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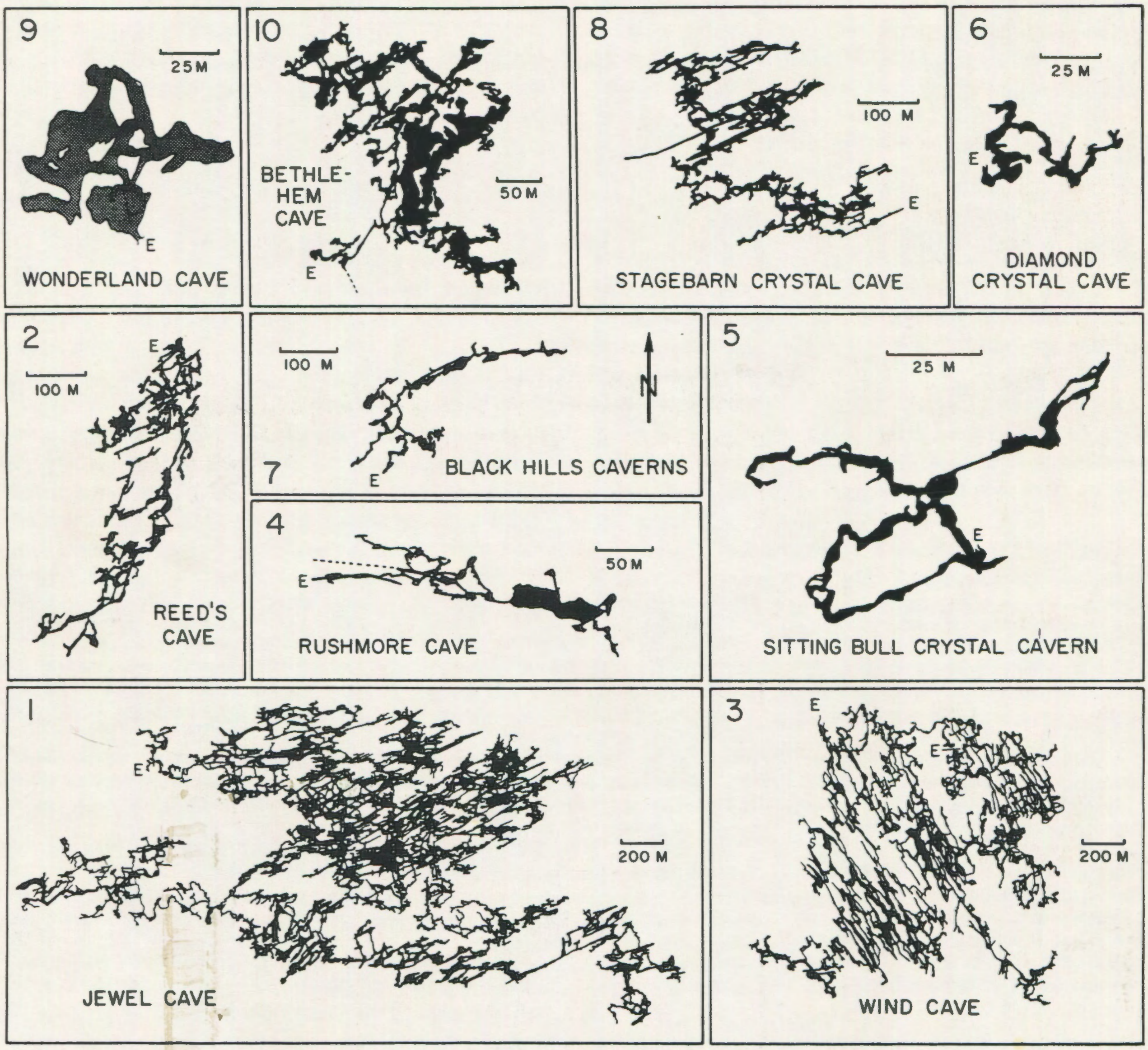

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Ford, Derek C.—Features of the Genesis of Jewel Cave and Wind Cave, Black Hills, South Dakota: *NSS Bulletin* **51**: **100-110**.

FEATURES OF THE GENESIS OF JEWEL CAVE AND WIND CAVE, BLACK HILLS, SOUTH DAKOTA

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Jewel Cave and Wind Cave, South Dakota, are here interpreted as multi-storey dissolutional mazes created during the present erosion cycle by deep phreatic waters that ascended through them. They formed where such groundwaters were focused to discharge through weaknesses in an overlying sandstone formation. The multi-storey structure is created by occurrence of different joint systems in adjacent beds or greater units, with inter-storey blocking layers such as thin clays often playing a role. In such structures, lower storeys tend to be more extensive; upper storeys may contain both outflow *and* adventitious *components. Mixing corrosion effects and migration of springs can complicate upper storeys. As such caves drain, condensation corrosion facets and pockets may be created.*

From U series dating and magnetic studies of normal speleothems and of subaqueous calcite encrustations, Jewel Cave drained more than 350,000 years ago. Its characteristic subaqueous spar sheets are certainly older than 1,250,000 years and probably greater than 2,500,000 years in age. Wind Cave has drained within the past 500,000 years or so. The mean rate of fall of the watertable in it is ~ 0.375 m per thousand years but the actual rate of fall has varied probably in response to Quaternary climatic fluctuations. Studies of stable isotope ratios indicate that the subaqueous deposits were precipitated from waters warmed to a probable range, 15–50°C. It is most likely that such waters were responsible for excavating the bulk of the caves as well, although there are older paleokarst remnants locally; thus, genesis of the caves is to be attributed to the type and scale of thermal water systems that feed the present hot springs in the Black Hills. Combinations of several different factors may account for the differing form, thickness and depth of deposition of the subaqueous calcites, including regulation of the rate of de-gassing by presence of caprocks.

INTRODUCTION

Jewel Cave and Wind Cave are complex cave systems that are of great interest to physical speleologists. This paper discusses four different but associated aspects of their complexity. Where it is relevant they are compared to maze caves in other regions. Readers who are not familiar with the Black Hills caves and their geology should first read the general reviews that A. N. and M. V. Palmer have prepared for this Symposium.

My knowledge of Jewel Cave is confined to the tourist paths plus short excursions from them. At Wind Cave I have also had several trips down to the Lakes. However, since 1982 my research group at McMaster University has been foremost in the isotopic analysis of samples of the characteristic cave calcites and the wall rock; therefore, conclusions and speculations derived from those analyses will be emphasized. Most samples were of small, naturally broken and fallen, speleothems whose precise site of origin could be established. At Jewel Cave there were also two samples of broken calcite spar that had been pushed aside as rubble during construction of the tourist path. Their sites of origin are uncertain but most probably lay within a few metres of the points where they were picked up.

