Microclimatic characterization of a karstic cave: human impact on microenvironmental parameters of a prehistoric rock art cave (Candamo Cave, northern Spain)

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Abstract The Candamo Cave contains an important group of paleolithic paintings which have been seriously deteriorated due to mass tourism. In this work, an analysis was carried out of different climatic parameters (CO_2, temperature, humidity, ^{222}Rn) during annual cycles with the cave closed to the public and during an experimental period of controlled visits. The effect of visits on the geochemical characteristics of karstic water was also analyzed together with the cave ventilation.
The natural variations in the cave air CO_2 were above 3000 ppm, the increase produced through visits was only 100–110 ppm and since the humidity is almost permanently at saturation point, the critical parameter which limits the visitor capacity becomes air temperature. The temperature changes during the annual cycle are of the order of 1 °C in the external part and less than 0.5 °C in the internal part of the cave and a maximum increase of 0.13 °C was observed during the period of the visits. The ^{222}Rn and CO_2 concentration minimums in the summer period (July–October) show that this is the most propitious time for visits, since the greatest ventilation is produced in the cave at this time and, therefore, the greatest capacity for recovery. The geochemistry of the water, on the other hand, indicated that this is the period of the year in which processes of wall corrosion can be most easily introduced, although this would be of limited magnitude. The visitor capacity calculated was 29 visitors/day.

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Introduction

The use of karstic terrain for recreation and tourist areas has been added to the numerous anthropic activities (deforestation, agriculture, water exploitation, mining, building) that deteriorate these delicate natural systems. Many caves house geological, biological and/or archaeological elements which can be considered cultural heritage and it is therefore necessary to make their availability to the public compatible with their suitable conservation. In caves which have artistic representations, accumulated experience has demonstrated that a regime of mass or uncontrolled visits is one of the most pernicious factors when it comes to the conservation of rock art. The documentation on the influence man on karstic caves is sparse, although it has increased in the past few years (Ek and Gewelt 1985; Williams 1987; Andrieux 1988; Ford 1990; Goldie 1993; Huppert and others 1993; and earlier references herein). With regard to this, Huppert and others (1993) considers that there are some 750 caves which can be visited throughout the world; there are more than a hundred caves which can be visited and which have palaeolithic wall art in the Iberian Peninsula alone. At the Spanish and French Round Table on the protection and conservation of paleolithic rock art which took place in Colombres (Asturias, Spain) in 1991, it was concluded that a scientific knowledge of the karstic and environmental parameters and the definition of a balanced threshold in each case (cave) is a key factor in the conservation of the rock art heritage and the subsequent establishment of an optimum rule on visits (Fortea 1993). In order to achieve this objective the separation between the natural environmental changes in the caves and those anthropically produced is essential and the execution of thorough multidisciplinary studies which include continuous follow-up of different environmental parameters is therefore necessary.

This paper shows the work carried out in this respect in the Cave of San Román de Candamo (Asturias, northern Spain), which was closed to the public in 1979 due to the serious deterioration caused by mass tourism. The environmental studies in Candamo Cave were carried out during the years 1989–1994 and were directed towards the study of two basic aspects:

1. The characterization of the natural microenvironmental conditions in the interior of the cave in terms of different parameters, such as temperature, relative humidity, CO_2 partial pressure, or ^{222}Rn concentration; a control was also carried out of the external environmental conditions (rainfall, temperature, relative humidity and atmospheric pressure).
2. An evaluation of the modifications induced in the microclimatic parameters of the cave and in the physical and chemical characteristics of the karstic water by a certain number of visitors, in terms of the above results and of those obtained in a pilot experiment with a regime of controlled visits.

Candamo Cave

Candamo Cave or the Cave of San Román de Candamo is located in the Cantabrian Cordillera in Asturias (northern Spain; Fig. 1). This cave has been known since the end of the nineteenth century, but the discovery of the prehistoric paintings and engravings dates from 1913. These paintings are the most western paleolithic wall representations known today; the majority of them can be catalogued in the Leroi-Gourhan style III which, culturally, covers a large part of the Solutrean and the whole of the Magdalenian (18000–13000 BC) (Hernández Pacheco 1919; Jordá 1968). The first effects of anthropic deterioration were before the discovery of the paintings as the speleothems were exploited for decorative effects in some constructions (interior details) in the neighboring town of San Román. With the discovery of the artistic representations, Candamo Cave was declared a National Monument in 1925 by the Spanish government and modified for visits, including the installation of artificial lighting. During the Spanish Civil War (1936–1939), Candamo Cave was used as a refuge. The conditioning work was considerable from the sixties onwards and the number of visitors increased. The cave was closed to the public in 1979 due to the increasing deterioration of the paintings and engravings, being practically cut off from the exterior by two metal doors. With the closing of the cave and the elimination of the old lighting system in 1988, the biological contamination in the internal area of the cave suffered an almost complete regression (Simó 1993). In the face of strong public demand for the cave to be reopened, the micrcoenvironmental studies presented in this work were started in 1989, the main objective of which was to establish conditions for opening the cave to the public whilst guaranteeing the correct conservation of the cave itself and of the art work it contains.

Candamo Cave belongs to a relict polygenic karst system which was initially developed during the Lower Pliocene (Hoyos and others 1993). It is situated in the upper part of the San Román heights (265 m) which descend to the valley of the Nalón River with a steep escarpment. It is developed in grey-coloured laminated limestone (Caliza de Montaña Formation, Upper Carboniferous). The cave is of reduced dimensions (Fig. 1), with a maximum length of 70 m in a N-S direction, a width of 17 m and height of 15 m in the Hall of Engravings. The estimated volume of the cavity that can be visited is 2105 m^3 and

