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Environmental pressures on conserving cave speleothems: effects of changing surface land use and increased cave tourism

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Speleothems (stalagmites, stalactites, etc.) have long drawn visitors underground to visit limestone caves throughout Europe, and since the start of the twentieth century many public show-caves have been established. For example, in the British Isles today there are over 20 show-caves; the most visited may receive in excess of 500 000 visitors annually.

Recent research has highlighted the potential destructive influence of visitors to caves by the effects of respiration, which can generate elevated CO_2 concentrations, and by their heating effect, which can raise temperatures by up to 3°C. Values of up to 5000 ppm of CO_2 have been reported in both private and public caves, but with clear evidence that the passage of visitors through the cave system causes increases of up to 200%. It has been suggested that such elevated CO_2 may cause the destruction of speleothems within the caves, as increased CO_2 leads to a higher equilibrium concentration of calcium within the drip waters feeding the speleothems, and hence causes dissolution of existing features, although it has to be noted that there is a significant natural variability of cave air CO_2 and it is against this that the anthropogenic effects of visitors has to be judged.

Data are presented here for both cave air CO_2 concentration and temperature, as well as a third variable, that of the drip-water calcium concentration, which is also a key determinant of speleothem growth and may be affected by surface land use changes. It is demonstrated that cave speleothems may be at risk from the increased passage of tourists, but that this risk is highest in caves where ventilation is poor and where either the calcium ion concentration of the drip waters is low ($<2{\cdot}0$ mmol l^{-1}) or where there have been or are likely to be significant changes in surface land use, which decrease the drip-water calcium concentrations and hence make corrosion more likely.

Keywords: speleothems, stalagmites, cave air CO_2, land use change, calcium ion concentrations, environmental impact of tourists.

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Introduction

Caves, caverns and grottoes are well known tourist attractions in many countries within Europe. For example, in France cave paintings and other hominid remains provide a major tourist attraction, drawing visitors primarily to the Dordogne region. In the British Isles, it is the cave speleothem deposits (stalagmites, stalactites, curtains, etc.) which provide the selling point and attract tourists. In addition, it is the speleothem deposits within British cave systems that often designates them Sites of Special Scientific Interest (SSSI) (Waltham *et al.*, 1997). The number of tourists visiting cave systems has increased over the last 50 years, with annual totals ranging from tens of thousands (e.g. 40 000 per year at Poole's Cavern, Derbyshire), to over half a million per year (e.g. Grotta di Castellana and Grotta Grande del Vento, Italy and Han sur Lesse, Belgium).

The presence of large numbers of tourists within natural cave systems has the potential for altering the local climatic and environmental conditions. In particular, the presence of lighting within the cave system may change the thermal conditions within the cave (Cigna, 1993), and also allow the invasion of light-loving species; in the Dordogne this, combined with the increase of CO_2