MORPHOGENESIS OF THE CAVES

The first aspect is the gross morphology of these two systems of caves. They belong to a class that may be termed "lifting mazes." In it the formative waters flow upwards from a lower joint system into an upper and different system that immediately overlies it. There may be several more of such superimposed systems; each of them constitutes one 'storey' in a multi-storey cave.[1] Typically, the joint systems in successive storeys display different frequencies or orientations, with the result that usually they can be differentiated on a map. Another general characteristic is that the passages following one particular joint set (orientation) in a given storey tend to be roughly equal in their cross-sectional area. This demands that the formative waters be phreatic and flowing in an unusually uniform pressure field for karst rocks, as W. M. Davis recognized long ago (Davis, 1930).

The most extensive examples of such lifting maze caves are Jewel and Wind, and the mazes of the Podolia and Bukovina districts of the Ukraine. The latter include Optimists' Cave (165 kms as at December 1988), Ozernaya (105 kms), Zolushka (82 kms), and many lesser examples such as Atlantida Cave (Fig. 1). They are developed in just 12 to 18 metres of gypsum that rests upon a limestone and sand

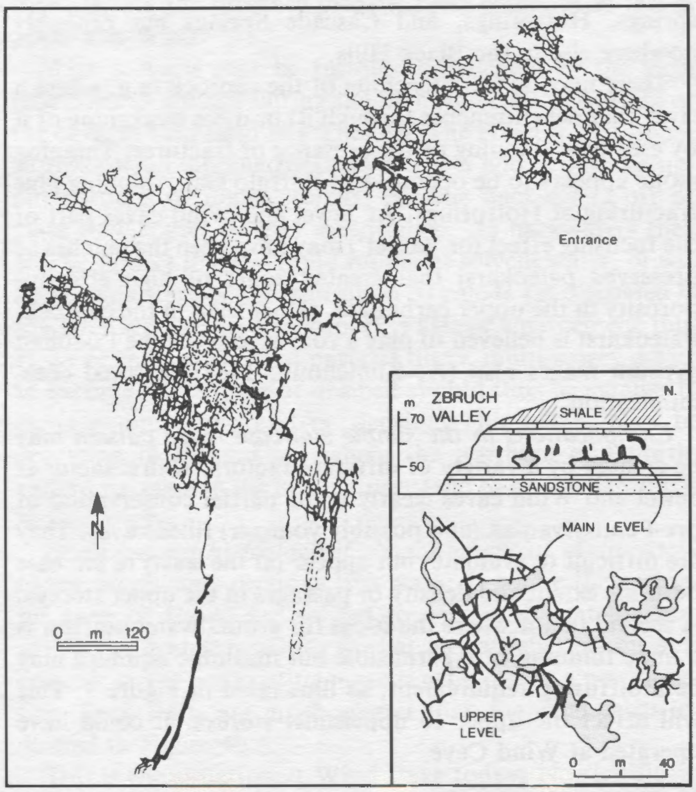

Figure 1. **Two examples of lifting mazes from the gypsum karst of the Ukraine, U.S.S.R. Optimists' Cave (principal illustration) now possesses 167 km of surveyed passages beneath an area less than one square km in extent. Atlantida Cave (inset) is a simpler example, with a large lower storey (or main level) and a fragmentary upper storey. (Adapted from Klimchouk and Andreichouk, 1986).**

aquifer and is capped (principally) by an impervious marine clay. They were created by shallow meteoric waters ascending from the sand stratum to spring lines that developed where rivers entrenched the clay (Klimchouk and Andreichouk, 1986).

Many shorter examples of lifting mazes occur at Budapest, Hungary. These are developed in clayey limestones capped by largely impervious marls and were created by deep thermal waters that ascended through them to springs along the Danube. There were possible mixing corrosion effects also. These caves have been intensively studied by Hungarian colleagues (cf. Muller and Sarvary, 1977). A final group of examples I have visited are the caves of McKittrick Hill, N.M. (Kunath, 1978). These are in well-bedded backreef limestones that are capped by a calcareous sandstone and were created by ascending meteoric waters or mixing waters with an H_2S component from the Pecos sedimentary basin (Hill, 1987).

From these examples a first conclusion we may draw is that the fundamental erosional morphology of lifting mazes

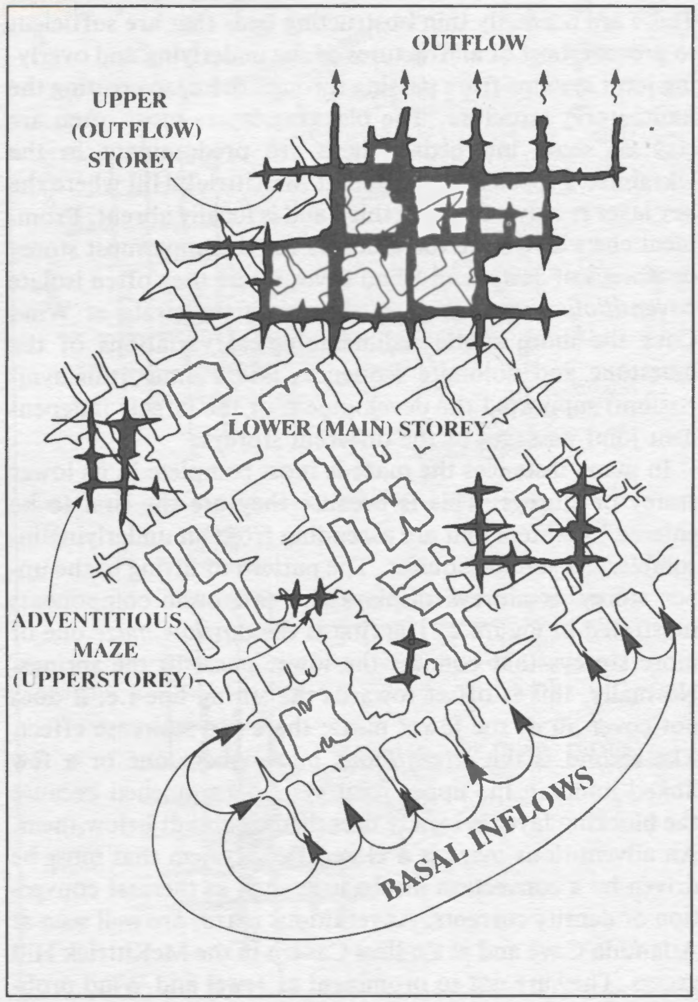

Figure 2. **The characteristic form and location of** ***outflow mazes*** **and** ***adventitious mazes*** **in upper cave storeys that are fed by water lifting from one or more lower storeys.**

can be created by a variety of groundwaters circulating through a variety of rocks in many different tectonic, geomorphic and climatic settings. What, then, are the significant features that they have in common? There appear to me to be three that are the most important:

1. *Occurrence of an underlying water source.* In most cases this is probably deeply circulating regional recharge in fracture aquifers (e.g. at Budapest; Muller, 1989). For Jewel and Wind caves the recharge area is the granitic and metamorphic core of the Black Hills, plus some of the exposed limestone. Volumes of flow generated per square km are usually small in such cases, with the consequences that discharge via the maze caves will be small and velocities in them will be low. In the Ukraine the recharge is a matter of more local, inter-valley flow between river channels at differing elevations (Klimchouk and Andreichouk, 1986).