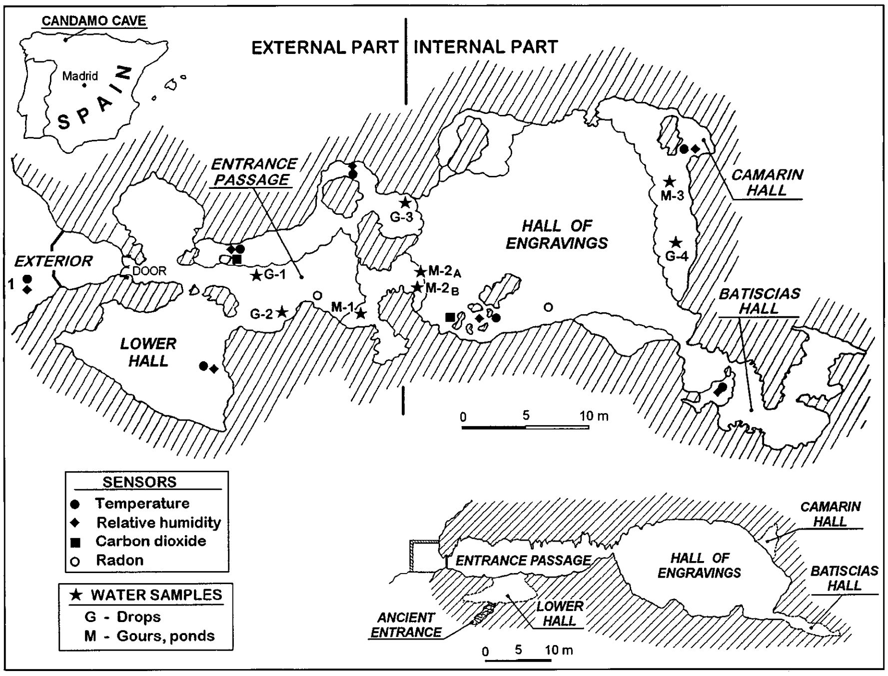

Fig. 1
Ground plan and profile of Candamo Cave with the location of all the sensors and sampling points

its surface area is 1100 m^2 . The known entrances to Candamo Cave, both that to the cave itself and that to the prehistoric site, have the remains of endokarstic wall and floor speleothems, for which reason these entrances correspond to karstic channels cut out by the evolution of the slope, at the same time indicating that the primitive cave was of greater dimensions, with passages and channels that have disappeared through erosion. At the present time, the local base level is more than 140 m below the cave, so that the circulation of water in the cave is reduced to that which is produced through the direct seepage and downward percolation of meteoric water via fissures and joints, which is translated into dripping and discontinuous laminar flows on the walls of the cave. However, this scant circulation of water is sufficient to maintain a high level of humidity in the interior of the cave.

Methodology

A geomorphological and microclimatic study was first carried out on the cave for the correct selection and design of the elements forming the system for measuring the microenvironmental parameters (SMMP) together with the measurement ranges of the different sensors and precise measurements were taken of all the parameters in the areas of the cave which were considered to be most characteristic. A system for acquiring data based on the use of a personal computer (PC) was designed and set up with this information (Fig. 1 shows the distribution of the sensors in the cave). All the parameters (temperature, humidity, CO_2) were measured automatically, one measurement being registered every hour during the annual cycles and one measurement every 5 min during the experimental visiting period.

Variations in the concentration of ^{222}Rn gas were used as an element for demonstrating the processes for renewing air in the cave. Landauer Track-Ech type commercial detectors were used for measurements over a longer period, with an integration period of one month. Active carbon traps (canisters) were employed for shorter periods, exposures of three days, and measurements were taken using gamma ray spectroscopy with an INA (TL) 3 × 3 inch detector. Likewise, measurements were made every 15 minutes with pylon AB5 scintillometer equipment with a diffusion detector.

Water samples (see Fig. 1) were taken in spring and winter on the 18–19th May and 12th December 1993, and correspond to dripping points and to standing water in pools. The infiltration flows and the total volume of water in the interior of the cave in both sets of samples were very scant. The temperature, electrical conductivity and pH were measured at the same time the sample was taken and the CO_2, HCO_3 and CO_3^{2-} contents were determined using standard titration methods. These samples were stored at a constant temperature (12–13 °C) and taken to the laboratory where the Ca and Mg content were analyzed two days later using a Perkin-Elmer 2380 atomic absorption spectrophotometer.

Measurements of CO_2 were made in the soil outside the cave in order to evaluate its contribution to the water percolating through the karst. Low volume probes were employed for this which were left to balance for 24 hours, the concentration of CO_2 was measured after this period using Dräger tubes. The measurements were carried out in the months of May and December, the months of maximum and minimum plant activity, on edaphic profiles (at a depth of 0.30–0.40 m) developed on overlying clayey materials and in cracks which were filled with clays rich in organic material from the exterior part of the cave.

Natural microenvironmental variations

The results obtained on the variations in the microenvironmental parameters of the cave and the ^{222}Rn concentrations during an annual cycle under natural conditions, during which the cave was closed to the public, are given below. The values that define the microenvironmental conditions of the cave, after somewhat more than 1 year of uninterrupted registration of the natural parameters, are shown in Fig. 2. The atmospheric pressure and rainfall values used are those provided by the National Meteorological Service station located at Asturias Airport, at a distance of less than 20 m from Candamo Cave.

Air temperature

The temperature outside the cave varies between a minimum temperature of 9.5 °C in winter and a maximum of 31.5 °C in summer (Fig. 2a). In the interior of the cave, the temperatures are more homogeneous over the year; the internal cave temperature varies 0.50 °C between 14.25 °C (spring) and 14.75 °C (autumn), whilst in the external part the annual variation is greater (1.15 °C), with a range of temperatures between 13.77 °C and 14.92 °C (Fig. 2b). Moreover, a thermal inversion phenomenon was observed by which, from the beginning of January to July, the inner part of the cave is slightly warmer and, from July to November/December this situation is reversed, the area at the entrance being warmer (Fig. 2c). The presence of the maximum annual variation in temperature in the lower passage of the external portion of the cave (Lower Hall; Fig. 2b) shows the proximity of some type of communication between this passage and the exterior, possibly through an area of an old archaeological site (Solutrean), whose communication with the exterior is obstructed by a pile of poorly sorted boulders and fine-grained sediments (Fig. 1). The daily temperature fluctuations in the interior of the cave are less than 0.03 °C and, therefore, these short-period variations are considered negligible with respect to the longer period or seasonal fluctuations.

