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NATIONAL SPELEOLOGICAL SOCIETY

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Minimum Diameter Stalagmites

Rane L. Curl *

ABSTRACT

The theory of Franke setting forth the factors controlling equilibrium stalagmite diameter at high drip rates is extended to the low-flow situation in which a minimum diameter is obtained. It is shown that the minimum cross-sectional area for a stalagmite must be determined by the ratio of incident drop volume to the thickness of the water film at the apex. Reasonable values for these quantities predict a minimum diameter of about 3 cm, close to that observed. An approximate model, the primary feature of which is the repetitive transient relaxation of the tip-growth of a stalagmite between drop impacts, is used to bridge between the high and the low flow regimes. The importance of presently little-known factors involving drop impact, mixing, crystallization from solution, and film flow in determining equilibrium stalagmite morphology are brought out.

INTRODUCTION

In a previous paper (Curl, 1972) the question of the smallest possible stalactite diameter was discussed and its answer was shown to involve the forces of surface tension and gravity. It is apparent that the identical factors cannot be operable in the complementary speleothem, the stalagmite, if only because of the absence of the phenomenon of the pendant drop. In addition, the normal range of diameters of stalagmites never includes any below about an inch—considerably larger than the 5 mm or so diameter of soda-straw stalactites. What, then, determines the lower limit on the size of a stalagmite?

Interest in stalagmite size goes back many years and has revolved primarily around the possibility of using such information for dating cave deposits and artifacts. The early observations are mentioned by Allison (1923), who attempted an ambitious classification of stalagmites into 32 "types" according to the formative factors of drip rate, air circulation, relative humidity, temperature, and solution concentration. This was all based on the observation of five stalagmites deposited from water that had leached lime from concrete. Some of Allison's conclusions seem reasonable, but his complete theory has little physical or chemical basis and has not been fruitful. The smallest of his study stalagmites had a diameter of 3.5 cm. His smallest theoretical type would have a diameter of 5 millimeters, but this has not been observed in nature. Allison's most useful conclusion (actually, a hypothesis) was that *symmetry* (meaning *uniform diameter*) *in a stalagmite indicates constant growth conditions,* and that such stalagmites are growing vertically without an attendant increase in diameter (as shown in Figure 3).

Hendrix (1950), writing about caves for a general audience, attempted to present Allison's theory. He introduced the better term "equilibrium diameter" to describe the growth of stalagmites with a constant diameter. Through an obscure argument he concluded that

$$d = K\sqrt{\frac{q}{E}} \qquad (1)$$

where d is the equilibrium diameter, K a constant, q the flow rate ("drip rate") of depositing solution, and E the "evaporation rate". As will be seen, this is similar to the "modern" theory for one regime of stalagmite growth.

Figure 1 shows examples of near-equilibrium stalagmite growth. Because the diameters of several adjacent *nearly* constant diameter stalagmites do differ, the conclu-

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Figure 1. Nearly uniform stalagmites in Medvedia Cave, Czechoslovakia. Photo by Vojtech Benický.

Figure 2. Center-right; Stalagmite in Le Grotte Rouchambou, Belgium, the variation in diameter of which is reported in text.

sion seems inescapable that constant diameter implies constant (if different) growth conditions. This theme, and its consequences, has been most thoroughly developed by Franke (1961 *ff*), who derived his interest primarily from studies of paleo-chronology and climatology.

It should be noted that, although the stalagmites in Figure 1 are individually of moderately constant diameter, there is some variation. Figure 2 shows a 70 cm high stalagmite in Le Grotte Rouchambou (Belgium) the diameter of which varies as follows: base, 8.9 cm; 20 cm up, 7.0 cm; 30 cm, 4.9 cm; 40 cm, 6.4 cm; 50 cm, 5.8 cm; and at the top, 4.8 cm. This represents more than a two-fold variation in cross-sectional area, despite the relatively uniform appearance. Nevertheless, the concept of a uniform, equilibrium stalagmite is a useful abstraction.

