Annales de la Société Géologique de Belgique, T. 108, 1985, pp. 283-291

DYNAMICS OF THE KARST SYSTEM; A REVIEW OF SOME RECENT WORK IN NORTH AMERICA

by

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(5 figures and 1 table)

RESUME. - Dynamique des processus karstiques. Aperçu de travaux récents en Amérique du Nord. Il est établi que la dissolution des carbonates est généralement effectuée par des eaux carbonatées. Les meilleures descriptions de l'état chimique des eaux sont tirées de calculs d'équilibres. Des modèles d'équilibre permettent de décrire la plupart des eaux naturelles, et même des eaux complexes, modifiées par le passage dans des résidus miniers. Déterminer, sur le terrain, le pH pour l'introduire dans les modèles reste un problème. La comparaison d'eaux équilibrées du monde entier révèle que système ouvert ou système fermé détermine de façon hautement significative la concentration d'une solution en équilibre. Dans les terrains karstiques bien développés, le principal facteur du degré de dissolution est la quantité d'eau qui coule. Aux échelles spatiales qui intéressent la majorité des karstologues, les facteurs cinétiques de la dissolution ne seront importants que pendant la formation des réseaux d'écoulement souterrain; néanmoins, certaines formes telles que les coups de gouge et les rillenkarren dépendent de facteurs cinétiques.

Il est habituel d'estimer l'âge de certaines formes par extrapolation à partir de temps de dissolution mesurés. Dans certains cas, de telles estimations peuvent maintenant être comparées aux datations absolues des concrétions de grottes par U/Th. L'étude de cas pris en régions tropicales, tempérées et subpolaires suggère que les extrapolations tendent à surestimer la vitesse de création du relief, donc à sous-estimer l'âge des formes.

ABSTRACT. - It is established that most carbonate solution is effected by carbonated waters. Best descriptions of the chemical state of the waters are obtained from calculations of equilibria. Equilibrium models now exist to describe most natural waters and even complex unnatural ones created by flow through mine tailings. Accurate field determination of pH to enter into the models remains a problem. Comparison of equilibrated waters worldwide reveals the open or closed system states prevailing in their flowpaths to be a highly significant determinant of equilibrium solute concentration. Available runoff is the foremost control of rate of solution in well developed karst terrains. Current understanding of solution kinetics suggests that at the spatial scales that are of interest to most karst researchers, kinetic factors will only be important during the initiation of groundwater flow networks, although some small evolved landforms such as scallops and rillenkarren are kinetically controlled.

It is common to extrapolate measured solution rates to long time periods in order to estimate ages of landforms, etc. Such estimates can now be compared to absolute ages determined by U-series dating of speleothems in some instances. Case studies from tropical, temperate, and subpolar areas suggest that such extrapolations tend to overestimate rates of relief creation i.e. to underestimate ages of landforms.

Dynamics of karst is a theme of this colloquium. The purpose of my paper is to review some recent work carried out in the dynamics by researchers in the United States and Canada. It concentrates on topics that I am most familiar with or interested in at the present time. Different perspectives on North American research can be obtained by reading chapters by Palmer, Drake and White in the book, "Groundwater as a Geomorphic Agent" (R.G. LaFleur, Editor, 1984).

The present paper is restricted to limestone and dolomite karst. It is divided into two parts :

1. dynamics approached by study of carbonate erosion processes, and
2. dynamics approached by study of (precipitated) erosion products i.e. calcite speleothems and travertines.

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1.- STUDIES OF CARBONATE EROSION PROCESSES

A.- CHEMICAL FACTORS

i) The necessity of a carbonate equilibria approach

In quantitative studies of karst waters, all North American workers now centre their analyses upon computations of the equilibrium state of the waters with respect to the minerals of interest, calcite and dolomite. This follows the recommendations of Garrels & Christ (1965). The logarithmic indices, SI_c and SI_d, are used, normally with the comprehensive FORTRAN programme of Wigley (1977). An SI_c value of 0.0 ± 0.02 implies that a water sample is precisely saturated with respect to calcite. Aggressive waters have negative values, supersaturated waters are positive.