2. *Presence of one or more inter-storey blocking layers.*

These are normally thin obstructing beds that are sufficient to prevent most or all fractures of the underlying and overlying joint systems from passing through them, so creating the multi-storey structure. The blocking layers most often are clay or shale interbeds. These are predominant in the Ukrainian gypsum mazes, and at McKittrick Hill where the key layer is only a few cms thick and is locally absent. Prominent chert layers are the blockers for the uppermost storey or storeys of Jewel and Wind caves where they often isolate *adventitious mazes* (Fig. 2). Lower in the strata at Wind Cave the more subtle sedimentological variations of the limestone and dolomite sequences (see Palmer, this symposium) supported the development of the largely independent joint passages of the different storeys.

In many instances the maze is most complete in its lower storey or storeys. This is because they are the first to be entered by waters that are ascending from an underlying insoluble/less soluble aquifer. The pattern of lifting to the upper storey or storeys displays the two basic components illustrated in Figure 2. The first is the *outflow maze,* one or more storeys that connect the lower maze to the springs. Normally, this is offset towards the spring line i.e. it does not cover all of the lower maze; there is a staircase effect. The second is the *adventitious maze* where one or a few linked joints in the upper joint system are opened because the blocking layer is locally breached or absent below them. An adventitious maze is a closed flow system that must be driven by a convection mechanism such as thermal convection or density currents. Adventitious mazes are well seen at Atlantida Cave and at Endless Cavern in the McKittrick Hill group. They are not so prominent at Jewel and Wind probably because the joints in the successive storeys are closely aligned and because mixing corrosion effects have extended the upper storeys there (see below). However, simple examples displaying cupola-form pocketing develop above the chert band at the Fairgrounds (Wind Cave) and elsewhere.

3. *Presence of a caprock* is also essential. The caprock is either insoluble or significantly less soluble than the maze cave rock and it functions either as an aquitard (less pervious) or an aquiclude (impervious). It is a barrier to the discharge of the artesian water. It has a much greater areal extent than the maze caves that develop beneath it. Where it is offset by faulting or attacked by subaerial erosion processes, etc. breaches or zones of lesser weakness will inevitably be created in it. The deep groundwaters are focused to discharge via those zones and they create the maze caves toward and beneath them. This is to assert that lifting maze caves are not present everywhere in the Pahasapa Limestone of the Black Hills but only where sufficient ascending flow could be concentrated. Such focusing of flow is quantitatively essential to create them, given that the rate of recharge to the deep aquifers is very low. Thus in my opinion modern lifting mazes are being created beneath the Buffalo Gap springs, Hotsprings, and Cascade Springs but probably nowhere else in the Black Hills.

There may be full breaching of the caprock (e.g. where a river channel entrenches through it) or mere weakening of it by erosional thinning or the presence of fractures. Thinning alone appears to be operative at Buffalo Gap, thinning plus fracturing at Hotsprings. At Jewel and Wind caves part of the focusing effect (or 'target') may have been the patches of preserved paleokarst that created zones of high effective porosity in the upper carbonate, rather than in the caprock. Paleokarst is believed to play a role in some of the Podolian gypsum mazes also (A. Klimchouk, 1987; personal communication.

Complications in the simple staircase maze pattern may be created by a variety of different factors. A first factor at Jewel and Wind caves clearly is the partial conservation of pre-Pennsylvanian (and possibly younger) filled caves. They are difficult to evaluate[2] but appear (at the least) to increase both the extent and density of passages in the upper storeys. A second factor where the focus for groundwater outflow is a mere thinning of a permeable but insoluble aquitard may be a diffusing requirement, as illustrated in Figure 3. This will affect the upper to uppermost storeys. It could have operated at Wind Cave.

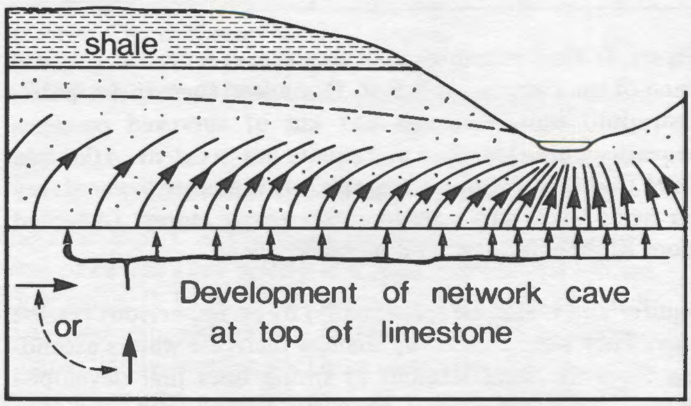

Figure 3. **Water flowing upwards in dissolutional conduits in limestones is compelled to diffuse in order to discharge through a sandstone cover. An upper storey maze at the top of the limestone marks the start of the diffusing process.**

Mixing corrosion is a third factor that is probably much more widely important in carbonate rock mazes. It is especially powerful where deep, warmed waters enriched in exhalative CO_2 and/or H_2S from reducing processes encounter cool meteoric waters with dissolved O_2. Figure 4a suggests that at Jewel and Wind there was potential for meteoric water supply both down dip and along strike to mix with the ascending waters. Mixing corrosion normally should be most effective in upper to uppermost storeys because meteoric waters will not circulate far below the caprock, but the presence of paleokarst complicates this at Jewel and Wind.

Maze patterns may be further complicated by the local migration of springs during the hydrologically active life of the cave, as suggested in Figure 4b. The effect is that upper storeys (or, in dipping rocks as at Jewel and Wind, the up-dip portions of upper storeys) become backwaters off of main flow routes or they are drained. As backwaters they will be subject to a less rapid supply of solvent water, or will switch to a state of net deposition of calcite (as discussed in the later sections of this paper). Passage enlargement thus slows or ceases. The first parts of tilted, multi-storey mazes to become backwaters or drained should thus be smaller in passage dimensons and/or density. This effect may be operating in Wind Cave where the northern and north-eastern passages in the upper storey tend to be smaller; dip is southeasterly.

Drainage and hydrological abandonment of multi-storey lifting mazes may occur in two ways: 1) where the springs (or zone of focus) are shifted to a new, distant location within the host formation, so that an entirely new maze is created, or the pre-existing maze is extended in a new direction. Such shifts are much greater than the local shifts indicated in Figure 4b.

This is the situation at Wind Cave today. No significant eroding waters flow in it but the lowest storey dips below a regional water table to become phreatic. It is an up-dip backwater. The springs probably shifted to Buffalo Gap, 8 km distant, but the pioneer dye tracing work that Professor Calvin Alexander is undertaking hints that the shift could have been to Hotsprings, 12 km away (C. Alexander, personal communication, 1988). 2) where the base level of erosion is lowered below the rock formation hosting the cave; in most instances, this means that the river creating the spring line valley has entrenched its channel below the formation. That is the case for a majority of the Podolian mazes. Jewel Cave appears to be essentially in this situation also. We cannot be sure because exploration has not yet attained the base of the host formation there. However, any basal standing water that is encountered in the future seems likely to be of local meteoric origin and perched, rather than backwater on a regional water table as at Wind Cave. In the past, however, Jewel Cave appears to have been a backwater for a very protracted period, as evidence cited in the next section suggests.