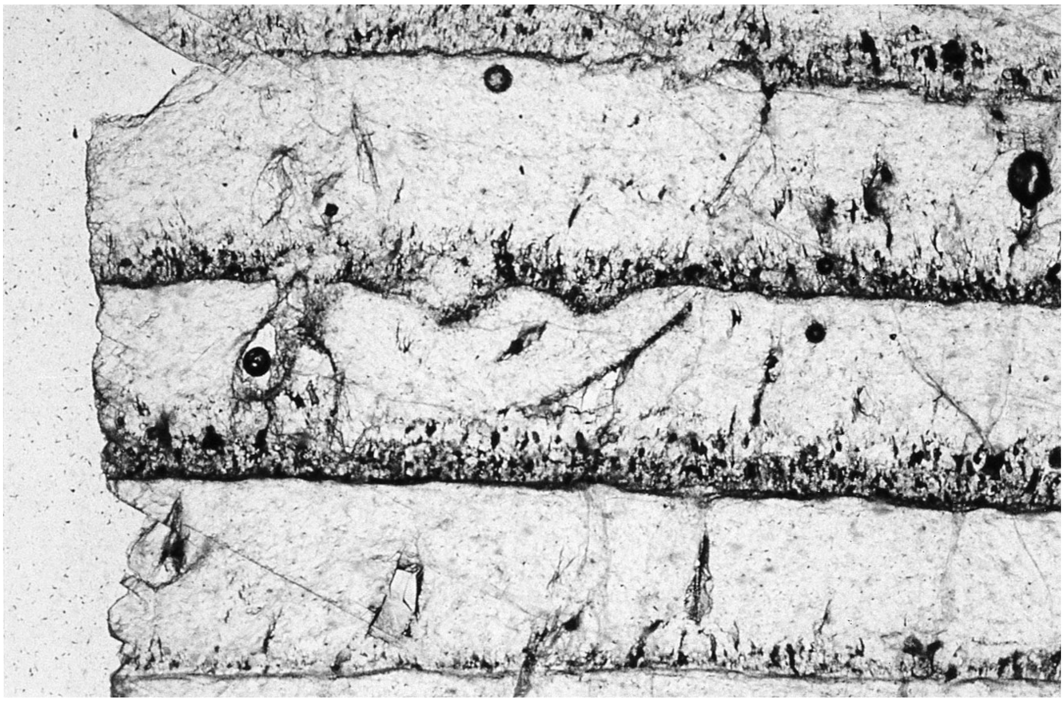

Figure 1. Corroded speleothem Din-stm1, developed on an artificial pavement constructed in 1959 in the Cave of Dinant (also called 'La Merveilleuse', Belgium). Vertical thin section, natural light, field height = 1 mm; hiatuses indicate annual corrosion caused by either natural and/or anthropogenic variations in CO_2.

concentration, caused algae damage to the cave paintings in the Lascaux cave and ultimately caused its closure and a replica cave to be constructed (Delluc and Delluc, 1984). The presence of a large number of visitors to the cave will also raise the temperature and decrease the humidity of the cave and has been well documented (Villar *et al.*, 1984; see also references in Cigna, 1993); for example, the combined effect of installing lighting and increased visitor numbers increased cave air temperature by 3°C in the Grotta di Castellana in Italy. Another cause for concern has been the impact of raising the CO_2 concentrations in the cave systems through the respiration of the tourists (Dragovich and Grose, 1980; Villar *et al.*, 1984; Craven, 1996). It has been suggested that increasing the concentration of CO_2 may cause speleothems within the cave to corrode rather than continue to grow, and thus destroy the main tourist attraction (Figure 1). In addition, at a concentration of 0·5%, both the US Government and UK long-term exposure CO_2 safety limits are reached; CO_2 toxicity can affect health at this concentration and higher depending on individual's metabolism and exposure time. Until recently, the only studies of CO_2 in cave systems have been empirical, with no theoretical underpinning (Dragovich and Grose, 1980; Villar *et al.*, 1984; Craven, 1996). In addition, if one considers the environmental threats to the preservation of speleothems, then one has also to consider both: (1) potential variations in the calcium ion concentration of the waters feeding them; and (2) temperature, as these are the other main factors determining speleothem growth (Dreybrodt, 1980, 1988). In this study the authors provide a theoretical model which will enable an improved risk assessment to determine which caves contain speleothems which may be under threat.

Theories of stalagmite deposition

Speleothems form by the degassing of waters that are supersaturated with calcium carbonate (Holland *et al.*, 1964). This supersaturation is achieved by the prior passage of the waters through the overlying soil; here the waters dissolve CO_2 that is present in elevated concentrations in the soil

