Human impact in a tourist karstic cave (Aracena, Spain)

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Abstract Human intrusion on the Cave of Marvels (southwestern Spain) has produced a series of effects on the water (fall in the level of the pools due to pumping from nearby wells), the air (increased temperature and CO_2 concentration as well as decreased relative humidity) and the rock. In addition, plant colonization, favored by the lighting system, has irreversibly altered numerous speleothems. The processes of degradation are especially intense in the sectors with less air volume and limited ventilation. The analysis of the cave deposits by scanning electron microscopy and thin section analysis revealed that floral pollution constitutes one of the most aggressive agents against the calcite and aragonite precipitates, being responsible for biochemical and biophysical degradation of the first order.

Key words Tourist cave · Human impact · Speleothem degradation · Biological weathering

Introduction

In recent years, interest in the underground karstic environment has grown, not only from a speleological or scientific viewpoint, but also from an economic perspective. The profits derived directly and indirectly from the touristic exploitation of caves can acquire substantial importance at local level. A good example of this is the Grotta Grande del Vento, one of the most important touristic caves in Italy, which received almost 9 million visitors between 1974 and 1990 (Bertolani and others 1991). In Aracena (southwestern Spain), a town of only 6000 inhabitants, the Cave of Marvels has over 160 000 visitors annually, undoubtedly constituting a notable source of income for this small population.

However, in some instances, the lack of regulation of the visits or of an adequate maintenance infrastructure can result in a serious threat to the underground environment (Cigna 1993). One of the major problems is the growth and proliferation of microflora (algae, lichens and mosses) as a consequence of inappropriate illumination, gravely damaging the speleothems and secondary carbonate deposits (Caumartin 1986).

The study of cave conservation in relation to tourism is not simple, since many factors and variables must be simultaneously taken into account. From the standpoint of the cave itself, the oldest and most common methodological approach is based on the concept of a speleological network, which treats caves as the only mechanism of transference between the endokarst and the exterior (Trombe 1952; Eraso 1969). Other authors consider a cave to be a closed system (Heaton 1986), using models based on physics to predict environmental variations induced by human presence (Villar and others 1984, 1986; Cigna 1987). Mangin and D'Hulst (1995) view the problem from a larger perspective, conceiving caves within their hydrogeological context and considering them as a system in dynamic equilibrium in which the energy inputs are equal to the outputs; excessive human pressure upsets the balance, producing a progressive environmental degradation. Such imbalance can be identified by correlative and spectral analyses of the different variables involved. This is a method frequently used in karstic hydrology and hydrogeology (Mangin 1984; Padilla and Pulido-Bosch 1995).

The fundamental mechanisms of anthropic alteration of speleothems are related to the processes of evaporation, condensation and augmentation of CO_2 concentration, though biological corrosion can result in more serious degradation by the involuntary introduction of microorganisms.

The cave and the monitoring network

The Cave of Marvels is situated in the southwest corner of Spain (Fig. 1), some 70 km from Portugal. This cave has a known length of 2130 m and, although its develop-

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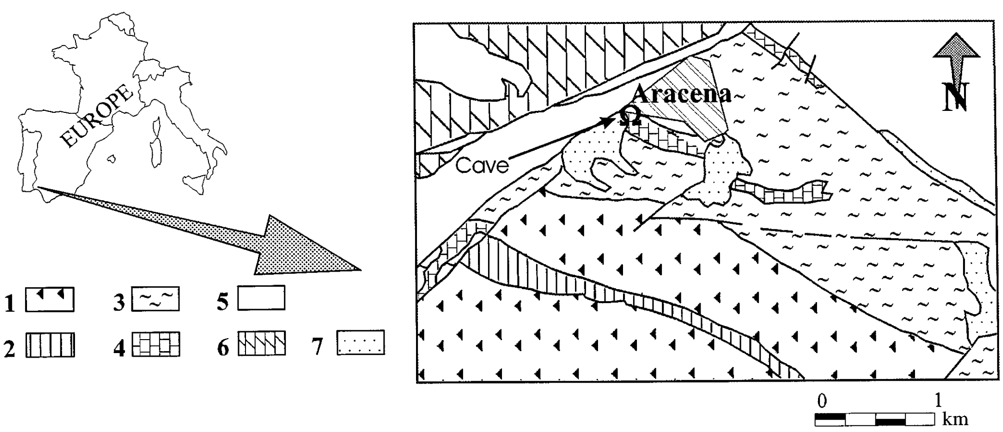


Fig. 1
Geographical and geological location of the cave. *1* ophiolites and amphibolites, *2* quartz-schistes, *3* gneiss, *4* marbles, *5* vulcanosedimentary rocks, *6* dolomites, *7* sands and gravels