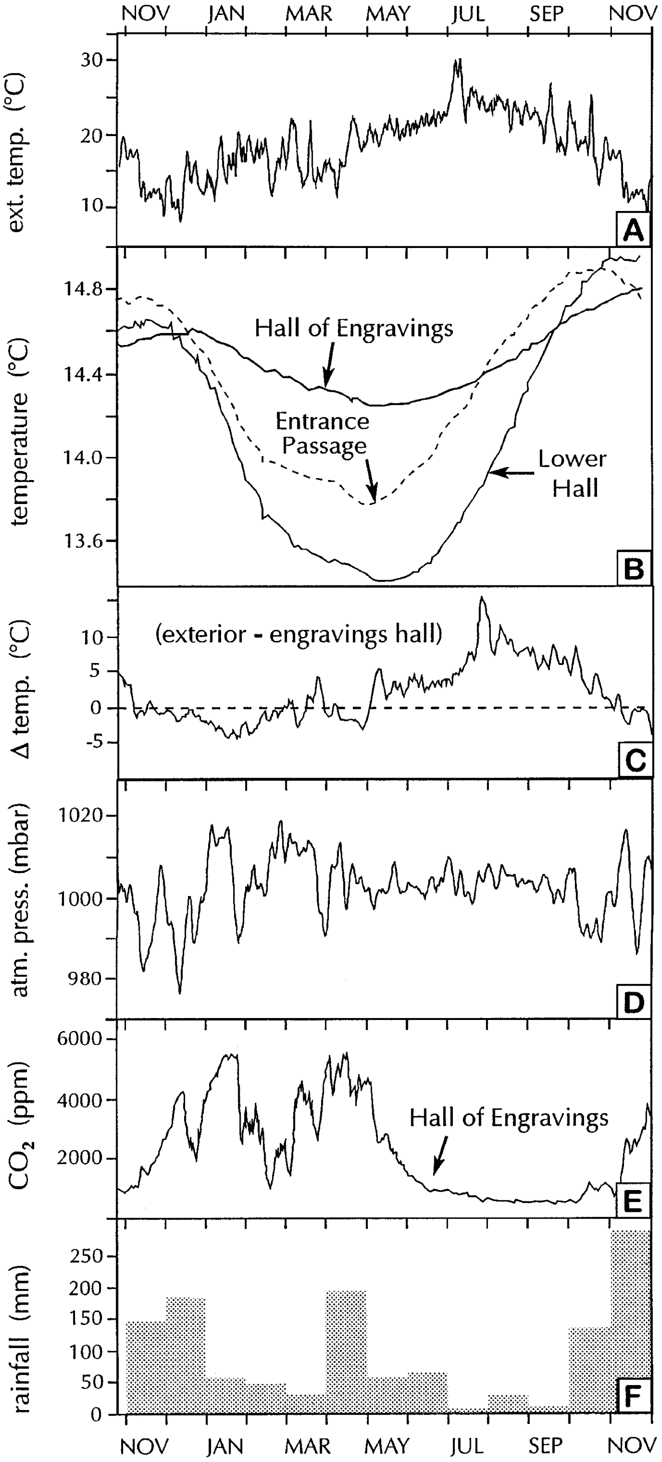

Fig. 2
Annual variations in the microenvironmental parameters in Candamo Cave. The time period shown corresponds to October, 1989–November, 1990: **a** temperature in the exterior of the cave; **b** temperature in three of the halls in the interior of the cave; **c** differences in temperature between the exterior and interior (Hall of Engravings) of the cave; **d** atmospheric pressure in the exterior of the cave; **e** concentration of CO_2 in the air in the Hall of Engravings; **f** precipitation in monthly intervals

Relative humidity of the air

The relative humidity of the air in the exterior of the cave varies from 50% as the minimum value in summer to 95% as the maximum value in autumn-winter. For the majority of the year it is above 90%. The relative humidity in the interior of the cave varies from 94% to 100%, both in the internal and external part, and for the majority of the year it is at saturation point.

Cave air CO_2

From 1979 to 1991, that is to say the period during which the cave was practically cut off from the exterior by two metal doors, the CO_2 content in the atmosphere of the cave came to exceed 6000 ppm, above the 5000 ppm considered to be the lower limit for human safety. After slots were put in the two doors of the cave, the CO_2 content dropped to average concentrations of 2000–3000 ppm. The measurements registered during a year with varying concentrations of CO_2 (Fig. 2e) showed the following:

1. The maximum values for the concentration of CO_2 reached over the year were around 5400 ppm, during winter and spring, while the minimum values were in the order of 450 ppm in summer. These long-term variations are controlled by the seasonal rainfall distribution in the area in which the cave is located.
2. During the autumn, winter and spring, the variations in the CO_2 content over monthly periods in the interior atmosphere of the cave are directly related to increases and decreases in the atmospheric pressure; this also coincides with higher temperatures in the interior of the cave with respect to the exterior.
3. On the other hand, during summer, when the temperatures in the interior of the cave are lower than in the exterior, the CO_2 content is less, rarely exceeding 500 ppm. This fact coincides with fewer fluctuations in the atmospheric pressure (Fig. 2d), with relatively low pressure values between 1000 and 1010 mbar and with the scant rainfall in the summer season (Fig. 2f).

Carbon dioxide in the water

The cave air CO_2 concentrations (ppm) were converted into P_{CO_2} (mbar) according to the expression of Ek and Gewelt (1986) with the object of comparing the P_{CO_2} in the air with the P_{CO_2} in the water in the 1993 samples. Table 1 shows that at the time that the karstic water sample was taken, the cave air P_{CO_2} showed very low values compared with those of the P_{CO_2} in the water; this large imbalance caused outgassing of the CO_2 dissolved in the water and its transfer to the cave atmosphere. Figure 3 gives data on the CO_2 concentration for Candamo Cave showing the directions of the CO_2 flow. As has been stated before, the water supply in the cave is due exclusively to the direct infiltration of the rainwater. The CO_2 produced in the soil by biological activity is dissolved by the rainwater which filters into it, this being the vehicle for transporting CO_2 to the interior of the karst (Ek and Gewelt 1985; Wood 1985). It is significant that for seasonal periods throughout the year (2.5–3 months) the greater CO_2 concentrations in the interior of the cave coincide

Table 1
P_{CO_2} values (mbar) in the karstic water and in the cave atmosphere during the sampling carried out in 1993

Water samples	May 1993		December 1993	
	P_{CO_2} water	P_{CO_2} air	P_{CO_2} water	P_{CO_2} air
M-2^{A}	4.69		16.97	
M-3	3.94		14.85	
G-1	6.02	max: 0.92	7.37	max: 0.79
G-2	5.75	min: 0.92	9.11	min: 0.48
G-3	4.14		12.55	
G-4	4.58		9.90	