It is recognised that there are problems with this approach, so that too much faith must not be placed in any one specific computed value. In particular, (a) effects of others ions not analysed for, and of ionic and molecular complexes, may distort results and (b) every computed value depends strongly upon the value of pH that is measured. We all appreciate that it is often difficult to stabilise a good pH meter in the field (though the modern, relatively cheap, digital meters seem better in this respect than expensive dial instruments). Our host in this colloquium, Dr. Camille Ek, has published a very good comparison of field and laboratory pH measurements of sample waters that needs to be kept continually in mind (Ek, 1973). However, despite its problems, the equilibrium approach prevails. Its results are usually strongly indicative of the real chemical balance in the water, so that it permits valid comparisons of different water samples or water sample sets and valid comparisons of the dynamic factors controlling their measured concentrations of dissolved limestone and dolomite. For example, two waters may each have a concentration of 200 mgL $CaCO_3$ and so appear identical. But often their dynamic history is quite different. They cannot validly be compared. It is an unfortunate fact that a majority of karst water sample sets so far published are without these computed equilibria and also lack certain measurements (e.g. HCO_3^-) necessary to calculate them. We can compare the crude limestone denudation rates obtained from these sets but not the details of CO_2 generation and solution that are believed to be so important in carbonate karst dynamics.

ii) Dr. J.J. Drake's models for equilibrated waters

My colleague, John Drake, has investigated some climatic controls of CO_2 production and carbonate rock solution at the global scale, obtaining very interesting results (Drake, 1980, 1983, 1984; Ford & Drake, 1982). He worked with 19 data sets where it could be shown that all samples were close to equilibrium (i.e. waters from tube wells and from phreatic springs with diffuse flow). It is therefore valid to compare them. The sets span three continents, and range from sub-arctic and alpine localities through the temperate regions to humid tropical sites.

From regression analyses of many data a simple model for the temperature dependence of biologic CO_2 in the soil is given by :

$$\log PCO_2^* = -2 + 0.04\ T \qquad (1)$$

T = temperature in degrees centigrade. PCO_2^* is the potential partial pressure of CO_2 (atmospheric), related to the actual partial pressure, PCO_2, by :

$$PCO_2 = (0.21 - PCO_2)/0.21\ PCO_2^* \qquad (2)$$

Equation 2 expresses the fact that as CO_2 builds up in a soil atmosphere towards a theoretical maximum of 0.21 atmosphere, CO_2-producing bacteria are increasingly killed off.

These equations are used to calculate the dependence of $CaCO_3$ solubility upon mean annual temperature in the three different dynamic situations shown in Figure 1. The first is that of the ordinary atmosphere ($\log PCO_2 = -3.5$), when solubility decreases with increasing temperature. The second is for an enriched CO_2 atmosphere and a **perfect** closed system; CO_2 first dissolves until the water is saturated with it, then the water passes into an anaerobic environment before beginning to dissolve carbonate rocks. CO_2 cannot be replenished from a gas atmosphere as it is being removed from the water during the carbonate solution. It is seem that the perfect closed system is quite strongly temperature-dependent. The third situation is that of the

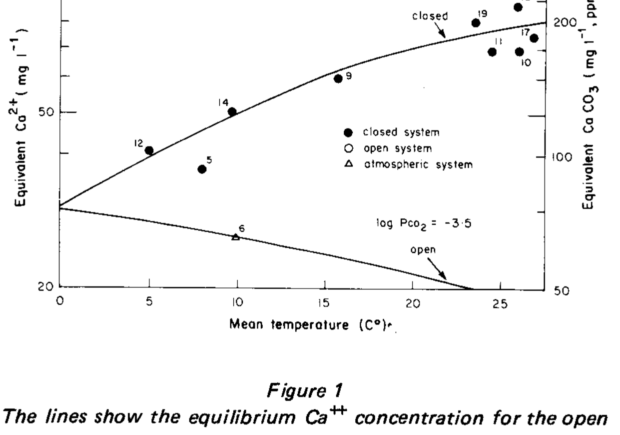

Figure 1

The lines show the equilibrium Ca^{++} concentration for the open and closed systems, $CaCO_3$-CO_2-H_2O, with a PCO_2 given as a function of mean annual temperature by equations 1 and 2. Data are mean values for sets of samples representing true mean groundwater conditions. From Ford & Drake, 1982.

perfect open system. CO_2-enriched soil air, water and carbonate rock are in continuous, interactive contact, so that dissolved CO_2 is replenished from the atmosphere as it is complexed in bicarbonate. There is moderate temperature dependence.