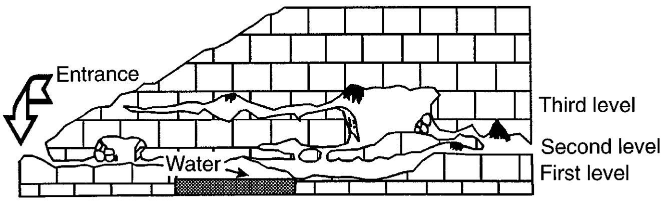


Fig. 2
Approximate schematic section of the Cave of Marvels

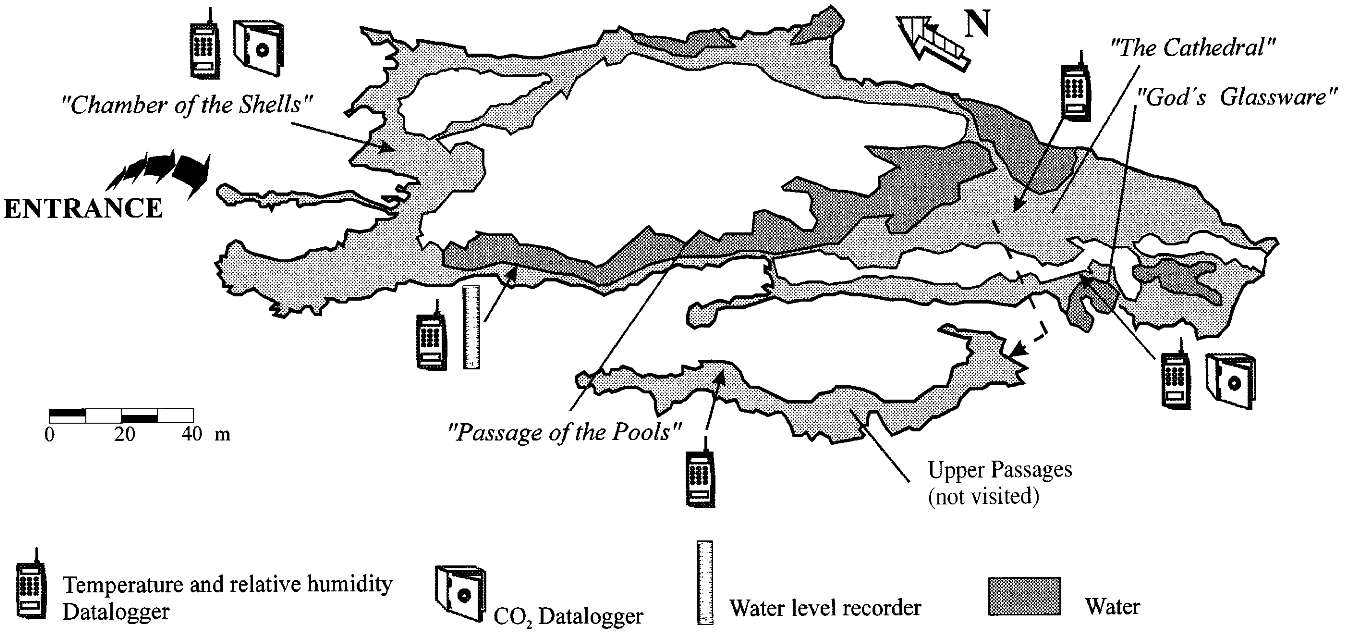
ment is predominantly horizontal, it has at least three distinguishable levels of karstification vertically superimposed. The first two levels correspond primarily to the present-day tourist route of 1000 m in length. The third remaining level is the highest and inaccessible to the public. The lowest of all are the flooded zones.

Discovered during the middle part of the nineteenth century, and prepared for tourist visits in 1911, the cave is particularly well known for its extraordinary abundance and variety of speleothems, both vadose and subaqueous deposits. In the zones farthest from the entry are abundant acicular aragonite and calcite excentrics.

The underground complex has developed in a small outcrop of marbles from the Lower Cambrian (Fig. 1). The water table in this small carbonate aquifer coincides with the flood level of the lowest passages of the cave (Fig. 2). There are also hanging levels of water which correspond to macrogour fill, today totally cut off from the water table.

At the beginning of 1993, the local authorities in charge of the exploitation and preservation of the cave began a conservation study. They established the first network for monitoring environmental parameters (Martín Rosales and others 1994), comprising five data loggers with a continuous record of temperature and air relative humidity, situated as shown in Fig. 3. The frequency of the measurements was set at every 15 min. In addition, a

Fig. 3
Cavity scheme and monitoring network



measuring station was installed for the continuous measurement of atmospheric carbon dioxide (CO_2), by means of a sensor based on selective absorption of an infrared light beam. The variations in the level of the pools were registered by direct daily reading of a limnimetric scale, which afterwards was replaced by an electronic probe with a measuring frequency also set at every 15 min. Periodically, profiles were taken of relative humidity, temperature and velocity of the air masses over the entire underground complex by means of portable measuring equipment.

In order to know the natural conditions of the cave without human influence, a monitoring system was set up in the sectors farthest from the tourist route (upper passages). This allowed us to compare the results with those obtained in passages open to tourists.

Principal human impacts

Impact on air

One of the most immediate effects of visitors to the cave is the increase in air temperature, as shown in Figs. 4–7. Figure 4 shows the temperature recorded during August 1994 in the chamber known as God's Glassware, where the temperature was measured every 15 min. This chamber is the most representative and spectacular within the cave, due to the abundance of concretions covering the walls, the ceiling and the floor; they consist of aragonite crystals, excentrics, gours, flowstones and globular speleothemes. The limited volume of this chamber, together with the scant ventilation available, means that the concretions are particularly vulnerable to the effects of visitors, since the passage of groups of tourists can raise the air temperature by up to 1 °C. There is a strong correlation between maximum temperatures and the number of daily visitors, despite the fact that other factors also influence thermal variability, such as the time that visiting groups remain in the proximity of the sensor and the time during which the chamber is illuminated (which is not necessarily the same as the former).