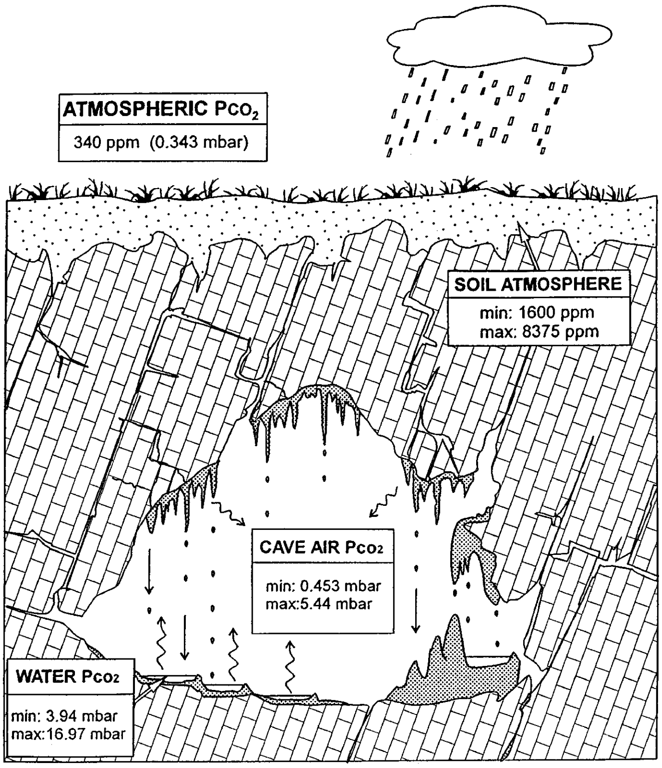

Fig. 3
CO_2 in Candamo Cave. The concentrations and directions of flow of CO_2 are shown in this idealized schematic of one of the rooms in Candamo Cave (see text for explanation)

with the periods of greatest pluviosity (Fig. 2e, f). There is a slight phase difference due to the infiltration time and recharging of the karst, somewhat longer after a period of summer dryness and shorter in the other seasons, when the karst still has sufficient reserves of water.

^{222}Rn concentration

The emission of ^{222}Rn can be considered constant per surface and time unit and it is not affected by the activity of the karst itself as is CO_2. The natural ventilation system for the cave is modelled on the data on ^{222}Rn concentration (Wilkening and Watkins 1976), thus obtaining the times for renewing the mass of air shown in Fig. 4a.

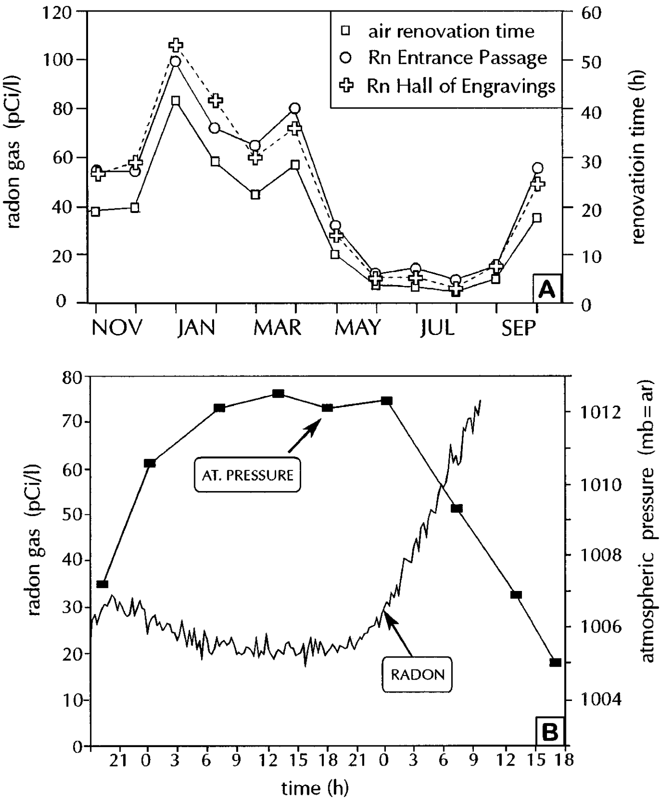

Fig. 4
^{222}Rn. **a** Annual variations in the concentration of radon both in the external part of the cave (Entrance passage) and in the internal part (Hall of Engravings); the time necessary for renewing the air calculated for the cavity is also given (see text). The interval of time shown corresponds to November, 1993–October, 1994. **b** Variations in the concentration of radon on a timescale of 48 h (10th–12th December 1993) and their relationship with the external atmospheric pressure

This data agrees with the concentrations of CO_2 (Fig. 2e) indicating that the June–September period is the one with the best ventilation and therefore the most suitable for possible visits to the cave, since it has the best possibility of response in this period.

The ^{222}Rn content in the air in the interior of the cave with the door closed without any slots in it, was some 430 pCi/l in March 1991; with the slots in the door, which was the condition under which this work was carried out, the ^{222}Rn content in the Hall of Engravings dropped to 40 pCi/l. For an estimated volume of 2105 m^3 and a total surface area for emission of 1100 m^2, a ventilation flow of 150 m^3/h and an air renewal time of 14 h was calculated. During the majority of the year the ^{222}Rn content is less than 60 pCi/l, which corresponds to an air renewal of less than 15 h. It is only during winter that these values are higher, when they can reach 40–50 h. On the monthly scale of the Rn measurements made, it would seem clear that the thermal gradient ($\Delta T = T_{ext} - T_{int}$) is the main control parameter for ventilation (Fig. 4a). Focussing on an hourly timescale, it was observed that there are various processes involved in ventilation control, since a clear inverse relationship was detected between the variations in atmospheric pressure and the radon concentrations during the periods when ΔT is near zero, such as December or March (Fig. 4b). However, it does not seem to be possible to be able to consider this mechanism of ventilation control on the basis of the difference in temperature as a general norm, since comparable cases to Candamo can be found in the literature such as the Baradla Cave in Hungary (Hakl and others 1993). Inverse relationships have also been found in other caves such as in other Hungarian caves (Kobal and others 1988; Geczy and others 1989) and in Carlsbad Cavern (Wilkening and Watkins 1976).

Mineral saturation state in the karstic water

The saturation state for each carbonatic mineral was calculated from the results of measuring the physical parameters and chemical composition of the water, determined both in situ and in the laboratory (Table 2). The speciation calculation necessary for determining the mineral saturation indices was made using the PHRQPITZ computer program (Plummer and others 1988); this program includes a large thermodynamic database which enables precise geochemical calculations to be made on natural water. With the exception of the G-3 May sample, the water analyzed was undersaturated with respect to calcite and aragonite, which are the most common carbonatic mineral phases in the host rock and in the karstic precipitates (speleothems) in the cave. This feature is consistent with the absence of contemporaneous active formation of any type of speleothems except for the G-3 point where recent minute cryptocrystalline precipitates are observed. The state of undersaturation was related to the low mineralization rates in the water analyzed, together with the high values of P_{co_2} (water) which ranged between 6.97 (M-2, December 1993) and 3.94 mbar (M-3, May 1993).