Franke's Theory

Figure 3 (after Franke, 1965) shows successive stages in the growth of an equilibrium-diameter stalagmite.

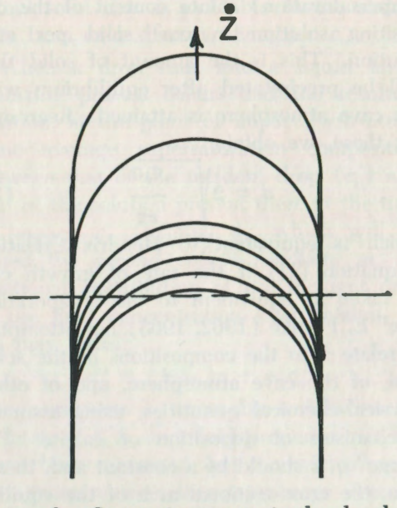

Figure 3. Successive stages in the development of an equilibrium stalagmite, shown in vertical section. The dotted line indicates a cross section that would show "growth rings" narrower near the outside. The equilibrium stalagmite grows upward at velocity $\dot{z}$.

As Franke has pointed out, cross sections show "growth" rings that are more closely spaced at greater distances from the axis simply because of the orientation of the developing "caps". Vertical sectioning of natural stalagmites has disclosed that there develop a succession of "caps" (often demarked by impurity layers) that taper to nothing as they descend down the side. This means, first, that all of the solute in drops falling on the stalagmite, in excess of saturation, can be deposited before the residual water runs off (or evaporates) and second, that the rate of *vertical* growth is the same at every radius from the axis of the stalagmite. (For this to be true, of course, the rate of crystal deposition must decrease as the slope of the surface becomes greater.) It then follows (Franke, 1962, 1963) that

$$\dot{z}A = \dot{z}\,\frac{\pi d^2}{4} = c_0 q \qquad (2)$$

where $\dot{z}$ is the rate of growth in height, A the cross-sectional area, and c_0 the available (supersaturation) solute content of the depositing solution in cm^3 solid per cm^3 solution. This is the amount of solid that will be precipitated after equilibrium with the cave atmosphere is attained. Rearranging these, we obtain

$$d = 2\sqrt{\frac{c_0 q}{\pi \dot{z}}} \qquad (3)$$

which is equivalent to Hendrix's relation (Equation [1]) if the rate of growth can be taken as equivalent to the "evaporation rate" *E*. Franke (1962, 1963) has attempted to relate $\dot{z}$ to the compositions of the solution, of the cave atmosphere, and of other physical-chemical quantities, using assumed mechanisms of deposition of calcite. For "large" q, $\dot{z}$ should be a constant and, therefore, the cross-sectional area of the equilibrium stalagmite should increase linearly with increasing flow.

What happens at low flows? Equation (3) says that d becomes zero when q goes to zero, all other things being constant. Since this is not observed in nature (there seems to exist a minimum diameter for equilibrium stalagmites) "other things" must not remain constant. In particular, $\dot{z}$ must become proportional to $c_0 q$ as q becomes small in order for a minimum diameter to exist. The reasons for this may now be developed to give a theory for *minimum diameter stalagmites.* As was the case with stalactites, an exploration of the limiting case should simplify the general "stalagmite" problem and thus help to clarify some of the factors at work.

Minimum Diameter

At the time that the data on the stalagmite shown in Figure 2 were obtained, the diameters of a number of others of small diameter (and usually of relatively small height, also) in the same cave were also measured. The values from a "random" sampling were 3.1, 3.7, 4.4, 4.9, 5.1, 5.6 and 5.9 cm. Three centimeters, thus, is about the minimum observed diameter, at least under the conditions in that cave.

The flow upon a stalagmite is, of course, not continuous but in the form of drops and, as q becomes small, these drops fall at longer and longer intervals. When the time interval becomes great enough, the initial solute in excess of saturation will be totally precipitated on the stalagmite before another drop arrives. In order to develop a simple concept of what would then happen, let us assume that when a drop of volume v falls upon the top of the stalagmite, it locally replaces the depleted solution there with solution of source supersaturation c_0. In addition, assume that the thickness of the thin water layer on the stalagmite top, δ, is moderately constant after the "splash" is over. The actual structure of the "water layer" is quite complicated as stalagmite surfaces are not perfectly smooth (Franke, 1968), but let us overlook this complexity.