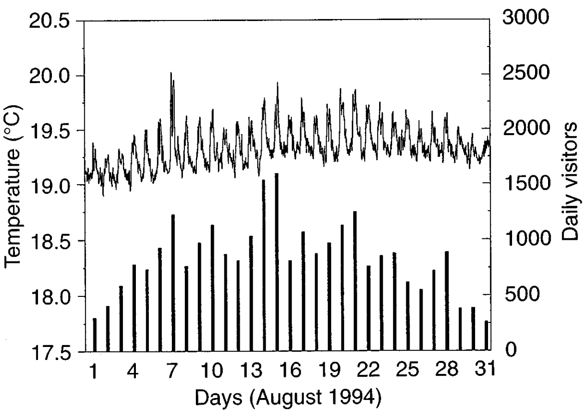


Fig. 4
Records of air temperature in the God's Glassware chamber and daily numbers of visitors during August 1994

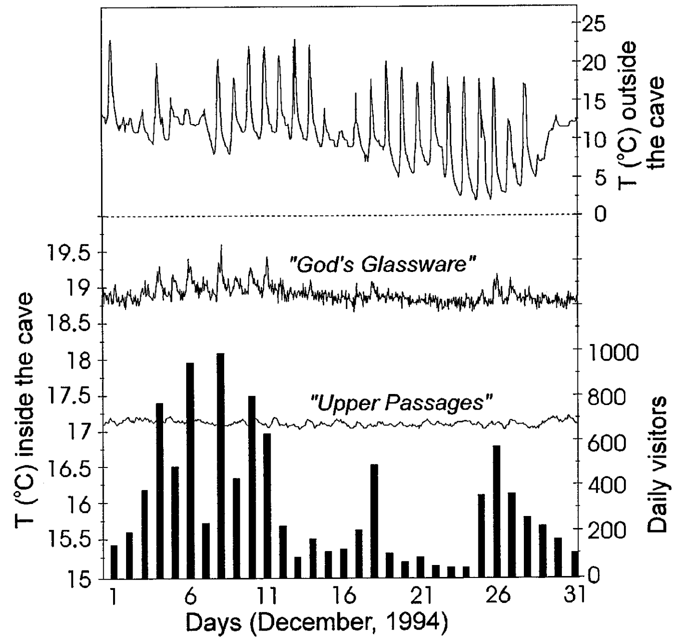


Fig. 5
Daily visitors to the cave and records of air temperature in the Upper Passages (not visited), the God's Glassware chamber and outside the cave, during December 1994

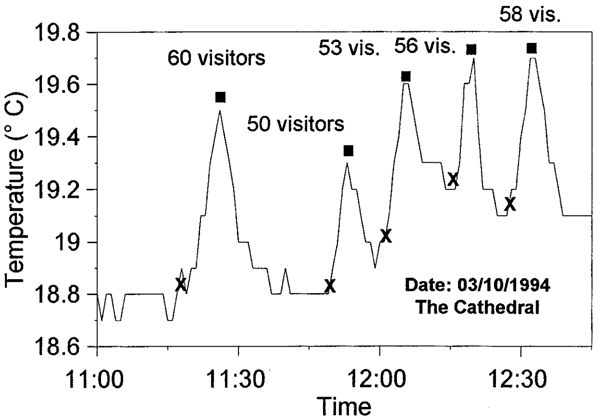


Fig. 6
Minute by minute records of the air temperature in the Cathedral chamber on 3 October 1994, with the number of people per visitor group, and the times of arrival (*crosses*) and departure (*black squares*) of the various groups

In daily terms, the air temperature in this chamber is closely related to the number of visitors, with a coefficient of correlation of 0.7; this coefficient is greater than that relating to exterior temperature ($r = 0.4$). This indicates that the heat produced by the visitors during their stay underground is the main cause of the modification to the natural temperature range. Nevertheless, the degree of correlation with exterior air temperature may be considered significant, though this is simply a consequence of the fact that both this parameter, and that of

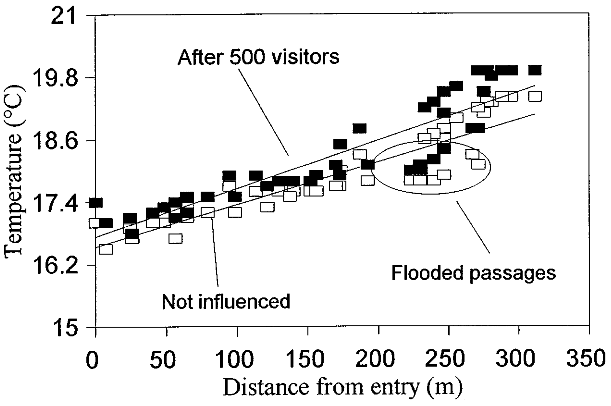


Fig. 7
Profiles for air temperature throughout the cave, not influenced (*empty squares*) and after the passage of 500 visitors (*black squares*)

visitor numbers present, clear daily periodicity. In other words, the times of greatest exterior sunlight approximately coincide with the period of daily visits, while the cave remains closed to the public during the night. The continuous thermal records obtained at other points in the cave show similar levels of correlation with exterior temperature and with the number of daily visitors, with the exception of the sensor located in the Upper Passages, unvisited and without illumination, where the correlation is very low or even negative, which indicates a very slight influence or that there is a considerable time-lag between the main factors of influence.