The arithmetic mean values of each of the 19 sample sets of equilibrated waters are also plotted onto Figure 1. I think that there is very good correspondence with Drake's models. (As a test, plot the data points without the model graphs. You will see a scatter suggesting no systematic relation between temperature and solute concentration). Scatter about the model lines can be explained by two effects; first, the data sets are imperfect because few water samples were precisely at equilibrium; second, perfect open and closed systems are not to be expected in Nature.

It is very interesting to note that most of the tropical waters display closed system behaviour. They are evidently gaining their CO_2 from true residual soils containing few limestone fragments. A majority of the temperate waters (5-12°C) in the set are passing through carbonate-rich glacial tills, outwash deposits, etc. overlying karst rocks. The tills present open system conditions. In the mean, there is more solution potential in the temperate environment despite the positive temperature dependence of CO_2 production. However, the temperate solutional attack is expended upon de-calcifying tills to quite an extent. The tropical attack is more directly upon the bedrock.

It is emphasised that Drake's analysis is founded upon the carbonate equilibria approach.

B.- KINETIC (PHYSICAL) FACTORS

Quite early work in the United States established two distinct approaches to kinetic studies. Kaye (1957) emphasised the role of a saturated boundary layer of water shielding the soluble rock from solvent ions in the body of the fluid. Weyl (1958) was concerned with bulk effects rather than interfaces, seeking to establish how much time was required to saturate a solution or how far it might penetrate along a fissure before becoming saturated and so unable to enlarge that fissure.

Boundary layer studies have since been applied to explain specific, small-scale karst landforms. Curl (1966) developed a mathematical theory of boundary layer discontinuities for solutional scallops. Its physical predictions were confirmed in a three-dimensional hardware (plaster-of-paris) model by Goodchild & Ford (1971), and a two-dimensional model by Blumberg & Curl (1974). Glew & Ford (1980) successfully simulated rillenkarren in a rainfall generator and showed that they are produced by raindrops penetrating an up-slope boundary layer.

Bulk effects have been studied experimentally by Berner & Morse (1974), and experimentally and theoretically by L.N. Plummer and his associates (Plummer & Wigley, 1976; Plummer, Wigley & Parkhurst, 1978; Plummer & Busenberg, 1982). The renowned karst scholar, William B. White, has long been interested (e.g. White & Longyear, 1962) and has been at the forefront in applying the rather abstruse experimental findings to questions of cave and karst landform genesis (e.g. White, 1977). Recently, he and Herman have mounted a new attack upon calcite and dolomite kinetics, with some very interesting results (Herman, 1982; White, 1984).

Berner & Morse (1974) dissolved calcite in artificial seawaters under a range of conditions. I have drawn their results in a highly modified form in Figure 2a. Following White, we may discern three distinct regions on this graph; the first is of great bulk solution associated with a pH change of three or more units. This will never be found in normal karst waters. It might occur in some highly saline brines associated with pyrite-sphalerite-galena ore emplacement into karst cavities (stratabound ore bodies). The second region is of a constant, moderate solution rate (or deposition rate, if reversed). This is the region of most karst measurement. The third region is of a very slow, final addition of solute to bring the solution precisely to saturation. It is approximately the equivalent of Weyl's (1958) > 90 °/o saturation region.