Influence of the visitors on the microenvironmental parameters

It is sufficiently well known that every visitor to a cave produces a series of variations in the interior microclimate of the cave due to his own metabolism. These variations are produced by the emission of heat through radiation via the skin, and by the production of CO_2 and H_2O vapor, together with the consumption of O_2 through respiration. In order to achieve a direct evaluation of the influence of visitors on the natural variations in the microenvironmental parameters, it was proposed to the Cultural Council of the Principality of Asturias that and experiment should be made for one month (20th August–20th September 1992), during the period in the year when there is the lowest concentration of CO_2 in the cave, with a reduced number of visitors (16 people, in 1 or 2 groups). The visitors would remain in the cave interior for a controlled time period of around 20 min, at a fixed hour (between 11.30–12.30), thus avoiding the effect of the short-period daily cycle. During this time the increase in CO_2 produced by the visitors would not exceed the maximum natural values. The visits were made with only the light provided by flashlights. The taking of measurements of the values of the different microenvironmental parameters was adjusted to one measurement every 5 minutes.

The volume of the Candamo Cave is estimated at 2105 m^3; according to the average values given by Andrieux (1988) and considering a 20-min visit, 16 people would produce a minimum heat emission of 208.5 kcal and 102.4 l of CO_2 and 102.4 g of water vapor would be added to the interior atmosphere of the cave. It was therefore concluded that the volume of the cave was sufficiently great to permit an experiment with this number of people without putting the microclimate of the cave in danger.

Table 2

Physical and chemical parameters of the karstic water and values of carbonatic mineral saturation indices (calcite and aragonite) [*E.C.* electrical conductivity (in μS/cm); *T* temperature (in °C); concentration (in mg/l)]

Sample	Date	E.C.	T (°C)	pH	CO_2	HCO_3^-	Ca	Mg	Calcite	Aragonite
M-1	May 93	318	12.4	7.25	15.8	187.2	57.2	4.5	−0.30	−0.50
M-2^A	May 93	269	13.0	6.85	10.1	140.5	47.3	4.4	−0.42	−0.62
M-2^B	May 93	261	13.0	6.80	10.3	142.1	46.9	4.4	−0.43	−0.62
M-3	May 93	263	13.3	6.60	8.4	119.4	45.4	3.9	−0.49	−0.69
G-1	May 93	226	12.5	6.50	12.0	136.9	42.5	4.4	−0.56	−0.76
G-3	May 93	382	12.3	6.95	9.1	271.0	77.5	4.5	+0.39	+0.19
G-4	May 93	265	12.5	6.70	10.0	134.0	43.0	4.5	−0.49	−0.69
M-2^A	Dec 93	–	13.9	6.85	–	140.2	41.0	4.9	−1.01	−1.21
M-3	Dec 93	–	14.1	6.90	–	137.2	44.3	4.2	−0.94	−1.13
G-1	Dec 93	–	13.3	7.20	–	137.2	43.0	2.5	−0.66	−0.86
G-2	Dec 93	–	13.3	7.25	–	192.1	56.1	4.8	−0.37	−0.56
G-3	Dec 93	–	13.4	7.20	–	237.8	80.0	4.5	−0.19	−0.39
G-4	Dec 93	–	13.4	7.20	–	186.0	60.0	4.4	−0.40	−0.60

Influence on temperature

During the period of the experiment, the entry the visitors into the cave interior produced an increase in temperature only detectabled in the passages and halls included in the route for the visit. The heat radiation generated did not reach all the points in the cave in the time period established for the visit. This was due to the low thermal conductivity of the calcareous rock, the water, and air (Mangin and Andrieux 1988). This means that long periods of exposure are necessary in order to detect changes in temperature over long distances.

The thermal variation produced by the visitors can be summarized translated as follows: (1) an increase of hundredths of a degree was produced with a maximum value of 0.15 °C in the Entrance Passage (Fig. 5a), of 0.10 °C in the Hall of Engravings itself (Fig. 5b) and of 0.05 °C in the Camarin Hall (Fig. 5c); (2) when the visit was divided into two groups of 8 people, the effect on the temperature was even less; and (3) it must be emphasized that the maximum value of 0.15 °C for the anthropic influence on the temperature is far below the natural annual variation values, both in the internal area of the cave (0.5 °C) and in the external area (more than 1 °C). It can be clearly seen in Fig. 6 that the temperatures maintain their natural tendency (seasonal) (see also Fig. 2b), both in the external (Entrance Passage) and the internal parts (Hall of Engravings and Camarin Hall) of the cave.

The following was observed in the follow-up on the daily evolution of the temperature: (1) for the temperature to drop to levels near the natural ones before the visit, a period of time of around one to two hours was necessary (Fig. 7); and (2) at the time of entry of the daily visit, the temperature value was some hundredths of a degree greater than at the entry time on the previous day, showing an overall tendency towards a thermal rise for the time studied. This represents an added and accumulative increase of 0.04 °C/month to the natural thermal gradient (0.07 °C/month) corresponding to the long period cycle in the Hall of Engravings and calculated for the period of the year that presents continuous rise of temperatures (Fig. 2b).

Influence on relative humidity

In spite of the modest waterflow observed during the sampling, this flow was sufficient for the relative humidity in the cave to be almost always at the saturation point. Since saturation was already achieved, the visits did not produce any change in this parameter, either by the addition of water vapor or the temperature increase which occurred.