The strongest impact on air temperature in the cave occurs during the summer months (July and August), the hottest period of the year and that of the greatest visitor numbers. Figs. 4 and 5 show records of air temperature during August and December 1994. Tourist groups enter the cave at a maximum periodicity of every 15 min, from 1030 until 0600 hours. This means that the illumination system, equipped with modular switches that are normally operated by the guide as each group passes through, remains in permanent operation during virtually all of the daily visiting period. The heat emitted by the incandescent lights accumulates with the calorific energy of the visitors and makes a notable contribution to the temperature increase within the cave.

The cave is open to the public throughout the year, and so it is difficult to determine the variations in environmental parameters that are not artificially induced or influenced. However, during the winter (as in the December example in Fig. 5), there are periods of reduced daily visitor numbers. The immediate effect of this circumstance is a smoothing of the temperature curves, and even the disappearance of the typical daily maxima, as shown for God's Glassware in Fig. 5. Again, there is a good agreement between temperature maxima in the visited part of the cave and the number of people entering it, while the influence of exterior temperatures (with a wide day–night temperature range) is almost unappreciable. In the Upper Passages the temperature is lower, with little variation. Here, it is difficult to attribute any tendency to the immediate effect of the main modifying factors (visitor numbers and exterior temperature).

The discrete measurement of air temperature records, obtained with portable equipment, provides a good illustration of the almost immediate influence of visitors and shows the alteration of the cave's natural thermal equilibrium. Figure 6 provides the temperature readings obtained minute by minute over a period of 105 min on 3 October 1994 in the chamber known as the Cathedral. The figure describes the number of people in each group and the arrival and departure times of the groups. It can be seen that, on the arrival of the group, there is an almost immediate increase in air temperature, which is always greater than 0.5 °C. When the group leaves the chamber there is a temperature decrease, which is also immediate. The figure also shows the cumulative effects of the successive visits on temperature levels. These results are interpreted as showing that natural factors that could affect air temperature in the cave are of secondary importance when compared to those of visitor numbers and the illumination system employed.

The small dimensions of the entrance to the underground complex (an artificial tunnel of 2 × 1.5 m) and the low rate of air flow (measured at 0.15 m^3/s) imply a low rate of ventilation, and thus the effects of the visitors become cumulative after short periods (Fig. 7). After the passage of 500 people in an interval of 4 h, the air temperature in the most distant sectors rises 0.6 °C. The correlation between the temperature and distance from the entrance in both cases exceeds 0.9; the cloud of points that shows a deviation with respect to the general trend (unusually low values) corresponds to the inundated passages, illustrating the thermoregulatory effect of water masses.

The increase in temperature deriving from the heat emitted by visitors and by the illumination system is accompanied by a simultaneous decrease in the relative humidity of the air (Figs. 8, 9). This is logical, as the saturating

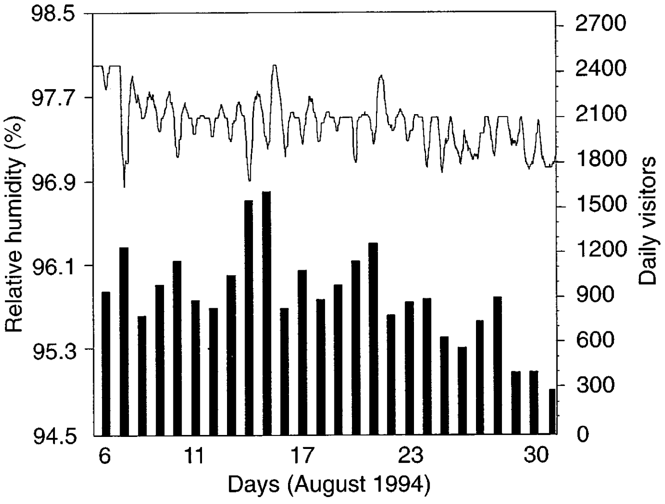


Fig. 8
Records of relative air humidity in the God's Glassware chamber and daily numbers of visitors during August 1994

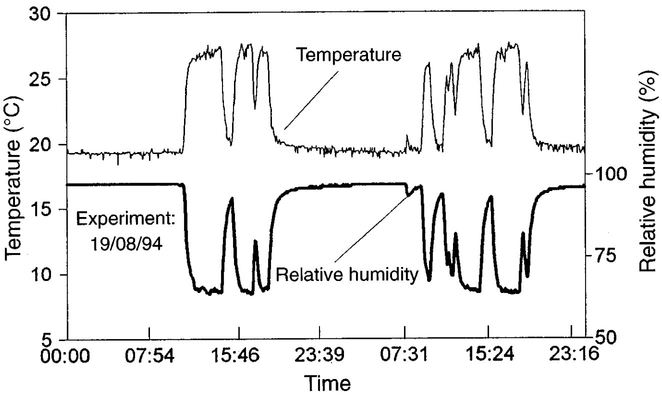


Fig. 9
Effect of the lighting systems on air temperature and relative humidity. Sensor located 0.5 m from the lamp

vapor pressure is directly proportional to temperature, though this is another impact or effect (non independent) caused by the exploitation of the cave for tourism. In most caves, particularly in the innermost parts, those most distant from the entrance, the absolute humidity is always very high – as a consequence of the constant presence of infiltrated water and inundated areas or where pools have formed – and close to saturation (relative humidity approaching 100%). For this reason, condensation phenomena are frequently observed, which contribute to the natural growth dynamics of the speleothems.