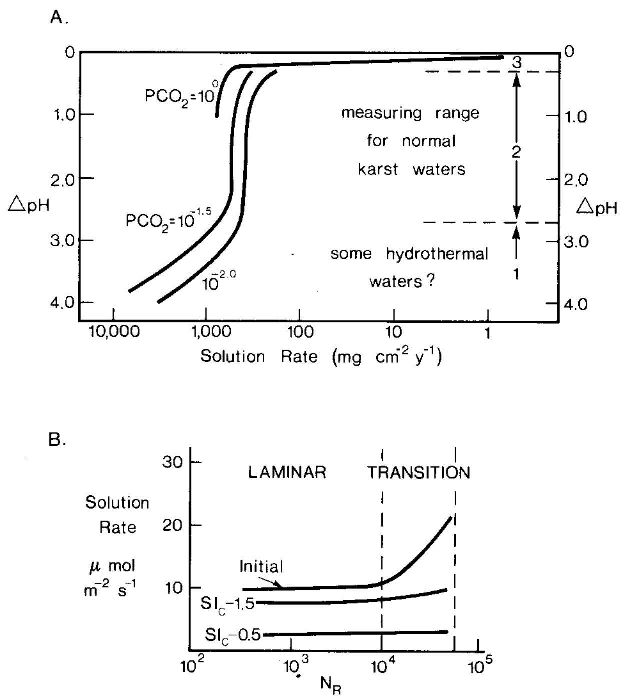

Figure 2

(a) The Berner & Morse (1974) experimental curves for calcite solution in artificial seawaters. For illustrative purposes, they have been highly modified by the author. (b) Calcite solution rate compared to flow type (Reynolds' Number). Results of experiments with a spinning disc apparatus (Herman, 1982).

White & Herman have extended this. Figure 2b shows their exciting results for the relationship of calcite solution rate to Reynolds Number (Herman, 1982).

Where the water is very aggressive, the solution rate increases quite markedly in the transition from laminar to turbulent flow. Using different lines of reasoning, White (1977) and Ford (1980) argued that, for all likely hydraulic gradients, transition to turbulent flow can occur at conduit diameters ranging 5-15 mm in diameter. When there is a continuous pipe or fissure of that diameter or greater between the source and the spring, a cave may be said to exist in limestone or dolomite. It may be enlarged quite rapidly. Smaller pipes and fissures are "protocaves", enlarging very slowly. Herman's experimental findings support these speculations.

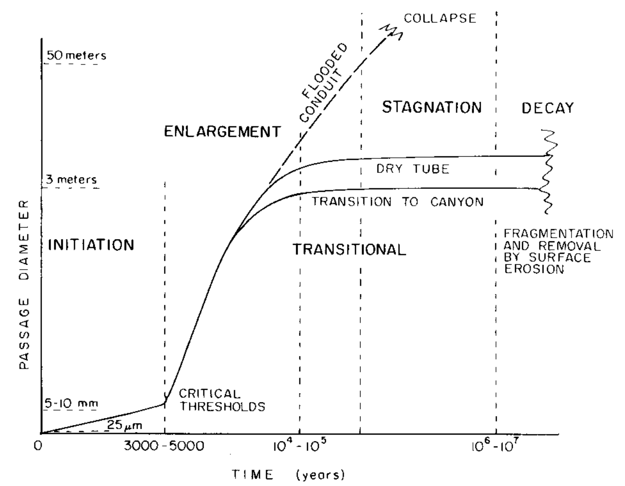

Figure 3

William B. White's representation of cave origin and development over time, based on current understanding of the solution kinetics of calcite. This figure published by kind permission of Dr. White.

Figure 3 is William White's latest development of this line of investigation. For a cave extending one km between sinkpoint and spring, we see slow, linear expansion in the proto-cave state for 3,000-5,000 years, succeeded by rapid enlargement once the critical 5-15 mm threshold is passed. From my own work I suspect that White has underestimated the proto-cave duration by roughly one order of magnitude (i.e. it is more likely 10,000-100,00 years). Bocker (1969) would place the minimum initial width for penetrable fissures at 10 µm, not 25 µm. However, the main conclusions of the figure stand. They are (1) that bulk solution kinetics are of little importance in limestone speleogenesis or surface landform development once the cave is established from the proto-cave (boundary layer solution kinetics remain important for specific features inside caves such as scallops, flutes, domepits, however) and (2) caves and surface karst features in principle may develop rapidly. White (personal communication, 1984) writes "It's an interesting conclusion that has come out of these geochemical models... that there is no difficulty in forming either caves or surface landforms in very short time. The problem is in slowing things down. We rarely see the karst process running flat out." In Part 2 of this review, we shall be able to compare these suggestions to some long-term mean erosion rates.

To conclude the kinetic review, Herman & White have also some interesting results for dolomite, which is rarely studied (White, 1984). In Berner and Morse' Region 2, solution of calcite proceeds at a moderate, constant rate until SI_C = 0.0 is closely approached. Herman (1982) found that `the dissolution rate of dolomite falls continuously by about an order of magniture between the initial solution and SI_d = -2." It then (between SI_d values of -2 and 0.0)... "becomes too slow to measure on a laboratory time scale"... (White, 1984, pp. 245 and 246). White suggests that these very slow kinetics explain the much more subdued character and smaller size of most dolomite karst features, surficial and underground. But in P.K. Weyl's terms L90 (or penetration distances to attain 90 °/o saturation) become much greater than in limestone. This helps to explain why many dolomites become excellent aquifers; their fissures are more uniformly enlarged in the proto-cave range of dimensions than in limestones.