With these assumptions, the growth in height *per drop* will be δc_0. This can be seen by realizing that, per unit area at the stalagmite apex, this is the *volume* of solid that will be precipitated—on this same unit area. Since equilibrium growth is being assumed, this will also be the vertical height grown at every radius on the stalagmite top. Because the volume of dissolved minerals that arrives in one drop is vc_0, and the volume finally deposited must be $\delta c_0 A_m$, where A_m is the minimum equilibrium cross-sectional area, there results $v = \delta A_m$, or

$$A_m = \frac{\pi d^2}{4} = \frac{v}{\delta} \qquad (4)$$

Subject to the assumptions that have been made, the minimum cross-sectional area of a stalagmite is just the incident drop volume divided by the thickness of the water film on the stalagmite top, and does not depend upon the composition of the solution or other factors! In terms of diameter,

$$d = 2\sqrt{\frac{v}{\pi \delta}} \qquad (5)$$

The simplicity of this is astonishing. Looking more closely, we see that δ is itself not simple, as it depends on the aforementioned surface roughness and, hence, upon microscopic details of crystallization, and also upon the mechanics of the impact and drainage of a drop falling on such a surface.

For a 3 cm stalagmite (about the observed minimum diameter) and drops of volume $v = 0.075$ cc (the volume of a drop falling from a minimum diameter stalactite developed at 10°C, using the drop-weight method of Harkins and Brown [1919]; see also Curl [1972]), Equation (5) gives a value of δ of 0.011 cm (.004 inches). This is not unreasonable, but no experimental or other theoretical values for it are available. With this degree of "success", it will be worthwhile to investigate extensions of the model and, in particular, to relax some of the assumptions and to extend the model to intermediate flows where neither Equation (3) nor (5) should apply.

It should be noted, that in both of the above cases it was necessary to consider only what happened on the apex of the stalagmite where drops fall; the assumption of equilibrium size (and shape) then, in effect, carried the rest of the stalagmite along. Morphological details of stalagmite "caps" would require a consideration of radial effects of flow and deposition which is beyond the scope of this paper. It will be worthwhile later, however, to consider how "splash cups" affect our results as these obviously increase δ considerably and might appear to negate Equation (5). If $\delta = 1$ cm and $v = .05$ cm^3, $d = 0.8$ cm, which is somewhat incompatible.

Transition—Theory

When a drop falls upon a stalagmite top, it splashes and some portion of the drop volume, plus some portion of the liquid already present, may splash off the stalagmite and not fall back upon it. This represents a partial loss in the solid available for deposition on the stalagmite. Let the fraction of the incident drop that remains on the stalagmite be ϕ_1, which will be called the *first splash function.* It must depend on, at least, d, δ, h (the height from which the drop fell), gravity, and fluid properties (including surface tension. The first splash function has not been previously measured, but it probably increases with increasing d or δ and decreases with increasing h. The actual solid that is available to the stalagmite from each drop is, then, $\phi_1 v\, c_0$.

When a drop falls into a liquid layer, a mixing process occurs and the resulting solution, at the point of impact, will attain some average supersaturation composition between that of the incident drop (c_0) and that of the solution present there at the time of impact, c. Defining ϕ_2, which will be called the *second splash function*, as the fractional contribution of the incident drop to the final concentration after mixing, c', we may write

$$c' = (1-\phi_2)c + \phi_2 c_0 \qquad (6)$$

The parameter ϕ_2 must be a function of, at least, v, δ, h, and fluid properties. It has never been measured, but it would presumably increase with increasing v or decreasing δ.