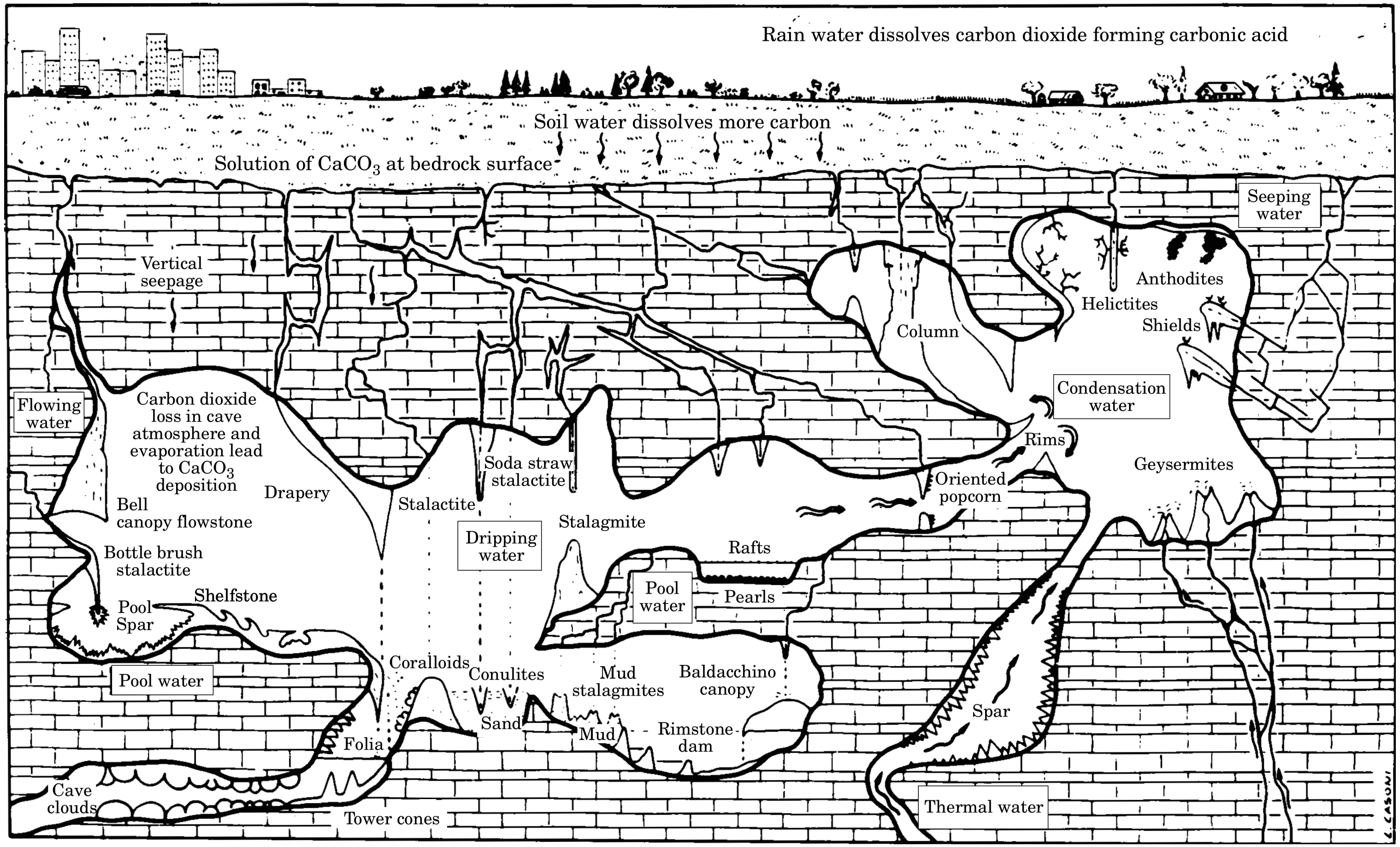

Figure 2. Speleothem formation process (from Hill and Forti, 1986).

profile (Figure 2). This CO_2 forms carbonic acid that dissolves the limestone:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad (1)$$

When the waters emerge in the cave voids and the above reaction proceeds in the reverse direction, they can potentially precipitate calcite in the form of speleothems. This is only possible if supersaturation with respect to calcite has been achieved, and because of inhibition effects for calcite crystal formation, a Saturation Index of >0·3 with respect to calcite is required for deposition to occur (Plummer and Busenberg, 1982). Should the cave air CO_2 be higher than that contained within the water then further dissolution of calcite will occur as the waters try to reach a new, higher equilibrium with respect to calcium ion concentration. If the latter process is due to an artificial increase in CO_2 (e.g. from the passage of tourists), then this dissolution may be of speleothem which has been deposited under previous conditions of low CO_2.

The geochemistry of speleothem deposition is well understood, both in terms of the process (Holland *et al.*, 1964) and the rate of the process (Dreybrodt, 1980; 1988; Baker and Smart, 1995; Baker *et al.*, 1998). In particular, although the calcium concentration of the water feeding the speleothems is partially dependent on the overlying soil and geology, the calcium ion concentration boundary between supersaturation (potentially speleothem depositing) and undersaturation (potentially speleothem eroding) is known to depend also on the temperature of the cave environment and the CO_2 concentration of the cave air (Dreybrodt, 1988). This relationship is demonstrated in Figure 3 for temperatures of 5 and 10°C, and suggests that in order to understand the effects of changing environmental conditions on speleothem formation, both the natural and anthropogenic variability of the calcium ion concentration in the waters supplying the speleothems, the cave air temperature and the air CO_2 concentration should be considered. In addition, the figure suggests that the most important factors leading to corrosion of the caves would be those of changes in drip-water calcium concentration and cave air CO_2. Dissolution or corrosion of existing speleothems by variations in these variables may occur over two time periods. Firstly, with long-term (inter-annual to centennial) increases in cave air CO_2 or decreases in water calcium ion concentration, corrosion will occur over a similar time period. Alternatively, seasonal corrosive events may occur. For example, maximum CO_2 concentrations are observed in summer (Ek and Gewelt, 1985). This timing often corresponds with the summer minimum of calcium ion concentration (Pitty, 1966; Baker, 1993). Thus corrosion of speleothems in summer would be the mostly likely seasonal effect of changing CO_2 and calcium ion concentration.