2.- STUDIES OF CARBONATE EROSION PRODUCTS

i) U-series dating of speleothems

We understand today that most karst solution occurs in the lower soil or at its base. This is the locus of greatest dynamic interest. It is a very difficult place to investigate directly. We also know that most solutes are quickly exported from karst basins, which are therefore in a net erosional condition (rather than experiencing net deposition). However, some solutes may be stored for long spans of time within the basin, in the form of calcite precipitates in caves and at springs. Most of these solutes derive from the soil base. Calcite speleothems therefore offer opportunities for indirect investigation of karst dynamics there, as well as other applications.

It is of the greatest significance that many speleothems can be quite accurately dated by U-series methods. This places all other types of speleothem investigations on a firm base of measured time. U-series methods may be extended back to 350,000-400,000 y B.P. Use of paleomagnetic signals permits less precise estimation back to 720,000 y (Latham *et al.,* 1979), while statistical averaging of regional U data sets gives gross age estimates in the range, 500,000-1,600,000 y B.P. (RUBE-dating; Ford, in Gascoyne *et al.,* 1983a). Thermoluminescence and electron spin resonance decay dating methods ("TL" and "ESR" - Ikeya, 1978; Wintle, 1978) are also being intensively investigated. For calcite there appear to be very serious limitations with both these methods; readers are advised to treat TL and ESR "dates" with the greatest caution at the present time, unless they are confirmed by independent U-series measurements.

The McMaster University laboratory team directed by Henry Schwarcz and me has been the effective pioneer of U-series dates of speleothems, and has obtained reproducible results many times with a wide variety of speleothems from all kinds of cave environments. There are now more than 20 other U-counting laboratories partly or wholly dedicated to speleothem dating. For example, early results of a Belgian group are presented in this colloquium.

U-dating has placed karst studies at the forefront of time-controlled geomorphological research. Some examples of its dynamic applications are summarised below.

ii) Crude denudation rates

An ordinary (aerobic) stalagmite or flowstone cannot begin growing in a phreatic passage until this has drained. In a vadose stream trench, speleothems will not normally begin to form until the low water surface of the stream has fallen at least a few cm below their elevation as a consequence of entrenchment. These observations are used by Ford (1973), Ford *et al.*, (1981), Gascoyne *et al.*, (1983a) to obtain some mean maximum entrenchment rates. From them, approximate ages for features as great as mountains and valleys can be estimated.

Some recent examples are quoted in Table 1, which is compiled from a mixture of published and unpublished McMaster results. Many readers will find the cave channel entrenchment rates surprisingly low. In some cases, they are much less than the mean **areal** denudation rates for their region as calculated from average solution data by Corbel's equation or its later variants ! Much of the explanation is implied in the examples from West Virginia (Worthington, 1984) and Belize (Miller, 1982). In each of these cases there has been no entrenchment at all for long spans of time, although flowing streams were always present in the passages. Here we see a part of the answer to the question posed by White and quoted earlier in this review. For long spans of time karst denudation may be arrested at particular sites. This appears to apply even in tropical humid regions where climates are more likely to be stable over long spans of time, as in the case of the Maya Mountains in Belize (Table 1A).

The glacial valley rates (Table 1B) encompass all processes of entrenchment (e.g. glacial scour, river channel abrasion), not merely carbonate solution.

iii) Growth records and stable isotope profiles of speleothems

Crude denudation rate studies as illustrated above use only the dated start of calcite deposition. Once begun, the growth histories of stalagmites and flow-

Table 1.- Some mean entrenchment rates established by U-series dating of speleothems.