Between drops, the deposition of solid depletes the solution of solute and c falls. It was the rate of this deposition process that Franke (1962, 1963, 1965) attempted to model. He considered processes controlled by disequilibrium either of dissolved carbon dioxide or of calcium ion, but the process has not been studied experimentally. For the present purposes, it will be sufficient to make several approximations in order to help bridge between the high flow and low flow limits.

First, assume that the rate of growth, $\dot{z}$, is proportional to the remaining supersaturation, c.

$$\dot{z} = kc \qquad (7)$$

This "linearizes" the problem. The constant k may be defined as the maximum rate of growth (at c_0) divided by c_0: i.e., $k = \dot{z}_{max}/c_0$. This assumption is most likely to be allowable if carbon dioxide equilibrium with the ambient atmosphere is attained by a drop prior to its falling upon the stalagmite. That is, the drop is initially at the maximum supersaturation with respect to calcite deposition. It is possible, however, for the solution to be initially aggressive because of the presence of excessive carbon dioxide in solution. Equation (7) clearly would not apply in such a situation, which would permit some initial dissolution prior to final deposition. In effect, a one solute system is being assumed; the complexities of the rates of simultaneous gaseous exchange with the atmosphere and of the dissolution and crystallization of calcite, involving a two-solute system, are not understood and are beyond an adequate treatment at this time.

Second, assume that the liquid layer on the top of the stalagmite is *well mixed* in depth, that is to say, that it is of uniform composition throughout its thickness δ, but is not necessarily so radially. A material balance on the solute in solution in the liquid layer at the stalagmite apex, in excess of saturation, then gives

$$\sigma \frac{dc}{dt} = -\dot{z} = -kc \qquad (8)$$

Writing an equation of this type or, equivalently, making the assumptions leading to it, is the same as assuming that the supersaturation falls in an exponential manner (the form of the solution for Equation [8]) between the arrival of drops, with a "time constant" $\tau = \delta/k$. Either τ or k may be taken as the characteristic rate parameter for this approximation to the supersaturation-relaxation process.

If drops of volume v and supersaturation c_o arrive at intervals of t' (in which case the average flow rate would be $\bar{q} = v/t'$), we may apply Equation (8) in the interval. The general solution to this is

$$c = a \exp\left(-\frac{kt}{\delta}\right) = a \exp(-t/\tau) \qquad (9)$$

where a is a constant of integration. The concentration pattern for the liquid at the stalagmite apex resulting from the arrival of consecutive drops is shown in Figure 4. If we assume that a drop arrives at $t = 0$, it then mixes with the solution already present according to Equation (6). That mixture, however, is the result of the concentration relaxation over the interval t' following the arrival of the previous drop. Therefore, for the terms in Equation (6) we may write, at $t = t'$,

$$c = a \exp(-t'/\tau) \qquad (10)$$

and at $t = 0$, but after arrival of a new drop,

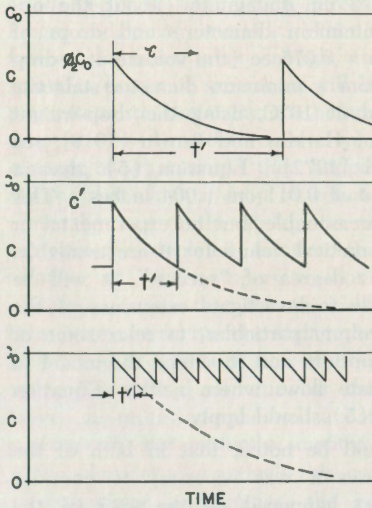

Figure 4. Time histories of the supersaturation at the apex of a stalagmite for different drop rates. ϕ_2 about 0.6. The time and concentration scales are arbitrary. Top: t' much greater than τ; c relaxes to zero and the minimum diameter results. Middle: t' comparable to τ. Transition between high and low flow regimes. Bottom: t' small compared to τ. c approaches c_o and maximum growth rate is approached in the "high flow" regime. The dashed curves indicate the composition relaxation in the absence of subsequent drops.