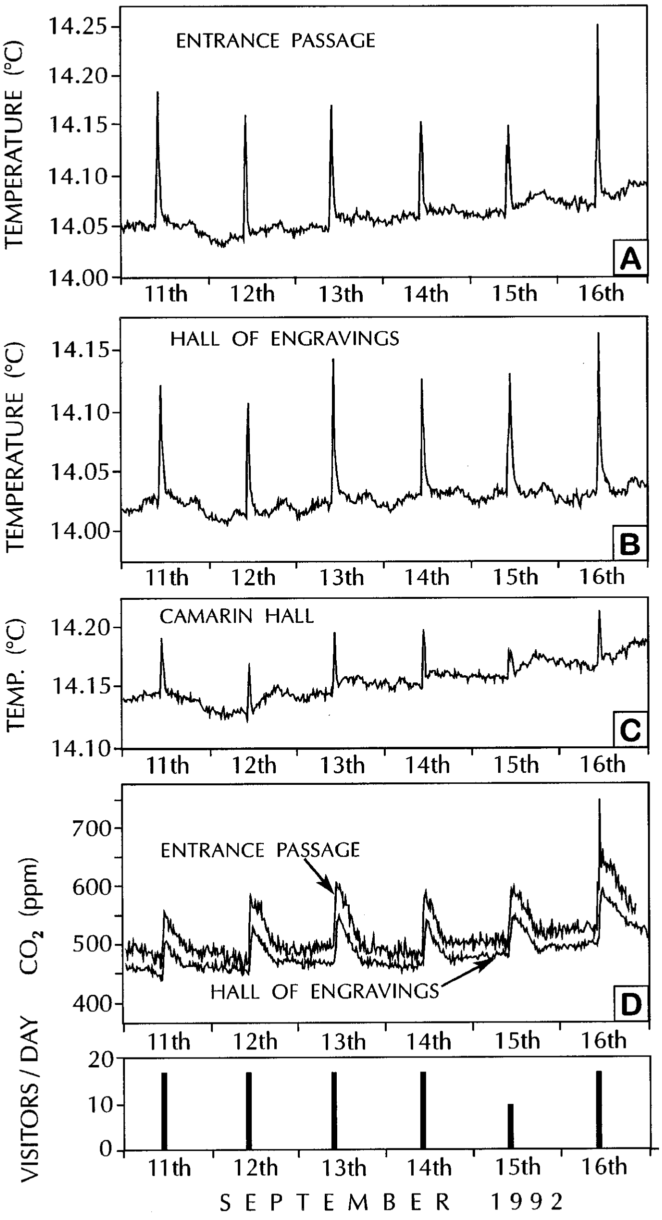

Fig. 5

Variations in the environmental parameters of temperature and CO_2 concentration in the air during the experimental visit period. In the lower part of the figure, the number of visitors into the cave is shown (visit duration approximately 20 min). The time interval given is 11th–16th September 1992: **a** temperature in the Entrance Passage; **b** temperature in the Hall of Engravings; **c** temperature in the Camarin Hall; **d** concentration of CO_2 in the air at the Entrance Passage and in the Hall of Engravings (See text for explanation)

Influence on carbon dioxide

Taking into account the fact that the visitors were present for around 20 min, an emission of 102.4 l of CO_2 was produced which represents only 0.00486% of the approximate volume of the cave, which is a minimum percentage. The variations in the concentration of CO_2 in the air produced through the effect of 16 visitors are shown in Figs. 5d and 6d. These represent an increase on the order of 100–110 ppm, a value very much below the natural variations in the cave with the present ventilation conditions (Fig. 6d). The atmosphere in the cave recovered its natural values 7 h after the visitors had left (Fig. 7).

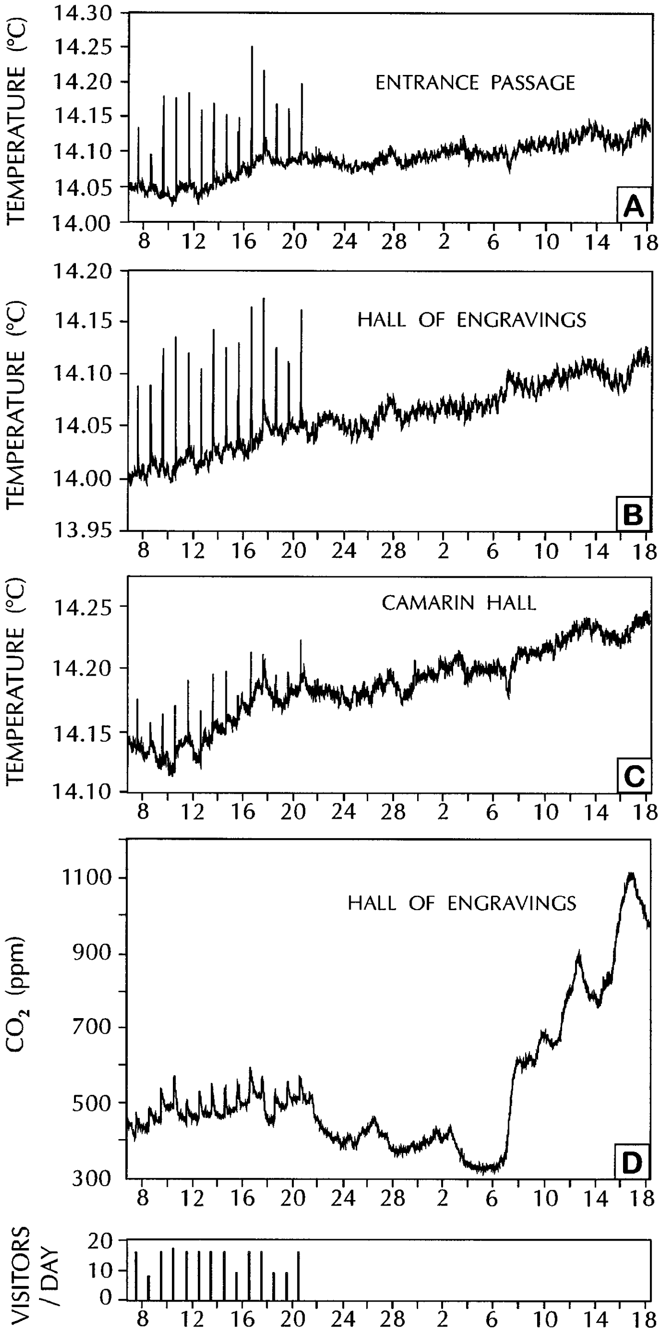

Fig. 6

Variations in the environmental parameters for temperature and CO_2 concentration in the air during and after the experimental visit period. The interval of time given is from 6th August to 18th September 1992: **a** temperature in the Entrance Passage; **b** temperature in the Hall of Engravings; **c** temperature in the Camarin Hall; **d** concentration of CO_2 in the air in the Hall of Engravings. Note how the trend towards the natural evolution of the parameters given is maintained (see annual variations in temperature and CO_2 in Fig. 3)

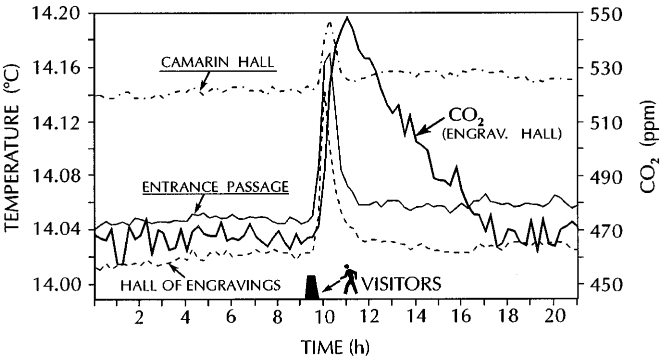

Fig. 7

Variations in the environmental parameters of temperature and the concentration of CO_2 in the air during one day (13th June 1992) of the experimental visit period

Influence on the geochemical equilibrium of water

As was seen in previous sections, the waters which infiltrated and those which accumulated in the interior of the cave showed a general undersaturated state with respect to the most common carbonatic mineral phases. One of the objects of the experiment with visitors was to check whether the variation caused in the CO_2 content and in the air temperature generated significant changes in this undersaturated state. During the period of the experimental visits, an increase in CO_2 was produced in the cave atmosphere of 100 ppm and a maximum air temperature increase of 0.15 °C. In the case of the CO_2 concentration, the slight increase observed did not have any influence on the Pco_2 in the water, since the values for this parameter were considerably higher than those for the Pco_2 in the air. In order to check the effect of the variation in temperature on the geochemical characteristics of the water, it was assumed that both the water that had percolated in and the standing water experienced a maximum homogeneous increase of 0.15 °C. Calculations were made on the state of the mineral saturation in each of the water samples, with the value of the original temperature modified. This small variation in the temperature did not procedure any significant change in the saturation indices.