A.- Some mean maximum entrenchment rates in cave bedrock channels

Site	Deepening rate cm/1,000 years	Timespan of measurement
Yorkshire, U.K.	2.2	
	3.7	110,000 years
	< 3.2	
Mendip, U.K.	~ 2.0	12,000
Burren, Ireland	< 3.0	60,000
Vancouver Island, Canada	< 5.0	60,000
West Virginia, U.S.A.	0.0	> 1,600,000 !!
(an underfit, perched stream in a trunk passage).		
Kentucky, U.S.A.	< 2.0	120,000
Maya Mountains, Belize	0.0	~ 180,000
(stable-to-aggrading, sub-polje cave)		

B.- Some mean maximum deepening rates in Mountain glacial valleys

Ice cap drain, Yorks, U.K.	~ 5.0	~ 200,000
Ice cap drain, Rocky Mountains, Canada	< 11.0	~ 200,000
Troughhead Valley, Rocky Mountains	~ 7.0	~ 350,000
Crowsnest Pass (a glacial venturi), Rocky Mountains	< 11.0	> 730,000

stones may display wide variations of rate. These reflect changes of conditions at the soil base (induced by climate or other factors), other affects of climatic change, or change of flood frequency within the caves.

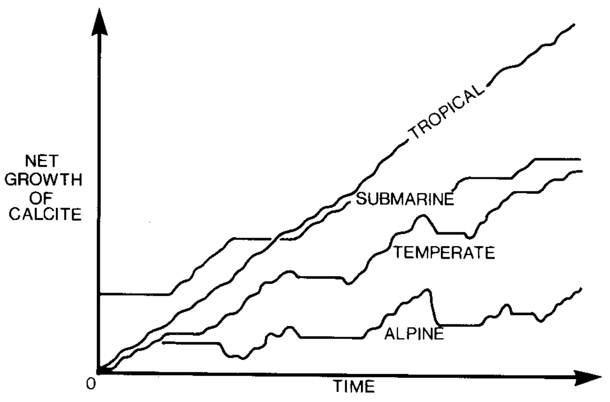

Figure 4
Some hypothetical growth curves for calcite stalagmites and flowstone. Adapted from Ford & Drake (1982) and based on many McMaster laboratory results.

Figure 4 (modified from Ford & Drake, 1982) explores these concepts. It compares hypothetical histories for alpine, temperate, tropical, and tropical submarine speleothems. We see a stalagmite in a tropical humid cave growing rather uniformly, though perhaps with dry season cessation (ultimately it should prove possible to resolve some speleothem records to their individual seasons). A temperate zone stalagmite, perhaps in Belgium, grows at a more varied rate for most of its history, and displays short periods of cessation with minor weathering or of re-solution (net erosion) where the water from the depositing drip source has become aggressive. We believe that this behaviour often reflects changes in the soil induced by the introduction of cool or periglacial conditions. The alpine stalagmite record is more emphatic; it grows only during interglacial or interstadial climatic peaks. The submarine stalagmite (e.g. Bermuda - Harmon *et al.,* 1978) is rather precisely out of phase with the alpine stalagmite; it grows only during the low sea level stands of glacial phases and is inundated during interglacials.

We are using such "start-stop" and "faster-slower" growth histories, controlled by several or many U-series dates per speleothem, to begin to reconstruct paleoclimates and soil dynamic sequences of karst areas. The scope for this work in all kinds of environments (arid and semi-arid as well as humid regions) is considerable. The principal publications up to the present are Harmon *et al.,* (1977) on the Rocky Mountains and Gascoyne *et al.,* (1983b) on the Yorkshire Dales of England, plus a general, less tightly controlled, data review by Hennig *et al.,* (1983).

There is potential for much more precise reconstruction of temperature histories by means of 0 isotope fractionations in calcite and H isotope fractionations in paleowaters (fluid inclusions) trapped within the growing speleothem. In ideal circumstances, a stalagmite will precisely record the change of mean annual temperature in a region, as this is reflected far inside a cave. The implications for karst dynamic reconstructions are obvious. 0 isotopes have been intensively investigated by Hendy & Wilson (1968), Thompson *et al.,* (1974), and Harmon *et al.,* (1978), fluid inclusions by Schwarcz *et al.,* (1976) and Yonge (1982).