In the Cave of Marvels, the relative humidity range, in both space and time, lies within the narrow band of 97–100%. The continuous measuring equipment installed in the cave and used for this parameter only detected important variations from saturation in God's Glassware (one of the smallest chambers of all those visited by tourists), with decreases of up to 2% when groups of visitors passed through (Fig. 5). This alteration of the natural equilibrium makes the normal production of condensation in the chamber more difficult (although, presumably, the visitors increase the absolute humidity of the air by their metabolic emissions of water vapor) and, indirectly, affects speleogenetic dynamics.

The system of incandescent illumination produces an effect on the relative humidity of the air similar to that produced by the visitors, though in this case it is even more drastic in the immediate proximity of the lights. Figure 9 shows an experimental record of temperature and relative humidity obtained from a sensor intentionally situated at 0.5 m from a light source. The temperature rose by up to 8 °C, corresponding to a decrease in relative humidity of up to 22%. Indeed, the concretions in the vicinity of the lights were found to be totally dry and free from condensation, except those that frequently received infiltrating water, in which case they were usually colonized by microorganisms.

Another factor analyzed was carbon dioxide. The natural concentration of CO_2 in caves is usually 2–20 times greater than that outside (sometimes more), the origin of which is primarily the respiration and oxidation of organic materials (Appelo and Postma 1993). For this reason, caves having a greater concentration of CO_2 are predominantly situated in tropical and temperate wet zones. The distribution of CO_2 in the interior of caves depends on many factors, among the most important being the natural ventilation of the complex (Fernández and others 1986). Ek and Gewelt (1985) found a high correlation between the CO_2 content of the air and the distance from the entrance, a fact related to the processes of ventilation and renewal of the underground air. This was demonstrated in the Cave of Marvels. In the chamber nearest the entrance (Chamber of the Shells), the concentrations of CO_2 ranged from 500 to 600 ppm, while in the most distant parts (God's Glassware) with poorer ventilation, the lowest value was 1500 ppm. As a result of the entry of visitors, the content of this gas reached values exceeding 5000 ppm (Fig. 10).

Figure 10 shows at least three relative maxima of CO_2 daily, which often exceed 5000 ppm (the upper detection limit of the equipment employed). The first two are clearly related to the numbers of visitors passing through the chamber, approximately half an hour after their entry into the cave. The interval between the two maxima corresponds to the lunchtime period from 1400 to 1600 hours, when the cave is closed to the public. The decrease in the concentration of CO_2 in the air after the cave's closure at 1900 hours is slower when there has been a greater total number of visitors, as shown by a comparison of the records corresponding to 18–20 July (Monday to Wednesday) with those for 17 July (Sunday). The third relative maximum occurs before midnight, and is probably related to the processes of biological respiration, due to the fact that photosynthetic activity is reduced and that there is less movement of air through the cave. The equation commonly used to describe this process, in a summarized way, is:

$$\text{Plant carbon} + O_2 = CO_2 + H_2O + \text{Heat}$$

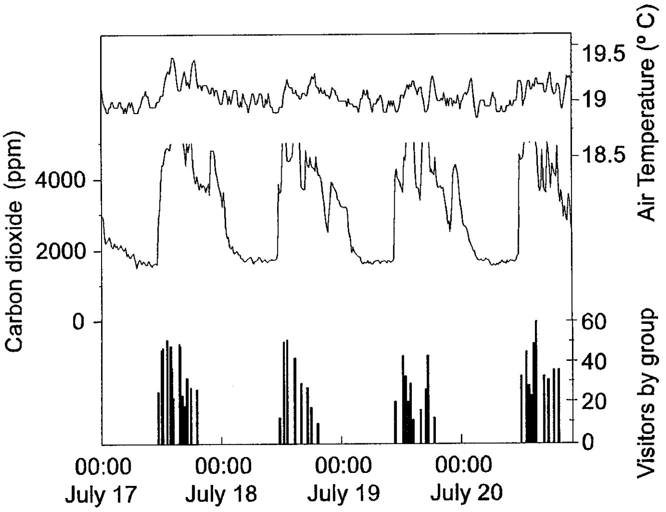


Fig. 10
Number of visitors per group, concentration of CO_2 and air temperature in the God's Glassware chamber, 17–20 July

This reaction implies the release of caloric energy, which would explain the slight increase in temperature at night, which sometimes coincides with the increase in CO_2. Only after this third maximum is there an almost complete recovery from the increase in CO_2, with a fairly stable value of around 1500 ppm being attained within a short time.

High concentrations of CO_2 can seriously affect underground environmental conditions and accelerate processes which under equilibrium would take place over longer periods or initiate those that would otherwise not take place at all.