A note on condensation corrosion. This is a cave-enlarging process insufficiently appreciated by English-speaking speleologists of my generation, perhaps because most of us trained in cool, humid meteoric water caves where it is not of much significance. Carol Hill has stressed it recently from her work in the warm, arid Guadalupe caves (Hill, 1987) but most work comes from Hungarian and Soviet speleologists working in thermal water caves or those

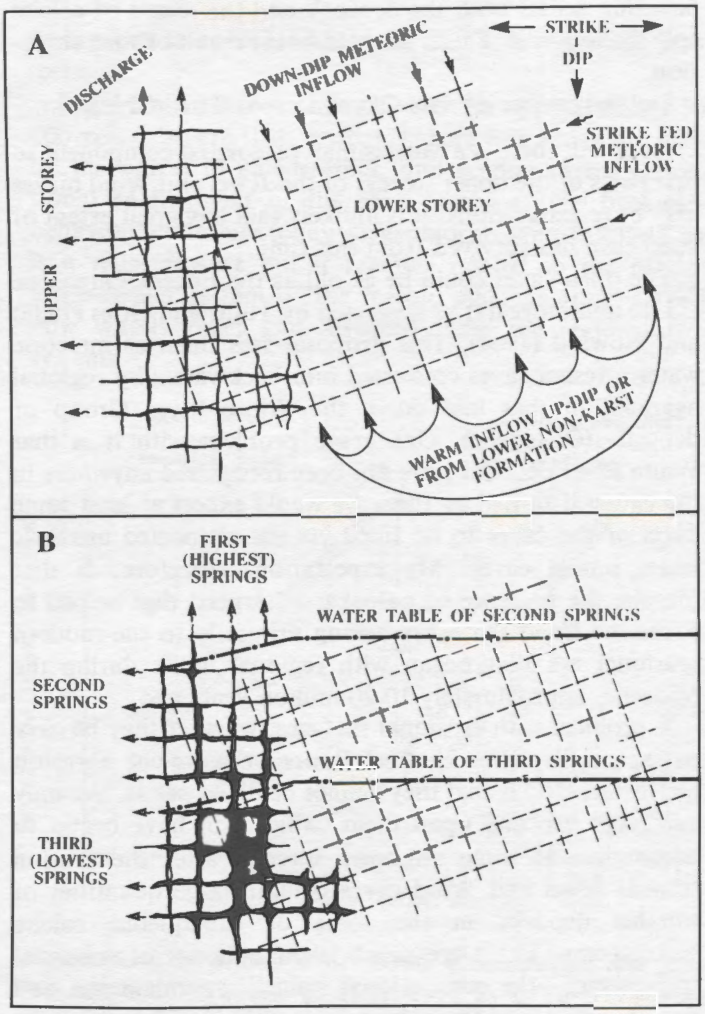

Figure 4. A. **An illustration of the potential for mixing corrosion to occur in geological situations such as those at Jewel and Wind caves. Mixing corrosion will preferentially create or enlarge upper storeys in a multi-storey maze.** ***B.*** **Illustrating the effect that local shifts of springs may have upon the enlargement of conduits in upper storeys.**

of the semi-arid Asian regions of the U.S.S.R. Of particular importance is theoretical modelling by Szunyogh (1984) who suggests that highly rounded (cupola-form) ceiling solution pockets in thermal caves are created by this process. Condensation corrosion would appear to be most potent where hot, CO_2-surcharged waters degas into confined caves. The saturated air is quickly condensed onto cooler upper walls.

Wind Cave displays cupola-form pockets above the chert layer at the Fairgrounds and elsewhere. These may be adventitious phreatic maze components, as suggested above, but they warrant consideration as features of condensation corrosion. More convincingly, around the Loft and other uppermost parts of Jewel Cave there is smooth dissolutional bevelling across both the bedrock and the sheets of calcite spar that cover it. This is likely to be the result of such corrosion.

THE ANTIQUITY OF THE CAVES AND OF THEIR DRAINING

As noted, there is a Mississipian paleokarst component so that parts of the upper storeys of the Jewel and Wind mazes may be re-excavations. It is unlikely that any great extent of open cave has survived from this time.

The open caves could be as old as the Eocene-Oligocene (35-40 million years) as suggested by Tullis and Gries (1938) and Howard (1964). This proposal sees them as meteoric water artesian caves converted into backwaters by regional aggradation that laid down the White River Group of deposits (Oligocene). One grave problem with it is that White River deposits have not been recognised anywhere in the caves; if buried by them we would expect at least some parts of the caves to be filled via the purported meteoric water intake caves. My expectation, therefore, is that (despite the presence of paleokarst 'targets' that helped to focus the flow) the caves belong primarily to the modern erosional era that began with regional uplift during the Miocene, approximately 10-20 million years ago.

A problem with erosional surfaces (whether they be cave passage walls, river channel floors or wave-cut abrasion platforms, etc.) is that they cannot be dated *per se*. We may date only deposits upon them, which will have begun to accumulate at some unknown interval after the erosion ceased. Jewel and Wind caves contain large quantities of suitable deposits in the form of subaqueous calcite speleothems. There are much lesser volumes of subaerial speleothems—the conventional stalactites, stalagmites and flowstones. All of these deposits may be dated by U series methods (Harmon and others, 1975; Ivanovich and Harmon, 1982) if they contain a sufficient concentration of trace uranium and are not highly contaminated by detrital clay.

Jewel Cave

Sample JC11 is a fragment from a large stalactite curtain that had fallen and shattered in a grotto in the lowest part of the tourist cave. Isotopic details of it and of other samples representative of those discussed here are given in Bakalowicz and others (1987). ^{230}Th:^{234}U dating reveals that its outer part grew around 100 000 years ago (100 ka). The inner part is older than 350 ka (the dating limit of the standard method), but not much older. This is from one of the largest subaerial speleothems seen in the tourist cave, which suggests the broad generalization that most conventional speleothem deposits in Jewel Cave may be younger than 500 ka. More certainly, JC11 indicates that the tourist cave has been drained and relict for at least 350 ka.

More significant are the sheets of subaqueous calcite spar that cover most of the walls. Their thickness is generally between 6 and 15 cm. I have studied eight samples taken from the highest to lowest occurrences close to the tourist path. All are similar, displaying euhedral form and very regular layering. They contain between 0.2 and 0.5 ppm (parts per million) of uranium, which is significantly less than in any other Jewel and Wind deposits. For example, stalactite JC11 has 1.7-7.5 ppm U which its meteoric feedwaters scavenged from the overlying paleokarst fill or Minnelusa sandstone. The waters that deposited the calcite spar cannot have followed that overhead route to their depositing site. This is the first of many separate geochemical and isotopic evidences tending to show that the spar waters are from deeper sources.