The stable isotope work has proved to be more problematic than was supposed in the pioneer years, 1966 to 1976. It appears that there is much poorly understood kinetic fractionation of isotopes occurring. This blurs or simply overwhelms the climatic signal in many cases. However, in Figure 5 I am reproducing two different kinds of successful records from four different geographical areas. In 5a we see isotope ratios (and mean regional temperatures ?) swinging up and down abruptly over timespans of a few thousand years. In the Yorkshire example growth ceased entirely on two occasions which probably represent times of greatest cold. The Vancouver Island case (Figure 5b and Gascoyne *et al.,* 1980) takes advantage of particular fractionation effects occurring in extreme marine climatic situations to calculate some absolute annual temperatures. These fall rather steadily for 30,000 years until the freezing point is reached at the beginning of the last glacial stade and speleothem growth ceases.

iv) Paleo-ecological investigations

Our reconstructions of the dynamic history of solution in the soil zone will be complete if it is possible to determine the type and density of vegetation overlying a cave at a given time, and also to establish something of the nature and comparative efficiency of organic decomposition processes (CO_2-liberating processes) active within the soil. The pioneer work in both of these potential areas of investigation is currently in progress.

Dr. Bruno Bastin, Université de Louvain, has pioneered the extraction and identification of pollen grains from speleothems. Pollen does not survive in ordinary clastic sedimentary deposits in caves (it is destroyed by oxidation). Bastin (1978) has provided a source of pollen that is very well preserved, and also may be dated by U-series measurement of the enclosing calcite. Unfortunately, only a little pollen can be extracted from most speleothems, so that the large statistical samples used by palynologists to identify particular floral assemblages will be difficult to obtain. Nevertheless, dated speleothem pollen will supply much information concerning the past vegetation cover.

Traditionally, the presence of much colour in calcite speleothems (particularly, shades of yellow, brown and red) was attributed to the simple incorporation of traces of metal, particularly Fe and Mn. Gas-