In situ measurements of the environmental factors controlling speleothem deposition

Cave air carbon dioxide

The concentration of CO_2 in cave atmospheres has been widely researched for natural environmental conditions (Ek and Gewelt, 1985) and shown to be highly variable, with values ranging from 340 to 10000 ppm (the latter significantly higher than most national health and safety limits). Much of this variability can be explained if there are changes in soil or vegetation type on the surface, as it is this soil CO_2 which typically provides the source of CO_2 in the cave. In addition, cave morphology can determine both the absolute concentrations of CO_2 and also spatial variability within a cave; for example a cave with two entrances may be well ventilated and thus excess CO_2 will be removed. Carbon dioxide has been demonstrated to be potentially higher (from $\times 1$ to $\times 4$) in the roof of caves rather than at the floor, especially in confined passages and over short time periods, as the roof is nearer to the input waters which are often degassing CO_2 (Atkinson, 1977), as well as over long time periods in descending dead-end passages where there is little air flow (Ek and Gewelt, 1985). Seasonal variations also occur, as soil CO_2 production is highest in summer, and thus cave air CO_2 levels also rise at this time; for example a $\times 3$ seasonal variation was recorded at Ste-Anne Cave at Tiliff in Belgium (Ek and Gewelt, 1985, and the authors observed a $\times 1{\cdot}75$–$2{\cdot}5$ increase in CO_2 in sum-

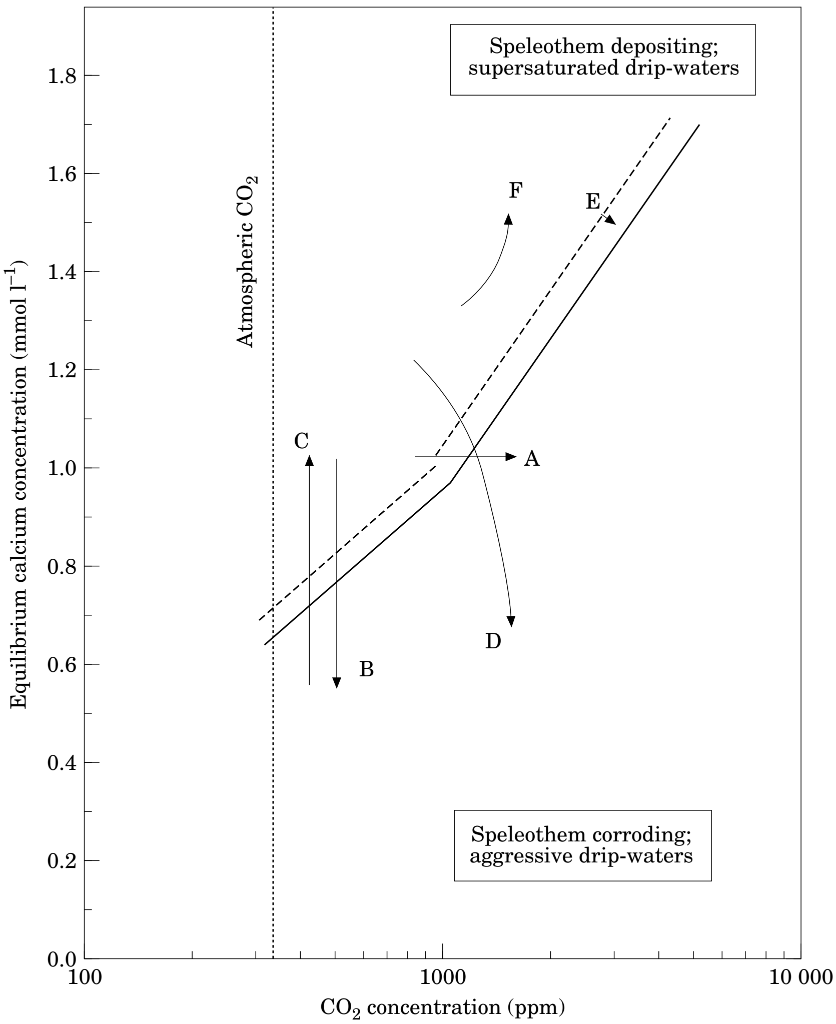

Figure 3. Relationship between changes in CO_2, temperature and calcium ion concentration and speleothem deposition and erosion. Temperatures of 5°C (dotted) and 10°C (solid) lines are shown. Hypothetical anthropogenic changes A to F in temperature, CO_2 and calcium ion concentration are shown (see text).