Impact on water

The Passage of the Pools is one of the most spectacular and attractive zones of the cave, since it has an underwater lighting system that illuminates the highly picturesque watery landscape of the gallery. The water level variation of the pools in the cave (with a maximum of 3 m being measured) has a notable influence on the total volume of air within the complex; this increases as the water level falls and decreases as it rises. The surface of the pools corresponds to the level of the water table of the small aquifer where the cave developed; recharge of the aquifer comes entirely from rainfall, the average annual value of which has been estimated at 990 mm. Daily tracking of the levels indicates relatively pronounced drops, particularly during 1993 and 1994, years of extreme drought.

The cause of the fall in level has been largely attributed to the pumping of water (7 l/s) from a well situated only 300 m from the cave (the water was used to supplement the town water supply). Interruption of the pumping, when there is no rainfall, immediately produces a slight recovery, or at least a stabilization, of the water level in the pools; this occurred several times between July and September 1994. In contrast, when pumping restarts (Fig. 11), the fall in the level is immediate and continuous, eliminating or notably reducing the recharge following periods of heavy rainfall, such as in May and October 1994.

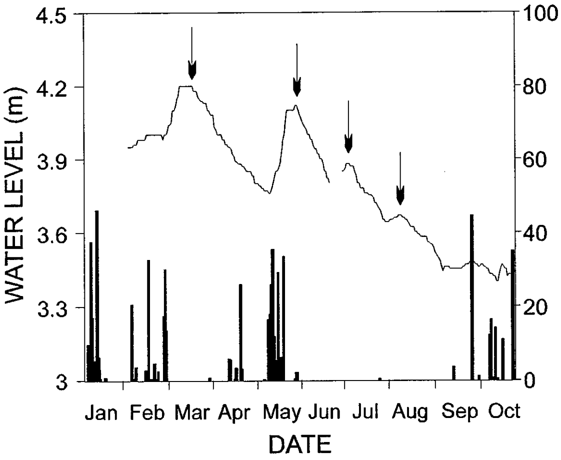


Fig. 11
Evolution of the water table (Passage of the Pools) and rainfall during 1994. *Arrows* indicate the start of pumping from a well near the cave

Taking into account the small recharge surface area of the carbonate outcrop in which the cave is located (just 0.22 km^2), the average rate of infiltration must be no greater than 3 l/s, with a higher recharge during periods of rainfall (when pumping is interrupted) and lower during dry periods (with the pumps functioning). Therefore, when water is extracted by the pumps, a disequilibrium is produced, at least in the short term, between the input and output, resulting in the immediate and progressive fall in the water table. The underwater lamps may then become visible above the water level in the pools, and the ornamental effect is lost.

Impact on the rock

It is evident that pronounced alterations in the basic climatic parameters of a cave upset the chemical equilibrium controlling the dissolution and precipitation of the carbonates. In this way, an increase in the concentration of CO_2 in the air could manage to generate waters that produce aggressive condensation and, thereby, produce processes of corrosion in the cave deposits. Nevertheless, added to this degradation produced by phenomena of inorganic dissolution is the biological corrosion. In fact, one of the most widespread problems of tourist caves is the appearance of microflora colonization (algae, lichens and mosses) associated with visitor influence (transporting spores) and, especially, inappropriate lighting systems. The luminous energy emitted by the lamps enables these microorganisms to synthesize the components necessary for vital functions, even acquiring mineral elements from the substrate which is being colonized. Once these microflora are established, their resistance to environmental conditions is very high; they are capable of remaining active for long periods of time, even in the total absence of light (Ruiz and others 1991). The role of these organisms in mechanically and chemically altering the carbonates has been illustrated by numerous authors (Fry 1927; Jones 1965; Viles 1987a, b). The consequence of this activity is the progressive decomposition of the rock on which two groups of fundamental mechanisms act. First, a chemical or biochemical alteration takes place: this is followed by a biophysical change, responsible for the mechanical disintegration of the substrate (Cooks and Otto 1990).

A total of 25 samples were taken of the formations and rock, both from the visited sectors and those inaccessible to the public, to carry out comparative analyses by scanning electron microscopy (SEM) and thin-section analysis. The aim of the sampling was to establish the current degree of conservation in the cave. In the sectors farthest from the tourist route, the speleothems showed no traces of advanced dissolution, though in some cases there was evidence of foreign elements on the surface of the crystals (Fig. 12). Some samples, especially those from the marbles not associated with plant pollution, showed