$$c' = a = (1-\phi_2)\, a \exp(-t'/\tau) + \phi_2 c_o \qquad (11)$$

Solving these two relations for a, and inserting the result into Equation (9), and that into Equation (8), there results

$$\dot{z} = \frac{k\phi_2 c_o \exp(-t/\tau)}{(1 - (1 - \phi_2)\exp(-t'/\tau))},\ 0<t<t' \qquad (12)$$

which gives the transient rate of growth between drop impacts. Averaging this over the interval t', we obtain the average rate of growth

$$\bar{\dot{z}} = \frac{\delta\phi_2 c_o}{t'} \frac{(1 - \exp(-t'/\tau))}{(1 - (1-\phi_2)\exp(-t'/\tau))} \qquad (13)$$

Referring again to Figure 4, in which Equation (10) is shown graphically, the effect of drip rate upon the composition pattern is shown. At low flows, c relaxes completely to zero. At high flows, it approaches a constant value of c_o. These are the limits of the simplified theories first discussed. Since the average rate of growth must also be proportional to the arrival rate of solute, $\bar{\dot{z}} = \phi_1 c_o \bar{q}/A$, it follows that

$$A = \frac{\pi d^2}{4} = \frac{t'\phi_1\bar{q}\,(1 - (1 - \phi_2)\exp(-\beta))}{\delta\,\phi_2\,(1 - \exp(-\beta))} \qquad (14)$$

where $\beta = t'/\tau\ (= kt'/\delta = v/\bar{q}\,\tau)$ is the dimensionless parameter controlling the transition from the "high" to the "low" flow behavior. It is, of course, just the ratio of the interval between drops to the characteristic relaxation time of composition. Equation (14) has for high and low limits,

$$\bar{q} \rightarrow \infty:\ A = \frac{\phi_1\bar{q}}{k} = \frac{\phi_1 c_o \bar{q}}{\dot{z}_{max}} \qquad (15)$$

and

$$\bar{q} \rightarrow 0:\ A_m = \frac{\phi_1 v}{\phi_2 \delta} \qquad (16)$$

which are just the original, simple relations with the splash functions introduced.

In Figure 5 is plotted A/A_m versus ϕ_2/β $(= \phi_2\tau\bar{q}/v)$ for various ϕ_2. The choice of variables is such that the two asymptotes for high and for low $\bar{q}$ are a single pair of straight lines. The intersection of the asymptotes at $\beta = \phi_2$ marks the transition between the two regimes. It is, in fact, not a bad approximation to use the asymptotes themselves, at least for ϕ_2 near 1.0, when the transition between the regimes is moderately abrupt. For example, at $\beta = \phi_2$, A/A_m = 1.58, which represents an increase in the minimum diameter of only about 25%. One implication is that when stalagmites get to diameters over 6 cm (assuming the minimum is about 3 cm), they probably are well into the high flow regime.

It is also apparent that the theoretical transition between the two regimes is rather independent of the details of the model used. Recognizing that the two asymptotes are represented by A/A_m equal to 1.0 at low ϕ_2/β or by ϕ_2/β itself at high values, an arbitrary empirical transition equation, based on no model whatsoever, might be chosen, such as

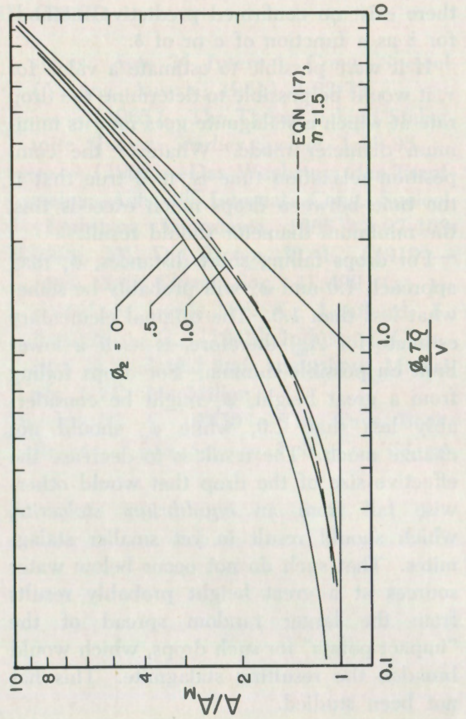

Figure 5. Stalagmite cross-section area, relative to the minimum, versus flow rate (nondimensionalized). The low and high flow asymptotes intersect at (1,1). An empirical transition relation, Equation (17), with n = 1.5, is shown by the dashed curve.