mer in the two Dordogne cave systems studied here.

It is against this natural variability of cave air CO_2 that the anthropogenic effects of visitors have to be judged. Each human typically exhales 3–4·5% CO_2. With a typical resting expiration rate, this amounts to 200 ml of CO_2 min^{-1}, so a party of 50 tourists will emit 10 l of CO_2 min^{-1} (Dragovich and Grose, 1980). The latter workers observed an increase in CO_2 in the Jenolan Caves, Australia, a cave receiving c. 100 000 visitors per year. CO_2 levels increased from 400 to 1500 ppm after tourist visits to the cave during the day; with the levels returning to atmospheric condition overnight. They observed that the highest daily peak CO_2 correlated with the number of tourists entering the cave on that day (r>0·85). Craven (1996) observed similar effects at Cango Cave in South Africa and similar results have been reported from the Grotte Font-de-Gaume in France (Daubisse *et al.*, 1984). In a 1995 study where over 3000 visitors were entering Cango Cave each day between 09:00 and 00:00 h CO_2 increased to a maximum of 27 000 ppm from an original value of 800 ppm (Craven, 1996). Few other studies have been published (Cigna, 1993 and references therein; Villar *et al.*, 1986; Ek, 1990; Huppert *et al.* 1993), but the results suggest that the impact of tourism on caves may increase the CO_2 concentrations by an order of magnitude, depending on the cave ventilation, and that these variations are likely to vary diurnally.

Calcium ion concentrations

The amount by which the calcium ion concentration of the waters feeding speleothems exceeds the corrosion boundary value (saturation index of calcite less than $\sim -0{\cdot}3$), and the sensitivity of the ion concentration to surface environmental change, both determine the importance of environmental changes on this variable. Absolute calcium ion concentration depends on: (1) the soil CO_2 production, which is related to soil temperature and moisture (Smith and Atkinson, 1976; Woo and Marsh, 1977), as this determines the acidity of the water; and (2) the pathway by which the water is transmitted through the limestone aquifer, which controls the extent to which complete saturation with respect to calcite is reached. These controls have been modelled to obtain a global relationship linking soil CO_2, temperature and water-flow path by back-calculating from empirical spring and well data (Drake, 1980; 1983). In addition, one would expect that because cave drip-water calcium ion concentration is derived from soil CO_2 dissolution of limestone, cave air CO_2 in natural caves will be higher in those with high drip-water calcium concentrations.

Although many studies have measured the calcium concentrations of waters in limestone springs, streams and bore holes (for example, Smith and Atkinson, 1976; Smart and Friederich, 1981; Pentecost, 1992) fewer have analysed those supplying speleothems due to the much lower discharge rates. These studies (for example, see Pitty, 1966; Stenner, 1973; Baker and Smart, 1995; Baker *et al.*, 1997) confirm a typical range of 0·2–4·0 mmol l^{-1} for waters which have evolved according to Equation (1), with higher values possible where enhanced dissolution of limestone has occurred due to the presence of sulphate minerals. Seasonal variation of calcium ion concentration occurs with coefficients of variation of between 1 and 100%, the variability being highly dependent on flow routing (Pitty, 1966; Smart and Friederich, 1981). Even fewer studies have investigated the effects of changing land use on drip-water calcium concentration, although any changes in soil CO_2 production will ultimately affect the waters. Baker and Smart (1995) suggest from stream calcium evidence from the Mendip Hills, SW England (Richards, 1987), that agricultural changes over the last 30 years have increased the calcium ion loading by $\times 2$; similarly Friederich and Smart (1982) observed significantly lower calcium ion concentrations at GB Cave within the section of the cave overlain by rough grassland compared to that which was used for arable crops. Baker and Smart (1995) observe a lower than average calcium load for speleothem forming drip waters at Kent's Cavern, a site overlain by private houses.