All spars are greater than 350 ka in age i.e. ^{230}Th:^{234}U = 1.00. In fact, within measuring error the ratio, ^{234}U:^{238}U, also equals 1.00. For technical reasons that cannot be discussed here (see Ivanovich and Harmon, 1982, page 68) an excess of ^{234}U atoms is normally precipitated (trapped) in cave calcite. Any excess at Jewel has decayed away. This suggests that the spars are older than 1 250 000-1 500 000 years (1.25-1.5 ma).

Spar samples from the lowest part of the tourist cave are particularly interesting because they display a systematic depletion in ^{234}U. The ratio, ^{234}U:^{238}U, is slightly less than 1.00 at their base (oldest part) and becomes lower towards the top (youngest part). This is significant for two reasons:

1) it suggests a principal source aquifer that was largely insoluble so that ^{234}U (the more readily erodible isotope of the ^{234}U,^{238}U pair) became depleted in the walls that enclosed its flow paths i.e. flow had been very long sustained before any deposition of the spar began. As shown by the U concentrations and by stable isotope evidence for the spars given in the next section, this source aquifer was most probably beneath the limestone and it supplied warm water.

2) a 'daughter deficient' dating technique can be applied to the spars (Ivanovich & Harmon, 1982, p. 61). This does not give their absolute age but does suggest the time that elapsed between deposition of the basal spar (least deficient) and that at the top. The calculated growth period for a sample 6 cm in thickness is approximately one million years i.e. a mean deposition rate of 0.06 mm per 1000 years. As noted, the texture of the spars suggests that they accumulated steadily rather than in an episodic manner, so that this mean rate is a significant one. It is very low indeed when compared to meteoric water speleothem deposition rates (Hill and Forti, 1986); it helps build a picture of very slow deposition from waters rising from an ancient aquifer. This is extended into a general model in the last section of the paper.

One of the daughter deficient spar samples from a low elevation in the cave was tested for its magnetic signal by Dr. A. G. Latham, the pioneer of magnetic studies of speleothems (Latham, 1981). The entire sample is magnetised normally (i.e. positive North). From the ^{234}U:^{238}U studies it is known that it is older than 1.25 ma and that it took ~1.0 million years to accumulate. The youngest available 'normal' magnetic interval of sufficient duration is the "Gauss," which extended from 2.5 to 3.4 ma BP. It is therefore concluded that the principal wall deposits in Jewel Cave most probably accumulated at some time before 2.5 ma BP.

Wind Cave

Wind Cave is 400 m lower in elevation than Jewel Cave, much closer to the major regional springs, and its lowest known parts are occupied by static backwaters today. It is expected to be significantly younger than Jewel Cave and this will be shown to be the case. Its quantities of precipitates are much smaller but have proven to be most useful for paleodrainage reconstruction.

Those parts of the cave that are highest in elevation are without calcite deposits except occasional stalactites from meteoric waters. As we descend downdip to upper storey areas such as the Fairgrounds (~1220 m above sea level) small nodular and sheet encrustations appear. Most of them are of subaqueous origin although there is some redeposition as evaporites. The abundance and thickness of subaqueous sheets increases markedly on the descent to the Lakes (lowest storey, 1120 m above sea level) perhaps being thickest in the area between Base Camp 1 and the L.A. Freeway. Locally the greatest thickness appears to accumulate on protrusions into the centres of passages where the rate of paleoflow will have been greatest; they are up to 4 cm thick (N.B. the same feature is seen in some of the Budapest thermal water caves). From isotopic analysis of two shards, the famous heligmite bushes such as "the Emperor Maximus" are also subaqueous growths. From Boxwork Chimney (1180 m) downwards there are accretions of calcite raft debris marking paleowaterlines. They continue to accumulate on the water table (Calcite Lake) today.

I have made more than 90 ^{230}Th:^{234}U determinations on 57 samples of crust and raft debris collected between the Fairgrounds and the modern water line. Their detailed analysis and the hydrological implications are being presented in a separate paper (Ford, Palmer, and Palmer *in litt.*). The principal conclusions are summarised in Figure 5.

The main point is that the lower 100 m of Wind Cave (i.e. the majority of its known passages) has drained within the past 300 000 years or so. From the highest dated deposits we may track this process of water table fall extending back beyond 500 ka BP—at that time most or all of the cave will have been water filled. The mean rate of fall has been ~0.375 m per 1000 years. This cannot be attributed to progressive lowering of the spring elevation—it is too rapid for that and the magnitude of the lowering is too great. Rather, most of the lowering must be attributed to increasing permeability in the Minnelusa sandstone that the groundwaters must ascend through to gain the modern spring points (whether these be at Buffalo Gap or Hotsprings).

Wind Cave has been a backwater for approximately 500 000 years; before that, probably there was active discharge up through it to paleosprings, and accompanying dissolutional enlargement of the cave passages. The backwater behaviour continues today. In geomorphic terms Wind Cave is a relict feature but it remains related to the modern groundwater system of the region, whereas Jewel Cave is now wholly relict and divorced from the regional flow systems.

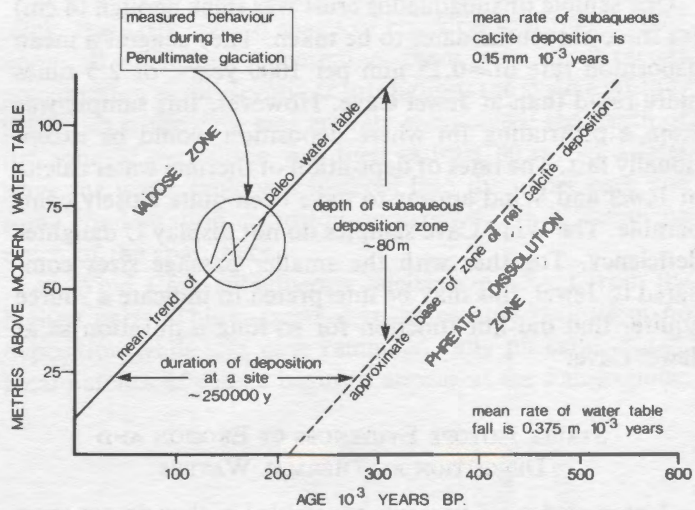

Figure 5. **The drainage of Wind Cave during the past 300,000–500,000 years, as determined by ^{230}Th:^{234}U dating of waterline and subaqueous calcite deposits.**

Figure 5 emphasizes several other features. The fall of the water table has not been steady. It has fallen about 10 m during the last 10 000 years (the Holocene period), a rate of ~1.0 m per 1000 years. At least half of this fall might be attributable to pumping of the aquifer; there is an important well 2 km distant. More significantly, dating of wall crusts, rafts and pool rims at the base of Boxwork Chimney show the water table falling, rising, then falling again through a range of 10 m at least once in the interval between (broadly) 180 and 130 ka BP. This is the upper part of the penultimate glaciation of North America (often termed the 'Illinoian Glaciation' in American literature although the type deposits in Illinois are not accurately dated). This water table fluctuation was probably a response to more arid and then more humid periods inside that cold phase. Or it could be a response to some non-systematic events such as a single catastrophic flood, though this seems less likely.