$$\frac{A}{A_m} = (1 + (\phi_2/\beta)^n)^{\frac{1}{n}} \qquad (17)$$

(where n is a "fitting" parameter) that is correct both at the low and at the high flow limits. It can be shown that when $\phi_2 = 0$, Equation (14) gives this exactly with n = 1.0, while with n = 1.5, Equation (17) is a good approximation to ϕ_2 = 1.0 (Figure 5). The point here is that the use of more-correct non-linear models in place of Equation (7) would change only the details, not the general transition behavior, of Equation (14). It remains, however, that there exist no confirmed predictive methods for $\dot{z}$ as a function of c or of δ.

If it were possible to estimate a value for τ, it would be possible to determine the drop rate at which a stalagmite goes into its minimum diameter mode. Whatever the composition relaxation time is, it is true that if the time between drops much exceeds this, the minimum diameter should result.

For drops falling short distances, ϕ_1 may approach 1.0 and ϕ_2 will probably be somewhat less than 1.0. The original elementary estimate for A_m, therefore, is itself a lower limit on possible minima. For drops falling from a great height, ϕ_1 might be considerably less than 1.0, while ϕ_2 should not change much. The result is to decrease the effective size of the drop that would otherwise fall from an *equilibrium stalactite*, which should result in yet smaller stalagmites. That such do not occur below water sources at a great height probably results from the larger random spread of the "impact points" for such drops, which would broaden the resulting stalagmite. This has not been studied.

Splash cups

Some stalagmites have cup-shaped tops, often referred to as *splash-cups*. Allison (1923) said that the "depth of the splash cup is increased by high evaporation, low concentration and rapid drip." There seem to be no particular reasons why this should be so. The falling drops could have excess carbon dioxide in solution and be thereby temporarily aggressive upon impact, thus cutting a depression in the top of a stalagmite, but this alone does not explain splash-cups; in the state of equilibrium growth, the bottom of the splash cup must be growing upward at the *same rate* as the rim of the cup and therefore, both points must have the same average supersaturation, or at least the same deposition rate. To have an equilibrium splash-cup, it is necessary only that there be a local minimum in the deposition rate at a radius lying between the center and rim of the cup. This would be a consequence of complex processes of mixing and splashing, interacting with (and ultimately forming) the shape of the top of the stalagmite. This is all beyond the scope of the present paper.

One point is relevant, however: as has been mentioned, a splash cup increases δ and, therefore, would appear to decrease the equilibrium minimum diameter. That such does not occur naturally to a dramatic degree must be related to the evident fact that ϕ_2, the second (mixing) splash function, must also decrease as δ increases. The previous arguments can, in fact, be inverted and the conclusion reached from the existence of a minimum stalagmite diameter of about 3 cm that ϕ_2 eventually must become approximately inversely proportional to δ. This would prevent the denominator of Equation (16) from changing in the presence of a significant splash-cup.

Conclusions

In comparing the present study with the conclusions previously deduced for minimum diameter stalactites, we see how different are the mechanisms in the two cases. The latter were controlled by the static balance between gravity and surface tension, while stalagmites apparently respond to dynamic processes of supply and drainage of incident drops and crystallization kinetics. It is stimulating to the imagination how much physics, chemistry and physical-chemistry is encompassed by something as "simple" as a stalactite-stalagmite pair.

The present analysis raises a number of questions—which may be its primary virtue. The two splash functions, ϕ_1 and ϕ_2, are ripe subjects for experimental study, as are the kinetics of calcite precipitation from thin films and the film-drainage process of speleothem surfaces. Clearly, all of these are involved in the general problem of speleothem morphology; that they appear immediately when even the most simplified situation is considered—the minimum diameter stalagmite—suggests the important role they will play in future studies.

