained by waters was around 56° C.

An unexpected finding has been that, while the temperature is very stable, even if in slow decline, the humidity shows strong variations, on both the short and seasonal time scales. This is probably due to meteoric water infiltrations along the Naica Fault and to movements of the hot-humid air bubble, which is in contact with Cristales (Figs. 7, 8, 9)

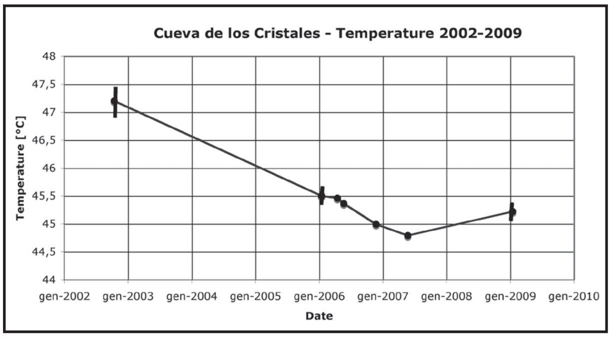

Figure 7: Temperature vs Time in Cristales Center-South.

6. Air draught

With the door nearly closed it is possible to perceive an air current coming from the cave. In May 2007 we have measured the air flow (50–100 l/s) and the moving pressure with a Testo instrument for differential pressure

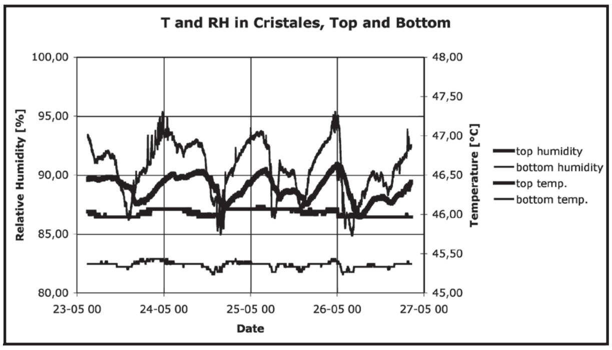

Figure 8: Temperature and Relative Humidity variations in Cristales.

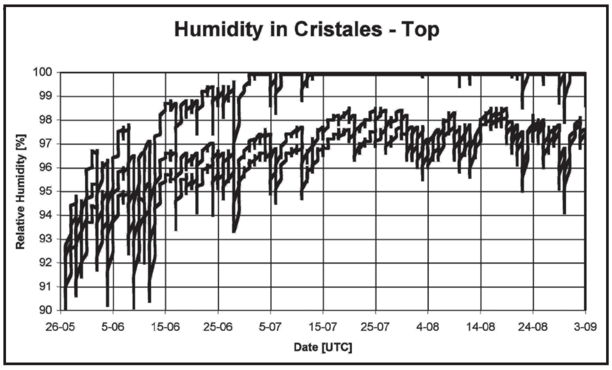

Figure 9: Relative Humidity in the Top Station, 3 sensors.

measurements. The Testo 6349 was outside the main door, connected with the cave by a tube (Fig. 10).

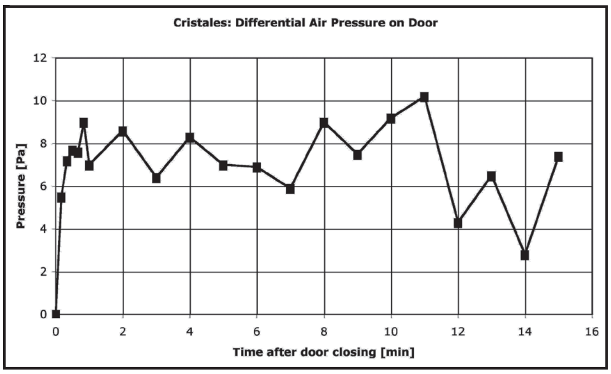

Figure 10: Differential Pressure on the main door after a sudden closure.

As expected, the pressure changes a lot due to infra-acoustic effects inside the mine, nevertheless it has an average value around 10 Pa, which corresponds to an air column 10-15 m high with a temperature difference around 10° C.

Also mines explosions have large effects on the cave. We have seen two types of behaviour: the overpressure flows out from cave after 6–8 s from the explosions, the overpressure coming to the cave from the mine galleries and bounces on the door. In the two cases, the overpressure or its bouncing is able to open the ajar door. The cave general structure as deduced by micro-meteorological data is shown in Figure 11.

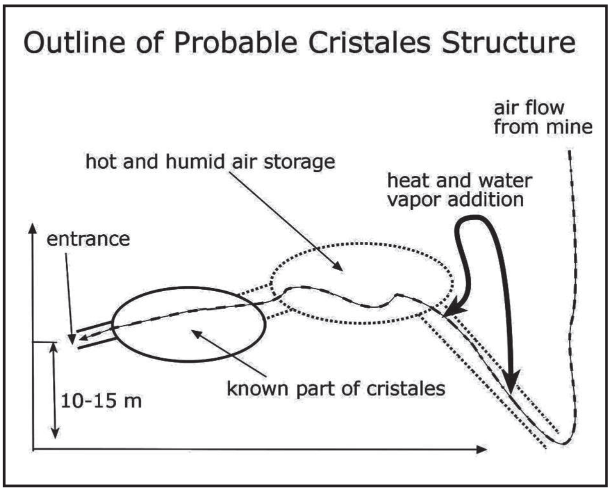

Figure 11: Probable shape of Cristales and connected structures.

7. Conclusions

These measurements have therefore shown us that the part of the cave which we know is only a fragment of a much vaster structure, which, depending on environmental conditions, introduces or extracts air from the environment we call "Cristales", including the surrounding cave like Ojo de la Reina. Moreover, the air currents show that the cave is connected to the mine through another passageway, probably fractures. Basically, these measurements show that the cave continues.

The heat loss, which was able to damage the crystal surfaces with vapor condensation,is probably finished, but a systematic monitoring of environmental parameters inside the cave is necessary to preserve it and, if necessary, to drive the internal atmosphere to a new state compatible with cave maintenance and study.

References

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