As well as this slight influence on the state of saturation of the water, the variations in temperature caused by the visits can directly affect the intensity of wall corrosion processes. The relative humidity of the air in the cave interior is maintained practically constant throughout the year, with values near saturation (100%). After the visits, the air temperature dropped fairly rapidly to the natural values (1–2 h), with the consequent decrease in the saturation water vapor pressure in the air. This caused a condensation phenomenon of chemically pure water on the walls of the cave, which are formed of limestone with 81–92% calcite and of wall speleothems with calcite percentages of around 98%. As has been mentioned in previous sections, the recovery time necessary for the CO_2 contents to return to their natural values after a visit is approximately 7 h. In this way, it can be assumed that the water accumulated on the surface of the walls will capture CO_2 from the air in the cave until it balances with the partial pressure of this gas in the air at the time of condensation. This capturing of CO_2 by the water reduces its pH and with it increases its capacity to dissolve calcite from the walls.

In order to check the theoretical differential effect of a natural condensation process and that caused by a visit period, both situations were simulated (Fig. 8). In both cases, the PHRQPITZ program was used to make the necessary geochemical calculations. Data on temperature and CO_2 on 17th September 1992 were taken as an example in the simulation of condensation and wall corrosion phenomenon after an experimental visit. In the first case it was assumed that at the time of theoretical natural condensation, the water was balanced with a Pco_2 of 0.475 mbar, at a temperature of 14.05 °C, causing the dissolution of 72.19 mg of calcite per litre of condensed water on the wall to be dissolved. In the second case, the visitors caused an increase of 0.09 °C in the temperature and an increase of 110 ppm of CO_2 in the air in the area of the large panel of paintings. When the visitors left, the temperature dropped and after condensation, the water was balanced with a Pco_2 of 0.584 mbar, slightly higher than in the previous case and a temperature of 14.06 °C. The water-calcite equilibrium was achieved after dissolving 77.48 mg of calcite per litre of condensed water. This caused an increase of 7.3% in the rate of wall corrosion, a phenomenon directly related to the conservation of the host rock for the paintings. However, it must be taken into account that the amount of water condensed through the effects of the visitors entering and leaving was 0.06 ml/m^3 of air; this means that for an estimated volume of 1250 m^3 in the Hall of Engravings, the total condensed water would only be 75 ml. Therefore, from a quantitative point of view, the process of corrosion through the condensation induced by the visitors would be of limited magnitude.

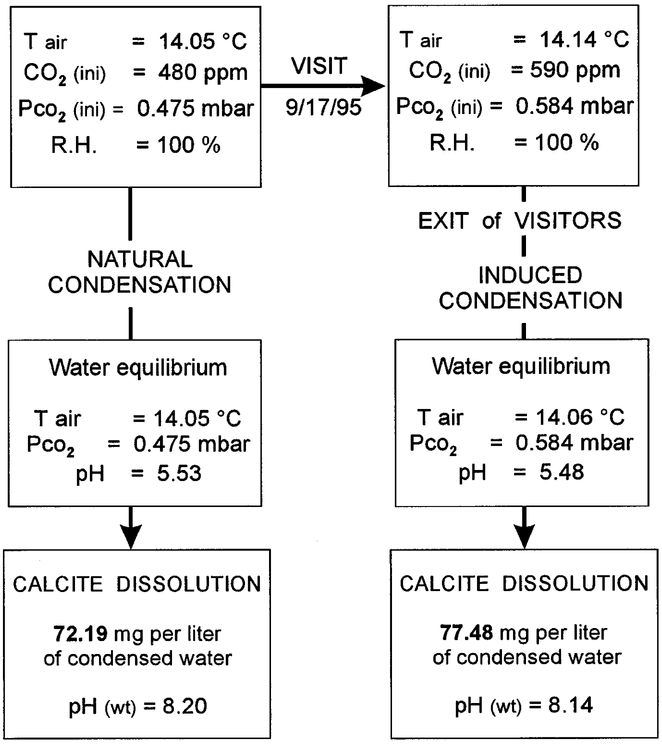

Fig. 8
Theoretical simulation of the effects of a natural condensation process and one caused by a period of visits

The data obtained in the simulation must be considered to be an estimate, since the geochemical model employed deals with chemical balance only from the thermodynamic point of view, without including chemical kinetics reactions criteria. Furthermore, it is important to emphasize that the simulated case was included in the period of the year in which the CO_2 in the air of the cave was lower; in the winter periods when levels above 3000 ppm are reached, the influence of the visitors on the corrosion processes would be proportionally less.

Calculation of the visitor capacity in the cave

Considering the karstic systems from the point of view of the flow and/or transfer of energy and mass and from the points of view of their environmental protection and tourist management, the karstic systems can be grouped schematically into three categories (Heaton 1986; Cigna 1993): (1) high-energy caves, when the natural flows of energy greatly exceed those created by the visitors; (2) intermediate-energy caves, when the magnitude of the two flows are similar; and (3) low-energy caves, when the flows of energy created by the visitors exceed the natural flows. Obviously, the last two categories are the most susceptible to induced alterability through the visits and this is where the visit/deterioration relationship must be optimized with regard to cultural and/or tourist enjoyment. Given the characteristics of the karst where the Candamo Cave is located and its morphometry, this could fall into the first category.

The concept of the visit capacity is essential for the management of any natural resource of touristic interest. Several authors (Middaugh 1977; Hammitt and Cole 1987) have indicated the difficulty in quantifying the visit capacity given the high number of variables at stake and the subjectivity of some of these, such as the value of the property to be protected, even leaving aside nonenvironmental factors such as economic and political factors. The specific application of this concept to caves has been recently discussed by various authors (Huppert and others 1993). Nevertheless, it has been demonstrated that every calculation on visit capacity for a cave must be backed up by an extensive multidisciplinary knowledge of the problem, although in our case, the calculation was carried out only in terms of environmental parameters.