Temperature

Figure 3 demonstrates that an increase in temperature will lessen the chance of corrosion of speleothems occurring, but also that the influence is negligible compared to changes in CO_2 and drip-water calcium concentration. Typically, caves exhibit few changes in temperature on either a diurnal or annual basis, as they are buffered from surface temperature changes, and have a temperature equal to the mean annual temperature (Wigley and Brown, 1977), with temperature variability increasing as the entrance to the cave is approached. Thus most caves within British Isles, France and Belgium have mean temperatures of between 8 and 13°C. The effects of tourism on cave temperatures which have been reported suggest that changes of up to 1°C are possible during the passage of tourist parties, and that the temperature declines back to the natural mean within 15–120 min (Cigna, 1993); the largest permanent rise in temperature has been observed by the same author to be 3°C over a 20-year period. Such variations suggest that temperature changes alone will have little effect on speleothem and cave-wall corrosion, although a secondary effect of lowering humidity may be significant (see below).

Comparison of hypothetical environmental effects and empirical data

From the evidence presented in the previous section, it is apparent that significant changes in all three variables that affect speleothem deposition can occur. These changes are presented in theoretical form in Figure 3, where six hypothetical changes in cave environmental conditions are shown. If the line of change passes from supersaturated to undersaturated waters there is the potential for corrosion of speleothems at the site:

A: postulates a change of $\times 2$ in CO_2 concentration of the cave atmosphere (i.e. due to the passage of tourists), without an associated change in drip-water calcium concentration (suggesting no change in overlying land use).

B: postulates a $\times 0{\cdot}5$ decrease in drip-water calcium concentration with no associated change in cave air CO_2 concentration, a possible effect of changing land use but no increase in tourism.

C: is the reverse of the above, where land use change may double the soil CO_2 concentrations and thus increase the calcium concentration of the waters feeding the speleothems, with no associated change in cave air CO_2.

D: postulates both a $\times 2$ increase in CO_2 and a $\times 0{\cdot}5$ change in calcium ion concentration. Figure 3 suggests that this combination of changes is potentially the most catastrophic as undersaturation is reached with a smaller change in calcium ion concentration and air CO_2 than would be necessary if only one of the two variables was affected. This hypothetical situation is precisely what can happen when show caves are constructed, with new buildings changing the land use above the cave as well as tourists increasing the CO_2 within the cave.

E: demonstrates the effect of a hypothetical increase of 3°C in the temperature of the cave, generated due to the installation of lighting and/or an increase in the number of tourists, with no change in the CO_2 of the cave air or calcium ion concentration of the drip waters.

F: is a hypothetical relationship between the calcium ion concentration of the waters and CO_2 under natural conditions, where increasing calcium in the drip waters and increased cave air CO_2 are both functions of changing soil conditions and thus co-vary.

Hypotheses A to F above are simplifications of the real impacts of environmental change on cave systems. In particular it has to be recognized that:

(1) Changes in flow path of the water feeding the speleothems may occur. Such changes in flow path may either increase or decrease the calcium load of the water because they may alter the residence time of the groundwater within the limestone. Such flow switching is part of the natural characteristics of karst groundwater flows (Smart and Friederich, 1981; Baker *et al.*, 1997), often observed as short-term effects after changes in rainfall intensity or quantity. However, long-term flow switching may also be induced by anthropogenic changes, such as increased irrigation of agricultural land or by the leaking of water mains in urban areas. Such effects would either divert the flow away from the 'natural' pathway, and thus stop speleothem deposition, or decrease the calcium ion concentration by decreasing the groundwater residence time, or both.

(2) Many of the anthropogenic effects will vary on a seasonal or daily time-scale, instead of being permanent, and often these will coincide with natural variations. One example would be the increase in CO_2 from tourists visiting the cave in summer, a period when cave air CO_2 would already be expected to be high due to natural processes. Winter conditions could well be more critical, even if visitor numbers are lower, as this is a period of low cave air CO_2 concentrations, and may thus result in a significant increase in CO_2 from natural levels. Similarly, land use changes may enhance the seasonal effect, especially if it is due to a change in use to arable agricultural production, as root respiration is concentrated within a short growing season.