It may be supposed that detailed work would reveal more of these fluctuations during the measured decline of the water table. They will explain the deposition of subaqueous crusts following vadose events such as the fall of grus (pulverised dolomite) and other detritus in the boxwork zone.

From a strict interpretation of the dating results there was contemporaneous deposition of calcite from the water surface to a depth of 80 m beneath it; this is the "subaqueous calcite deposition zone." Below this depth no deposition was possible and, perhaps, late stage and/or incongruous dissolution of the rock was occurring. In my opinion, the value of 80 m is a maximum. The true depth of deposition is more likely 50-60 m, being extended to the apparent maximum depth of 80 m by unresolved fluctuations of the water table and error margins in the dating.

One sample of subaqueous crust was thick enough (4 cm) for three sequential dates to be taken. They suggest a mean deposition rate of ~0.15 mm per 1000 years, or 2.5 times more rapid than at Jewel Cave. However, this sample was from a protruding fin where deposition would be exceptionally fast. The rates of deposition of thermal water calcite in Jewel and Wind appear to have been quite closely comparable. The Wind Cave samples do not display U daughter deficiency. Together with the smaller passage sizes compared to Jewel, this may be interpreted to indicate a source aquifer that did not function for so long a duration as at Jewel Cave.

STABLE ISOTOPE EVIDENCES OF EROSION AND DEPOSITION BY THERMAL WATERS

Isotopes of most elements are stable i.e. they do not spontaneously emit nucleons from their nuclei. Stable isotopes of interest here are those of C and O that make up the CO_3 (carbonate) in the speleothems and the wall rocks of the caves. We compare the ratio of the rare isotope, ^{13}C, to the abundant isotope, ^{12}C, and similarly ^{18}O (rare) to ^{16}O (abundant). Different ratios in different samples may reflect the dominance of different processes, or the same process operating at different temperatures.

Bakalowicz and others (1987) have reported in some detail upon $^{13}C/^{12}C$ and $^{18}O/^{16}O$ relationships in Jewel and Wind caves. The subaqueous calcites display a distinctive thermal water isotopic signal when compared to the ordinary (meteoric water) stalactites and stalagmites. There are also alteration trends in the wall rocks.

These results are summarised in Figure 6. Normal marine limestones and dolomites (such as those containing Jewel and Wind caves) will plot within ± 5‰ of the origin of the figure. The "Hydrothermal Calcite Box" is drawn as a boundary to enclose all previously published values for North American calcites that were unquestionably deposited from thermal waters (e.g. from the gour terraces at Yellowstone National Park; Truesdell and Hulston, 1980). In comparison to the marine rocks, these calcites are somewhat depleted in ^{13}C and strongly depleted in ^{18}O.

The Jewel and Wind subaqueous calcites all plot within 'the Box.' The Wind Cave boxwork calcites are 'deepest' in it: from a temperature relationship proposed by O'Neil and others (1969) they were deposited from waters between 30° and 60° C. They include the oldest thermal deposits in Wind and (it is argued below) were deposited from waters still capable of dissolving dolomite. The calcite crusts and ices of lower Wind Cave are similar to the younger boxwork or a little less depleted in ^{18}O, a relation consistent with the supposition that they were deposited from progressively cooling, progressively falling, backwaters.

Isotope ratios of the Jewel Cave spar sheets form a tightly clustered group that plots on the trend between unaltered bedrocks and Wind Cave deposits. They are only just within 'the Box' and yield O'Neil temperatures between 15° and 35° C. This implies cooler waters from a longer groundwater flowpath, which fits very well with the picture of a long-lived, insoluble source aquifer that was obtained from the $^{234}U:^{238}U$ data on these same spars.

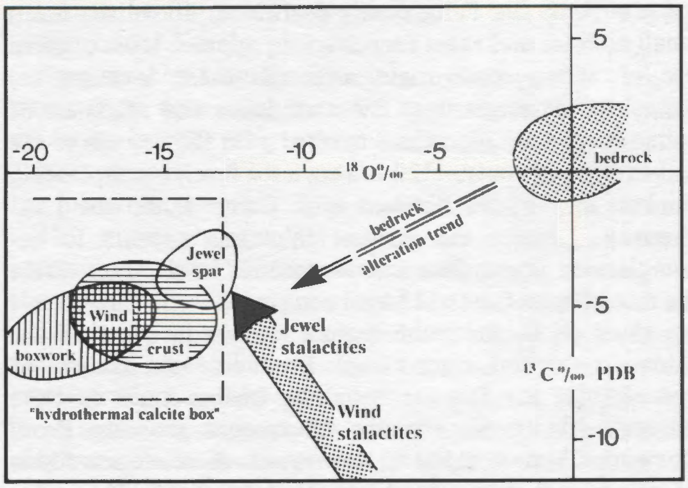

Figure 6. **Carbon and oxygen stable isotopic data for sample bedrocks, subaqueous calcite deposits and normal (vadose) speleothems from Jewel and Wind caves. Generalized from data reported in Bakalowicz and others, 1987. See the present text for discussion.**

We investigated rock samples from the walls of the caves and determined that their outermost few cm had been altered by isotopic exchange with the hot waters. There is a very clear trend (see Bakalowicz et al., 1987, Fig. 6). The Jewel Cave rock is the more deeply and extensively altered, in keeping with the longer duration of its exposure to the waters.

Conventional stalactites and stalagmites in Wind Cave plot around -10‰ ^{13}C and ^{18}O. This is well outside of 'the Box' and in equilibrium with the modern air temperatures in the cave. These are ordinary deposits from meteoric waters. However, Jewel Cave stalactites are notably enriched in ^{13}C

(-8 up to -5‰) and somewhat depleted in ^{18}O. This suggests that their meteoric source waters have exchanged isotopes with rock that is thermally altered to quite considerable depths along the microfissures that those source waters must flow through. Once again, this observation fits with the picture of longer exposure to thermal waters at Jewel Cave.

That the stable isotope results show that the subaqueous deposits were precipitated from thermal waters does not prove that the caves were largely or entirely excavated by such waters, but it is strongly suggestive of the point. Figure 7 emphasizes this. The boxwork is calcite encrustation (overgrowth) upon vein calcite in dolomitic beds that are densely fractured. It formed in thermal waters capable of dissolving dolomite (Mg ion), but only with concomitant deposition of Ca ion (= "incongruous dissolution of dolomite"). In the boxwork zone of Wind Cave it is common to find boxwork 30 cm deep in passages one metre wide (Fig. 7a); 60% of the width of such passages must have been excavated by the thermal waters and we may confidently suppose that 100% of it was. Such a direct relationship cannot be observed in wider passages because surviving boxwork is rarely deeper than 30–50 cm (Fig. 7b).