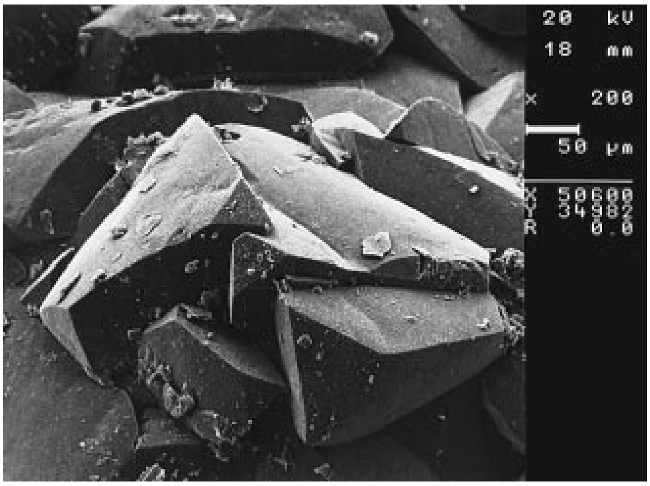


Fig. 12
Sample of speleothem taken in the sectors far from the tourist route

blocky etching, textures which were attributable to inorganic dissolution processes.
However, the samples affected by processes of plant colonization betrayed a microtopography completely different from that of the former sample group. They showed systematic, circular etched pits and tunnels (Fig. 13a, b), textures intimately related with organic etching (Moses and others 1995). In some of the samples, the alteration process proved especially intense, as in the case of Fig. 13c, which shows a clear example of crystal etching. The sample of acicular aragonite extracted from sectors near the former samples also showed strong alteration processes, principally crystal etching and mechanical disaggregation. The high porosity of this aggregated mineral makes it particularly susceptible to chemical erosion, as it has a greater surface area in contact with the mineralized fluids.

Conclusions

Human influence in the Cave of Marvels has altered the dynamic equilibrium of its natural environment. This imbalance has had serious effects on the air, including of increased temperature, decreased relative humidity and a greater concentration of CO_2. The $C0_2$ exhaled by the visitors is far from being the only factor responsible for the degradation found in the cave deposits.
The new environmental conditions imposed by human intervention in this fragile system (higher temperatures, lighting system) have encouraged the colonization and spread of numerous microflora in various sectors of the cave, where the floral activity is leaving its mark on the substrate in the form of weathering, algal pits, tunnels and crystal etching. Another impact is that pumping from the aquifer near the cave has lowered the water level of the pools inside the cave.

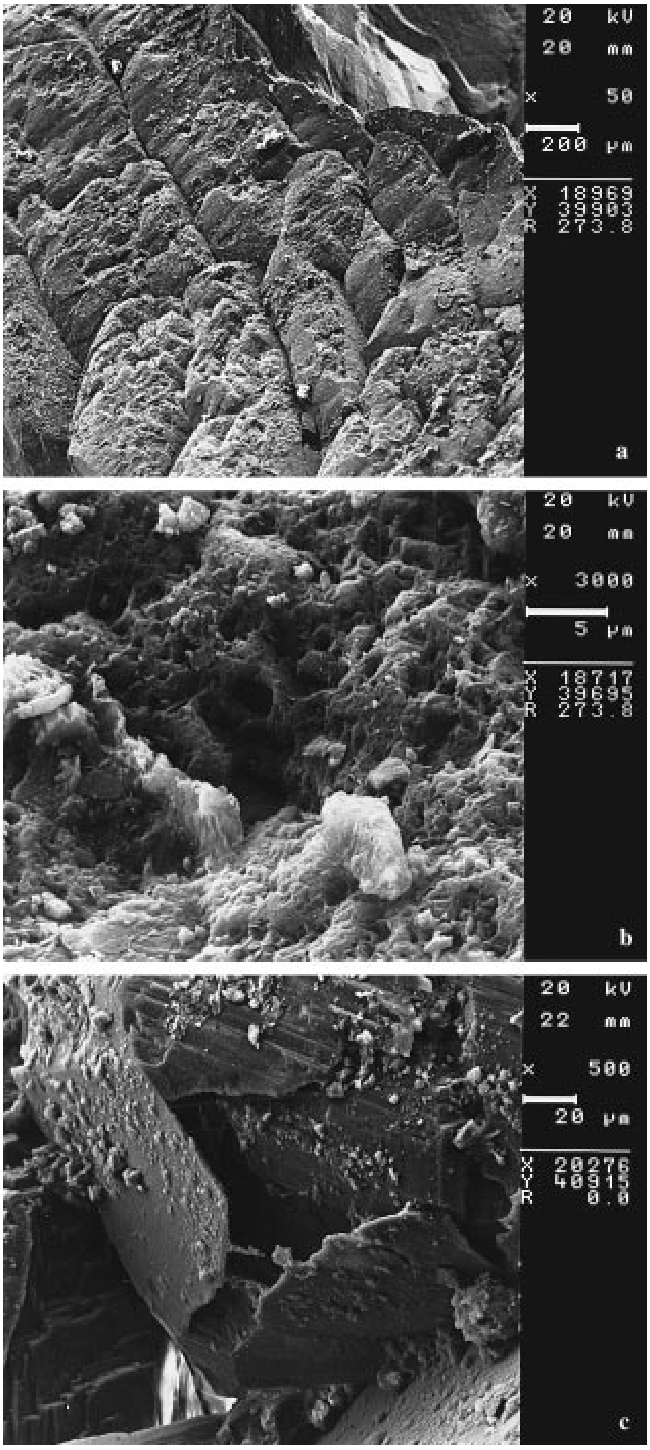


Fig. 13
Speleothems affected by processes of plant colonization, showing **a**, **b** algal and weathering pits and tunnels, and **c** crystal etching

The general effects of the three environments are not independent of each other, but rather the alteration of one system (air) implies direct or indirect change in the other two (Fig. 14). The result of this chain of processes is the