(3) As the boundary between supersaturated and aggressive waters is approached, the growth rate of speleothems is known to decrease as equilibrium is reached (White, 1984; Dreybrodt, 1988). Thus the hypotheses in Figure 3 do not take account of time evolution, which may lessen the effect of environmental changes if they involve a slow change in the evolution of the waters near to equilibrium. In addition, inhibition of calcite crystal precipitation may occur at calcium ion concentrations and cave air CO_2 concentrations above the saturation threshold (typically the saturation index of calcite $>0{\cdot}3$; Plummer and Busenberg, 1982); therefore speleothem deposition may cease before

Table 1. Environmental conditions at nine cave systems in Europe and USA

Location	Drip-water calcium concentration (mmol l^{-1})	Surface vegetation	Cave air CO_2 (ppm)	Comments
Kent's Cavern, Torquay	2·09 ± 0·58 (N = 36)	Gardens	340–500 (N = 5)	Show-cave and SSSI
Brownes Folly Mine, Bathford	2·29 ± 0·37 (N = 84)	Secondary woodland	300–1400 (N = 4)	Nature Reserve
Grotte de Villars, Dordogne	3·23 ± 0·54 (N = 36)	Secondary woodland	800–3000 (N = 6)	Show-cave Site Classé
La Faurie, Dordogne	4·11 ± 0·87 (N = 10)	Grassland	800–4500 (N = 3)	–
Uamh an Tartair, Assynt	0·92 ± 0·07 (N = 23)	Peat	340 (N = 6)	SSSI
GB Cave, Mendip Hills	1·59 ± 0·39 (N = 6)	Arable/ grassland	340–400 (N = 3)	Calcium data from Stenner (1973) CO_2 data from P. L. Smart (pers. Comm.) SSSI
Poole's Cavern, Peak District	2·43 ± 0·17 (N = 72)	Secondary woodland	340–500 (N = 5)	Calcium data from Pitty (1966) Show-cave and SSSI

SSSI, Site of Special Scientific Interest.

the boundary between supersaturation and aggressive waters is reached.

(4) As temperature increases within the cave system, the relative humidity is likely to decrease, as determined at several sites by Cigna (1993). Decreased humidity within a cave is likely to increase the evaporation rate of water within the cave, which has the potential for depositing evaporative calcite. This may have a different crystal structure to calcite formed by the usual process of the degassing of CO_2, being more porous (Genty *et al.*, 1997), and often classed as being crumbing or matt in appearance and thus less appealing to the tourist. While knowledge of this process is limited, a small change in temperature or relative humidity near a threshold value for evaporative calcite formation may cause significant visual changes.

In Table 1 and Figure 4 we present data for cave sites for which calcium ion concentration, cave air CO_2 and temperature are known or can be estimated. Data for Pooles Cavern (Derbyshire, England) and GB Cave (Mendip Hills, England) have been compiled from the literature (Stenner, 1973; Friederich and Smart, 1982; Hill, 1986; Pitty, 1966); data for other sites (Browns Folly Mine, Wiltshire, England; La Faurie and Grottes de Villars, Dordogne, France) have been collected by the authors (Baker *et al.*, 1998; Genty, unpubl. data; Baker, unpubl. data). Although in some instances the data are limited (especially with respect to the number of cave air CO_2 samples), several points can be noted. In particular, it can be seen that sites with a calcium ion concentration of below 2·0 mmol l^{-1} are more prone to suffer from environmental changes as they are closer to equilibrium and small changes in CO_2 are likely to cause a shift from supersaturated to aggressive waters. All British Isles sites fall within this category, conversely, caves within France and Belgium tend to have a mean calcium ion concentration of over 3·0 mmol l^{-1}, and thus would seem to be less likely to suffer from any observed amount of change in drip-water calcium ion concentration or change in cave air CO_2.

Environmental pressures and cave conservation

This study has highlighted the relative importance of changes in environmental conditions on the preservation of cave stalactites