In summary, temperature and isotopic conditions essentially identical to those measured in the hot springs of the Black Hills today readily explain the subaqueous deposits. Some of these latter are probably greater than 2.5 million years in age, others are forming now. Ages of the deposits indicate that the caves were slow to drain, and probably slow to form also. Cave excavation thus is concordant also with the amounts of water being discharged at the thermal springs today. It does not appear necessary to postulate some precursor, radically different, hydrological system to explain their formation.

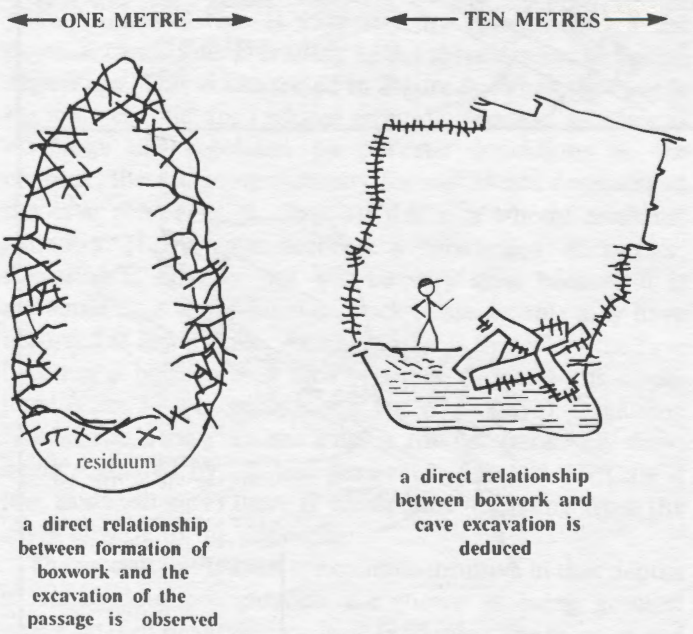

Figure 7. **Relationships between the deposition of boxwork and the dissolutional excavation of passages.**

INTERPRETING THE DEPTHS OF SUBAQUEOUS CALCITE DEPOSITION IN THERMAL WATER CAVES

The basis of this final topic is illustrated in Figure 8. This depicts the modes of subaqueous precipitation and the depths to which it extended at a given time, in the three groups of thermal water maze caves that I have had an opportunity to study.

At Jewel Cave the deposits consist almost exclusively of thick, regularly layered sheets of euhedral spar that formed upon all surfaces. Apparently, there was simultaneous precipitation at all elevations throughout the system. It thus began when the cave was entirely submerged; the depth of the zone of deposition was then at least 80 m. At a later stage the water table was lowered into the upper cave and some condensation corrosion occurred above it, removing much of the spar there.

At Wind Cave subaqueous calcites are absent from the highest parts. This suggests that there could be little or no deposition while this cave remained fully phreatic. Small, local patches of calcite begin to appear at the Fairgrounds,

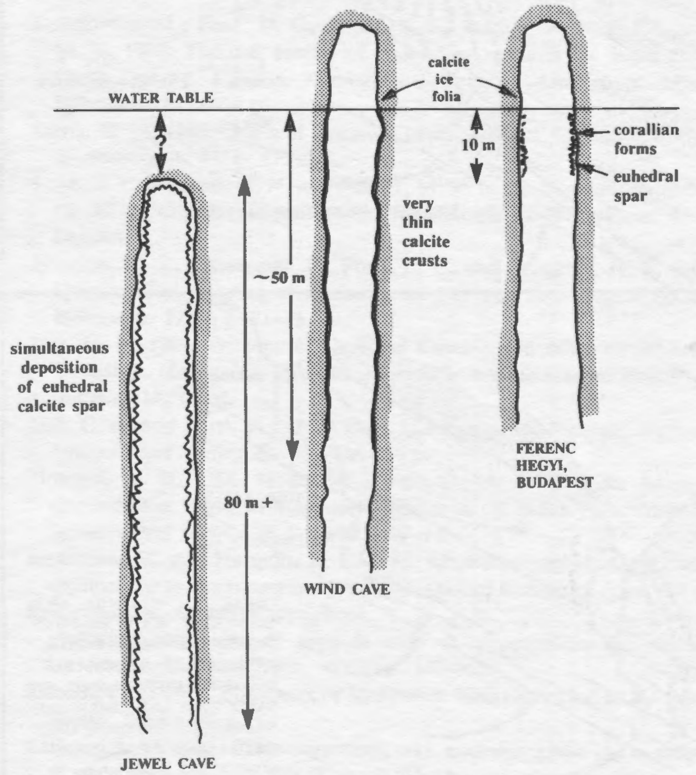

Figure 8. **Types of subaqueous deposits and the depths of their deposition at Jewel Cave, Wind Cave and a Budapest cave. The figure is simplified and schematic.**

and increase in thickness and extent below them. The calcites are always thin, and contain some interlaminations of red clay apparently reworked from the paleokarst fillings. In the lower half of the cave there are also calcite raft debris and shelfstone to mark the rest positions of a falling water table. The depth of the zone of deposition beneath any given water table elevation was 50–60 m or possibly less.

At Budapest exploration thus far has discovered only comparatively small fragments of maze caves scattered at different elevations in well dissected hills. With some exceptions, the subaqueous deposits are sparse, being notably smaller in volume than in middle and lower Wind Cave. They display strong vertical zonation. Deposits are thickest at the paleo water line, comprising shelfstone, folia and raft debris. Botryoidal coatings grow for a few metres below, then are succeeded by patches of euhedral spar 0.5–2.0 cm in thickness. There is no precipitation below approximately ten metres.

The intriguing problem is to establish why these differing modes and depths of deposition should occur. I have no pat answers. Below are some suggestions and speculations that may assist future work in these fascinating caves.

(1) *Solute concentrations and saturation state in the waters* may have differed substantially between the three sites. Potentially, such variation could explain all of the difference observed in the deposits. However, considered as the only category of variables, this requires that supersaturation be greatest at Jewel Cave (because deposition extended to the greatest depth there); that is not supported by the evidence for the *rate* of calcite deposition which tends to show that it was probably least at this cave.