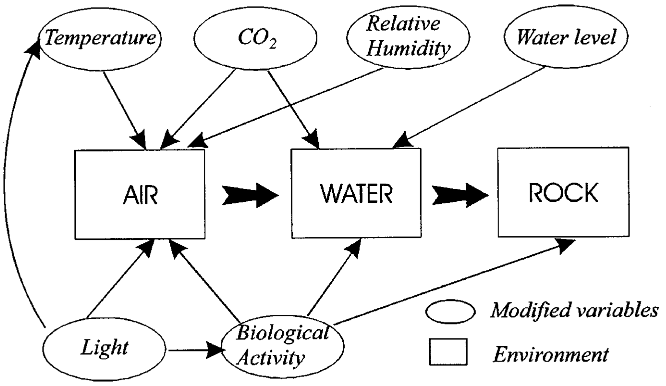


Fig. 14
General scheme of human effects on the natural environment of the Cave of Marvels

degradation of the crystallizations of calcite and aragonite, which are the great attraction of the cave.

References

Appelo CAJ, Postma D (1993) Geochemistry, groundwater and pollution. A.A. Balkema, Rotterdam, p 536

Bertolani M, Cigna A, Maccio S; Morbidelli L, Sighinolfi G (1991) The karst system "Grotta Grande del Vento-Grotta del Fiume" and the conservation of its environment. In: Sauro U (ed), Proceedings of the International Conference on environmental changes in karst areas, vol 13. Universitá di Padova, Dipartimento di Geografía, pp 289–298

Caumartin V (1986) La conservation des concrétions dans les cavernes aménagées. In: Pere P (ed), 9° Congreso Internacional de Espeleología, Barcelona (Spain). Fed. Esp. Espeleol. 2:223–225

Cigna A (1987) La capacitá ricettiva delle grotte turistiche quale parametro per la salvaguardia dell'ambiente sotterraneo-caso delle Grotte di Castellana. La Grotte d'Italia, Serie IV, 15:999–1012

Cigna A (1993) Environmental management of tourist caves: the examples of Grotta di Castellana and Grotta Grande del Vento, Italy. Environmental Geol, 21:173–180

Cooks J, Otto E (1990) The weathering effects of the lichen *Lecidea Aff Sarcogynoidoes (koerb.)* on Magaliesberg quartzite. Earth Surf Processes Landforms 15:491–500

Ek C, Gewelt M (1985) Carbon dioxide in cave atmospheres. New results in Belgium and comparison with some others countries. Earth Surf Processes Landforms 10:173–187

Eraso A (1969) La corrosión climática en las cavernas. Bol Geol Miner T LXXX-VI:564–581

Fernández PL, Gutiérrez I, Quindós LS, Soto J, Villar E (1986) Natural ventilation of the Paintings Room in the Altamira Cave. Nature 321:586–588

Fry EJ (1927) The mechanical action of crustaceous lichens on substrata of shale, schist, gneiss, limestone and obsidian. Ann Bot, XLI (CLXIII):436–465

Heaton T (1986) Caves: a tremendous range of energy environments on Earth. Natl Speleol Soc News August:301–304

Jones RJ (1965) Aspects of biological weathering of limestone pavement. Proc Geol Assoc 76:421–433

Mangin A (1984) Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoire et spectrale. J Hydrol 67:25–43.

Mangin A, D'Hulst D (1995) Fréquentation des grottes touristiques et conservation. Méthode d'approche pour en étudier les effets et proposer une réglementation. In: Cigna A (ed), Simposio Internazionale Grotte Turistiche e Monitoraggio Ambientale, Stazione Scient. Bossea Italia, pp 117–145

Martín-Rosales W, Rodríguez CM, López-Chicano M, Pulido-Bosch A, Vallejos A (1994) Análisis de la influencia antrópica sobre la Gruta de las Maravillas de Aracena, (España). In: Pulido A, Fagundo JR, Rodriguez J (eds), El Karst y los acuíferos kársticos. Univ. de Granada, pp 279–290

Moses C, Spate AP, Smith DI, Greenaway A (1995) Limestone weathering in eastern Australia. Part 2. Surface micromorphology study. Earth Surf Processes Landforms. 20:501–514

Padilla A, Pulido-Bosch A (1995) Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. J hydrol 168:73–89

Ruiz J, Marín F, Ojeda F, Marín F, Berros J, Marín E (1991) Estudio macroscópico "in situ" y microscópico de algas verdes y verdeazuladas del interior de la cueva de Nerja. In: Marín F (ed), Investigación biológica y edafológica de la cueva de Nerja (Málaga). Patronato Cueva de Nerja. pp 113–117

Trombe F (1952) Traité de Speleologie. Payot, Paris

Viles H (1987a) Blue-green algae and terrestrial limestone weathering on Aldabra Atoll: an SEM and light microscope study. Earth Surf Processes Landforms 12:319–330

Viles H (1987b) A quantitative scanning electron microscope study of evidence for lichen weathering of limestone. Mendip Hills, Somerset. Earth Surf Processes Landforms 12:467–473

Villar E, Bonet A, Díaz B, Fernández PL, Gutiérrez I, Quindós LS, Solana JR, Soto J (1984) Ambient temperature variations in the Hall of Paintings of Altamira Cave due to the presence of visitors. Cave Sci 11:99–104

Villar E, Fernández PL, Gutiérrez I, Quindós LS, Soto J (1986) Influence of visitors on carbon concentrations in Altamira Cave. Cave Sci 13:21–23