As has been previously mentioned, the visitors had a different influence on the various environmental parameters of the cave. The problem lies in quantifying a limit of acceptability for a change in a parameter in the karstic environment and translating this to an optimum number of visits, i.e., maximum visits with minimum deterioration. With regard to this, the visitor capacity can be defined as the maximum number of visitors per unit of time, which does not imply any modification in the critical factor or parameter above its natural fluctuation limits (Cigna 1983). The parameter most susceptible to modification will be the critical factor for calculating the visitor capacity.

As it was demonstrated in the experiment with 16 visitors/day that the only microenvironmental parameter which suffered appreciable modifications was temperature, an attempt was made to reach an approximation of the theoretical number of visitors/day which should be admitted to the cave, taking the results obtained with respect to this parameter in the experimental period as a reference. The calculation of the maximum number of visitors was made using the most favourable period of the year, when the interior temperatures are the lowest, so that the visitors do not produce any increase in temperature greater than the smallest value for natural variation (0.5 °C). That is to say, the sum of the increases in temperature produced by visitors must be less than 0.5 °C. The summer months (June, July, and August) were chosen because this is when there is greater demand from visitors, and the conditions and results from the previous experiment with daily visits could be assumed. Figure 9 shows a graph of temperature change versus the number of visitors and gives the results of the simulation for 3 months of continuous visits with a variable number of visitors/day (safety limits have been used in the design of this graph). The ΔT_1 line shows the added increase in temperature above the natural temperature in the cave interior in terms of the number of visitors. The value 0.12 °C on the y-axis refers to an increase of 0.04 °C/month produced by visits of 16 people during the 3 months assuming an accumulative character. The ΔT_2 line shows the maximum increase in temperature above the natural temperature in the cave interior produced by a visit of 16 people. The value 0.15 °C on the y-axis is the maximum increase in temperature for a visit (measured in the Entrance Passage, Fig. 5a). The $\Delta T_1 + \Delta T_2$ line represents the sum of the increases in temperature which would be produced with different numbers of visitors. A safety limit of 0.5 °C was established which corresponds to the annual value of lowest variation in temperature in the cave interior. This is shown by the dashed horizontal line. The point of intersection of the straight $\Delta T_1 + \Delta T_2$ line with the 0.5 °C horizontal line defines a maximum number of 29 visitors/day. In view of these results, a more efficient recovery of the microenvironmental thermal parameters of the cave can be achieved by establishing rest periods between visits. This would result in a lesser slope for the ΔT_1 line and, therefore, the admission of more visitors per day.

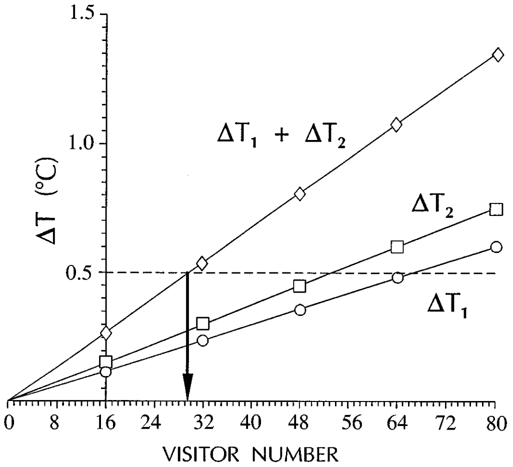

Fig. 9
Calculation of the visitor capacity for Candamo Cave using the increase in temperature in the air of the cave as a critical factor or parameter. In this case the maximum value considered is 0.5 °C, which is the maximum limit of natural fluctuation (see text for explanation)

Conclusions

From the results obtained in one year of measuring the microenvironmental parameters, the following conclusions may be drawn:

1. The temperature in the interior of the cave is very homogeneous presenting a maximum annual variation of 0.5 °C, whilst the temperature variation in the external part is greater (1.15 °C).
2. The relative humidity in the cave interior is kept in a state of saturation for the greater part of the year, with a maximum variation of between 94 and 100%.
3. The karstic waters analyzed are undersaturated respect to calcite and aragonite. Therefore, the active formation of speleothems of these mineral phases can not be easily observed in the cave.
4. The CO_2 concentrations measured in the soils and fissures in the rock of the upper external part of the cave, varies between 1678 and 8375 ppm. Biological activity on the external floor of the cave is sufficiently important as a producer of CO_2 to justify maximum values for CO_2 concentration in the cave interior through the percolation of meteoric waters. The maximum values measured in the cave air (5400 ppm) were reached during spring and winter, periods which have the highest rainfall; the minimum values were (450 ppm) recorded during the summer, coinciding with minimum precipitation. The approximate monthly period variations in the CO_2 concentration, in the interior of the cave, are influenced by the atmospheric pressure and by the temperature differences between the exterior and the interior of the cave. Data on ^{222}Rn indicates that during the summer period a rapid

and effective renewal of the air in the cave is produced. It has been proved that a great disequilibrium between the Pco_2 in the karstic water and the Pco_2 in the air exists, the former being much higher than the latter.

A restriction in the number of visitors was established (16 visitors/day) during the experimentation period to avoid any significant alteration in the cave conditions. After evaluating the influence of visitors on the microclimatic parameters of the cave and the chemical characteristics of the karstic water, the following observations may be made:

1. Modifications that a regime of visits such as this one produces on the carbon dioxide concentrations in the cave are always included in the natural variation margins of this parameter. These variations represent an increase on the order of 100–110 ppm. The atmosphere of the cave recovers its natural values 7 h after the visitors have left.
2. The visits did not produce any significant change in the values for the relative humidity of the air, nor on the mineral saturation state of the karstic water.
3. The entry of visitors produced a maximum increase in temperature of 0.15 °C; increases of up to 0.1 °C were detected in the Hall of Engravings, both values are less than the natural thermal variation of the cave. One to two hours were necessary for the cave to recover its natural thermal values. An increase of 0.04 °C/month in the cave air temperature was observed during the experiment interval.
4. The combined effect of the increase in CO_2 and the variations in the temperature may have a direct effect on the intensity of the wall corrosion processes. It is important to emphasize that the condensation phenomenon produced after the visitors had left the cave was quantitively minimal, but the possible cumulative effects of a larger number of visits or a longer visit duration on the temperature values could considerably increase the effects of corrosion through condensation.

From the results obtained, it is deduced that the summer period (May–September), characterized by greater atmospheric stability, is best suited for visits, since the rate at which the air in the cave recovers is rapid. This minimizes possible anthropic influence. The calculation of the maximum number of visitors that may enter the Candamo Cave is based on the parameter that is most susceptible to suffering modifications as a consequence of their entry, in this case, temperature. The final result indicates that the maximum number advisable for the microclimatic conditions not to suffer significant changes is 29 people/day. After this study was completed, the cave was reopened in July 1994, with a maximum number of 25 visitors a day.

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