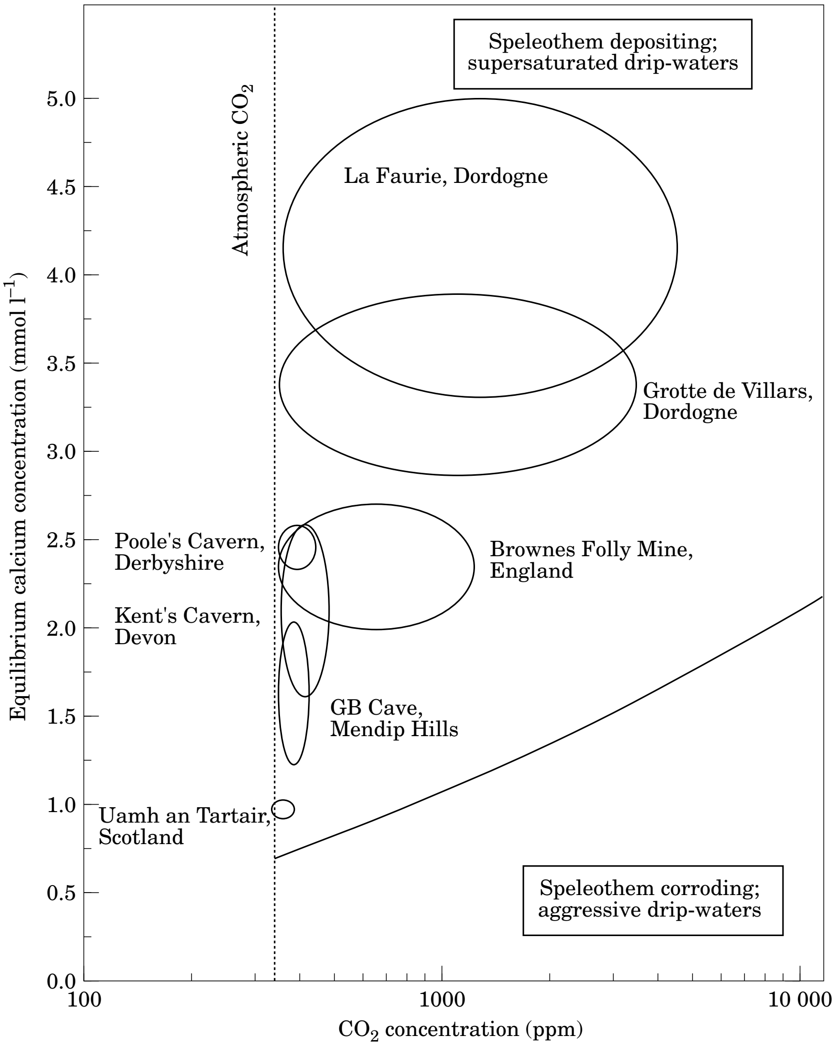

Figure 4. Actual ranges of calcium ion concentration and CO_2 for seven cave systems. Threshold between corrosion and deposition for 10°C is shown; all cave sites are within ± 1°C of this value except Uamh an Tartair (6·5°C).

and stalagmites. In particular, although previous studies have concentrated on the effects of increased CO_2 derived from tourist respiration, this study suggests that changes in calcium ion concentration may be more important. In addition, the sensitivity of a cave to environmental change can be readily monitored; calcium ion concentrations of cave waters can be determined automatically by utilizing conductivity meters which have been calibrated against calcium ion concentration (Ford and Williams, 1989); CO_2 can also be automatically monitored using CO_2 samplers, and temperature can also be automatically logged. Such data logged for a variety of locations and water sources over an annual cycle will determine the sensitivity of the site to environmental change and permit the action of any necessary remedial measures. Controlling CO_2 and temperature may require installation of a fan to circulate the air (Daubisse *et al.*, 1984) which may have the secondary benefit of reducing the elevated radon levels often found within cave systems (Hyland and Gunn, 1994). Controlling calcium ion concentration is less simple and may require strict controls on the use of overlying land (for example, Gillieson, 1996).

In this study, the cave system most sensitive to changes in environment is Uamh an Tartair, NW Scotland, a site which is not a show-cave but is a SSSI. This site is so close to the boundary between speleothem deposition and erosion that even a doubling of atmospheric CO_2, as postulated by greenhouse gas climate change scenarios (Houghton *et al.*, 1990), may be sufficient to destroy the stalagmites at this well-ventilated site. Analysis of thin sections of supposedly 'actively forming' stalagmites at the site (i.e. those with active drip sources) reveal that although the waters are slightly supersaturated with calcite, the stalagmites have not been growing over the last 1000–2000 years. These stalagmites, which started to grow 5000 to 10 000 years ago (Baker *et al.*, 1993 and unpubl. data), are thus most sensitive to destruction by yet another anthropogenic cause. For show caves, the significant implication of results presented in this study is that land use changes are potentially more important influences on speleothem deposition than tourist number increases. In economic terms, this offers the possibility of major show-caves controlling the impacts of tourism on cave stalagmites and stalactites by the careful modification of surface vegetation, such as replanting or vegetation control.

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