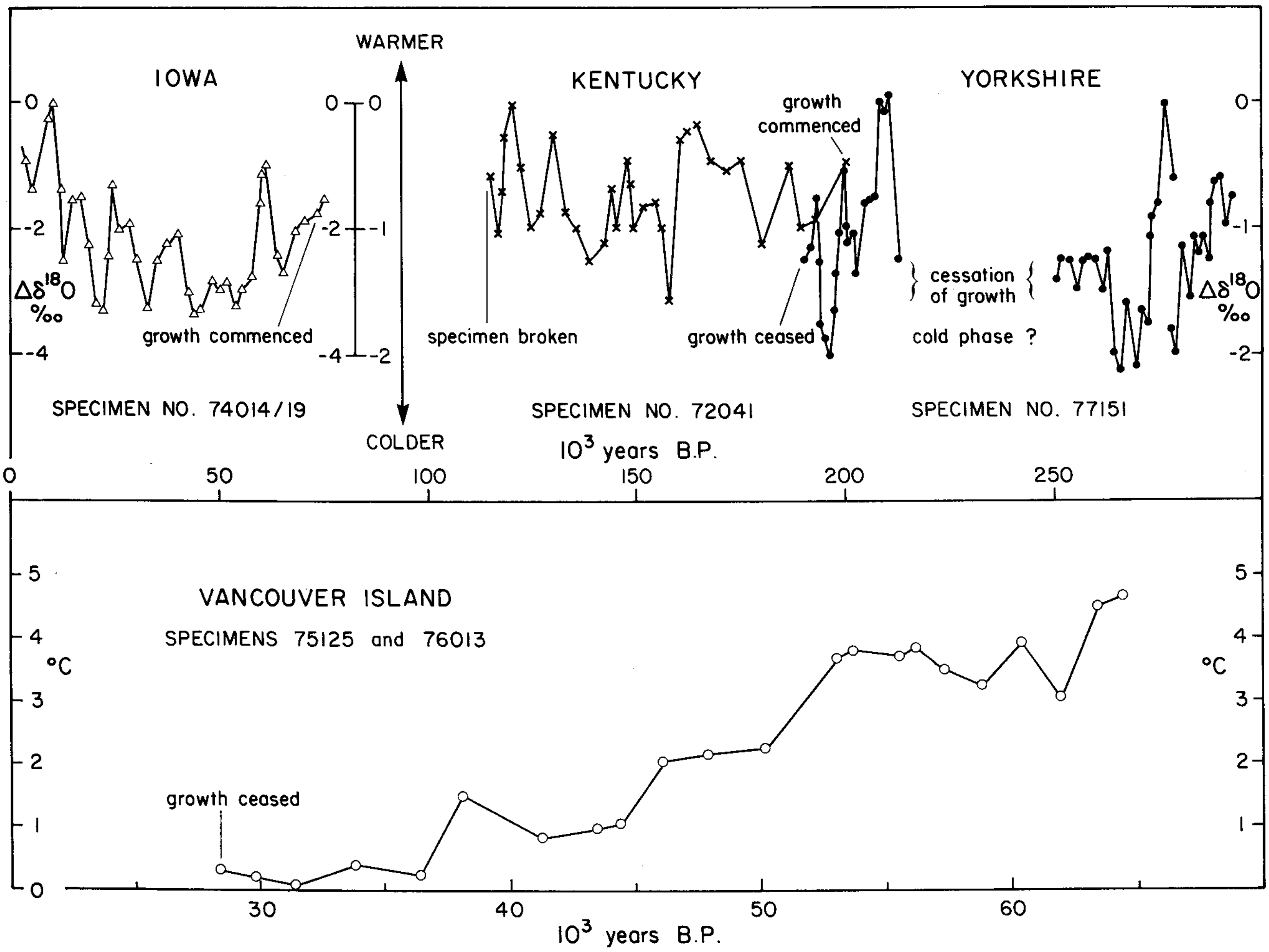

Figure 5.- (a) Examples of $\delta^{18}O$ isotope records from dated stalagmites collected in Iowa and Kentucky, U.S.A., and Yorkshire, England. Change of ^{18}O permil is normalised to zero at the peaks in the records (the inferred warmest positions) to facilitate comparison (from Harmon et al., *1978 and Gascoyne, 1980). (b) A $\delta^{18}O$ stalagmite record converted to the calculated change of mean annual air temperature during the period of growth, 64,000-28,000 years B.P., at a cave in Vancouver Island, (from Gascoyne* et al., *1980).*

coyne (1977) suggested that much of the colour was due to the presence of organic matter which was chelating the metals. This has been followed up at our Mc Master laboratories by Dr. M.J. Bakalowicz, (Laboratoire souterrain du C.N.R.S., France) and Dr. S.-E. Lauritzen, (University of Oslo), and independently by Dr. White at Pennsylvania State University. The work is in progress and not formally published. Suffice it to say that the presence of humic and fulvic acids has been confirmed in dark speleothems ranging in location from subarctic to tropical humid environments, and ranging in age from Holocene to > 720,000 years. It is hoped that further study (a) will complement pollen data to help verify the type of floral assemblage, and (b) will indicate the comparative magnitude of organic decomposition occurring in different soils.

v) Reconstructing flood frequencies

It has been argued elsewhere (Ford, 1980; Ford & Drake, 1982) that there is no dynamic threshold to the karst solution process, as there is for most other erosion processes. Because of this, the effects of extreme events such as rare but great floods, are more damped and less significant in karst than in almost any other geomorphic system. As a consequence, long-term averaged reconstructions as described above are more valid. Nevertheless, as students of caves we all appreciate that big floods can be significant at local scales in karst terrains. They can clog a passage, or clear it, in a matter of moments. Therefore, in addition to reconstructing solution dynamics in the soil zone it is useful to establish the magnitude and frequency of the rare but large flood events that may occur in an area.

Many speleothems are periodically innundated and preserve a thin coating of mud that becomes incorporated into the growing calcite when the flood has gone. They are potential recorders of flood frequency. There are difficulties. In many cases, floods are so frequent that the individual mud layers cannot be distinguished from one another. In such cases, too, the mud may supply abundant contaminant ^{230}Thorium which destroys the possibility of accurate U-series dating. However, Worthington (1984) has shown that in some cases, the flood recording in speleothems that are clean enough to date accurately can be very good.

His field site was the Friars Hole Cave System (~ 70 km of passages) in West Virginia. Low level passages are frequently flooded there today and nearly devoid of speleothems. High level passages have evidently not flooded at all within the U-series time range i.e. during the past 350,000 years. Stalagmites from some intermediate level passages show prominent flood layers between clean calcite and appear to be satisfactory recorders. The one record studied in detail displays approximately 40 floods between 11,500 and 7,000 years B.P. During the first 2,000 years of the record, recurrence intervals between consecutive floods were as low as ~ 20 years and there were six very big floods, each of which left the studied stalagmite partly buried in fresh mud. In the later part of the record, the recurrence interval extends out to 400 years and there are no very big floods.

It is clear that this line of investigation holds much promise for the student of karst dynamics and also for the general geomorphologist, engineer, etc. who is concerned to establish magnitude and frequency flood records for a region containing some karst and caves.

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