(2) *Time available for deposition at a given site* is a second possible type of control. There are two different effects: *first*, is the longevity of a stable water fill (table) with hydrochemical conditions permitting deposition. At Jewel

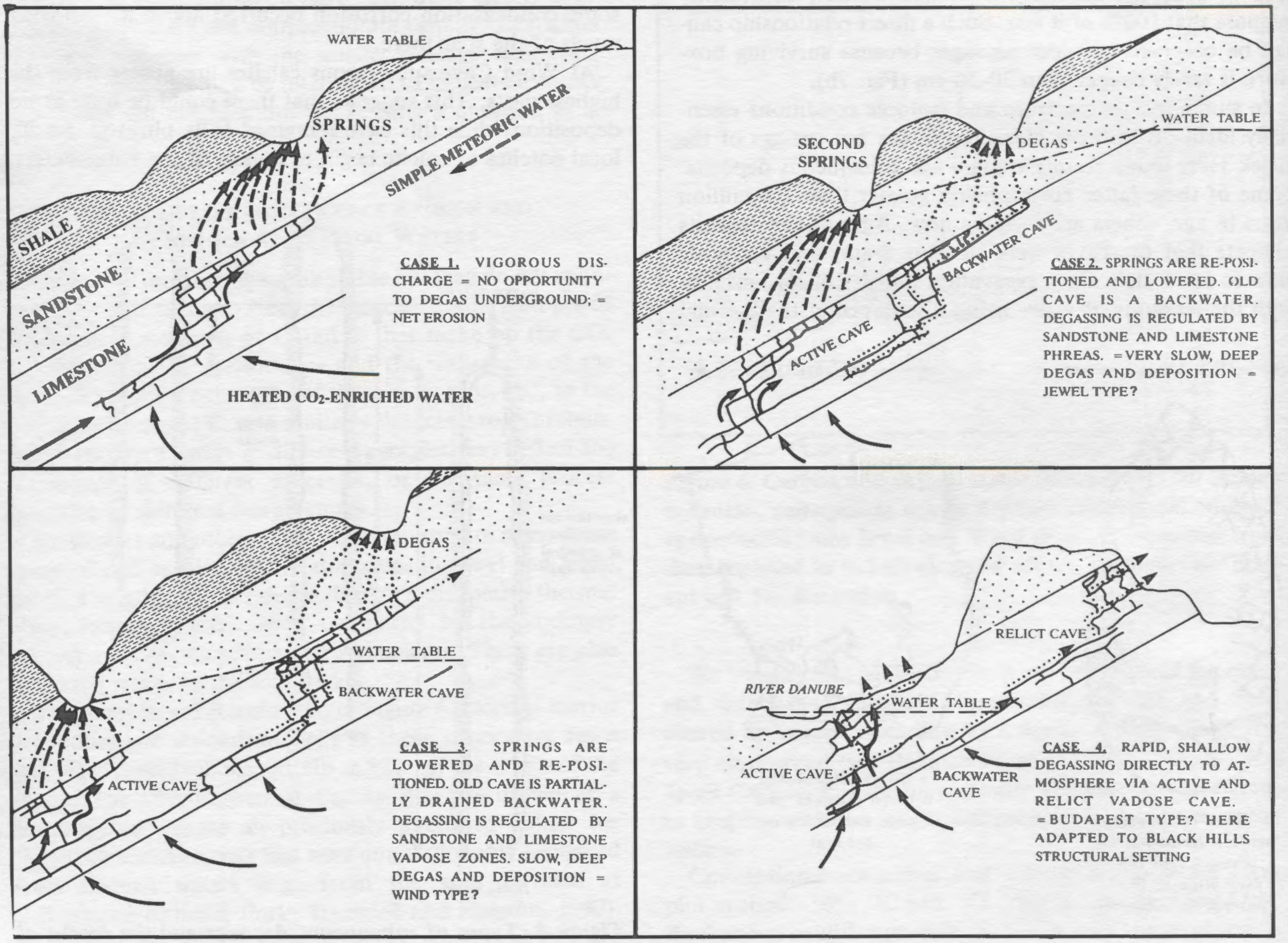

Figure 9. **Four hypothetical models to depict differing relationships between caprock regulation of groundwater flow, the degassing of deep phreatic groundwater, and consequent dissolution or deposition of calcite in the phreatic zone.**

Cave the ^{234}U:^{238}U evidence indicates that the entire system was a submerged and passive receptor of spar accumulation for a period not less than one million years. It was then at some unknown depth beneath the water table. At Wind Cave, extrapolation of the ^{230}Th:^{234}U dating evidence shows that the water table has descended rather steadily through the cave during the last one half million years. When that period began the entire cave probably was in a net eroding condition; i.e., it was still enlarging and thus no calcite crusts could accumulate. At Budapest the timespan available for subaqueous deposition at a given site was probably even shorter because this is a region of active tectonic uplift that also suffers much greater perturbations from Quaternary glaciation effects than do the Black Hills.

The *second effect* of time is the rate of exchange of phreatic water from which deposition may occur. If a given parcel of water is discharged at the springs before it has had the opportunity to degas there can be no subaqueous precipitation from it. One suspects that as a rule when a cave (even a maze) is functioning as the main discharge channel for thermal waters either there is no deposition or it is largely limited to the waterline. Divers report no deposits below one-two metres in the active outlets of the Budapest caves today. Deeper deposition can begin only where part or all of a system has become a backwater, as in modern Wind Cave.

Longevity of a given water table position and low rate of exchange of water can be mutually reinforcing effects. Jewel Cave may display the greatest and deepest deposits because it was an especially sluggish backwater for a particularly long span of time.

(3) *Caprock regulation of the rate of degassing* is a further possible control that is suggested by comparison of the physical conditions prevailing at the three cave sites during deposition. This is illustrated in Figure 9. When the cave is the main channel for regional groundwaters and all rates of discharge are regulated by phreatic conditions in the caprock, there is no opportunity for significant degassing in the cave zone (Fig. 9, Case 1): this is a wholly erosional situation. If the cave becomes a submerged backwater, degassing is possible but will be very slow because it is regulated by a water-filled caprock (Case 2); this may have occurred at Jewel Cave. An alternative is that when the cave becomes a backwater it also becomes vadose in its upper parts (Case 3—a possible model for Wind Cave). Degassing is more rapid than in Case 2 but is still comparatively slow, being regulated by the less permeable caprock. In Case 4 (the Budapest case) there is unimpeded degassing from the caves directly to the atmosphere.

The models in Figure 9 are counter-intuitive in that depths of subaqueous precipitation are shown as being greatest where rates of degassing are least (and, also, the thermal and pressure gradients). However, they do accord to what is understood of the differing hydrophysical environments of the caves at time of deposition. Other things being equal, rate of exchange of the water would also be least in a Case 2 situation, so that rate of exchange effects may be combining with caprock regulation to achieve the great depth of subaqueous deposition that apparently occurred at Jewel Cave.

CONCLUSIONS

Jewel Cave and Wind Cave may be interpreted as multistorey lifting mazes created during the present erosion cycle by waters ascending through them. Mixing corrosion involving lateral (dip- and strike-sourced) groundwaters may have played a role. The ascending groundwaters were heated, probably of the type and magnitude being discharged at Black Hills hot springs today. The subaqueous precipitates were deposited from these heated waters when the caves became backwaters as a consequence of shift of springs. Combinations of several different factors may account for the differing crystal habits, thicknesses and sub-water table depths of calcite precipitation.

The subaqueous precipitates in Jewel Cave are probably older than 2,500,000 years B.P. Wind Cave is much younger. Most of its deposits have formed, and it has drained to expose them, within the past 500,000 years.

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