Literature Cited

Allison, V. C. (1923)—The Growth of Stalagmites and Stalactites: *Jour. Geol.* 31: 106-125.

Curl, R. L. (1972)—Minimum Diameter Stalactites: *NSS Bulletin* 34:129-136.

Franke, H. W. (1961a)—Der schichtenweise Aufbau der Bodenzapfen: *Die Höhle* 12:8-12.

——— (1961b)—Formgesetze des Höhlensinters: Symposium Internat. Speleol., Varenna, Italy, 1960.

——— (1962)—Die Beziehungen zwischen Versinterung und Korrosion: *Die Höhle* 13:77-82.

——— (1963)—Formprinzipien des Tropfsteins: Acts 3d Internat. Cong. Speleol. (Vienna, Austria, 1961) 2:63-72.

——— (1965)—The Theory behind Stalagmite Shapes: *Studies Speleol.* 1:89-95.

——— (1968)—Das Wachstum der Tropfsteine: Acts 4th Internat. Cong. Speleol. (Ljubljana, Yugoslavia, 1965) 3:97-103.

Harkins, W. D.; Brown, F. E. (1919)—*Jour. Am. Chem. Soc.* 41:499 (as reported in Lewis, W. K.; Lombard, S.; Broughton, G., [1948] Industrial Chemistry of Colloidal and Amorphous Materials: NYC, MacMillan).

Hendrix, C. E. (1950)—The Cave Book: Revere, Earth Science Pub. Co., 68 pp.

HYDROLOGY OF THE LIMESTONE AQUIFERS OF SOUTHERN INDIANA

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The karst aquifers of southern Indiana comprise a 400-foot thick sequence of Mississippian limestone dipping to the west-southwest at an average of 30 feet per mile. Three major aquifers can be recognized: the massive Salem and upper Harrodsburg limestones, which form the lowest of the three aquifers; the overlying shaly St. Louis limestone; and the relatively thin-bedded Paoli and Ste. Genevieve limestones, which form the uppermost aquifer. Extensive cave systems are found in all three units. Cave patterns and well data indicate that ground-water flow is strongly influenced by bedding planes in the upper part of the limestone sequence and that there is here very little control by joints. Bedding-plane control of ground-water flow decreases and joint control increases downward in the section, to such an extent that the influence of joints is comparable to, or greater than, that of bedding planes. Caves in the two upper aquifers tend to be strongly concordant with the local geologic structure, although this tendency decreases downward in the section. Recharge to the uppermost aquifer is restricted by an insoluble caprock, so that cave systems there assume generally linear patterns and have few active tributaries. The two lower aquifers underlie an extensive sinkhole plain. Recharge takes place through each sinkhole, resulting in dendritic cave patterns. Most subsurface drainage paths in the sinkhole plain are genetically related to former surface routes, a relationship which does not exist in the uppermost aquifer. Very few karst groundwater systems are developed in more than one of the three major aquifers.

ENVIRONMENTAL PROBLEMS IN INDIANA'S LOST RIVER KARST WATERSHED

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Communities located in the well-developed karst region of southern Indiana have long encountered problems in developing and maintaining adequate water supplies and in ensuring sanitary waste disposal systems. The community of Orleans is located in such a region, known as the Lost River Watershed. That portion of the Lost River Watershed in which Orleans is situated is the Mitchell Plain, a low-lying karst plateau developed on soluble limestones of the Meramec series (Middle and Upper Mississippian).

A hydrologic study of the Lost River Watershed established that underground channels of concentrated flow exist and that problems of water supply and waste disposal are directly related to them. The high velocities of the ground water in the subterranean conduits of this area, and the inefficiency of the conduits as purifiers, has resulted in severe ground- and surface-water pollution in the Lost River Watershed.

The karst-related environmental problems of Orleans have been documented for nearly fifty years. Bedrock wells drilled in this area yielded very-hard water. This fact, coupled with the high cost of demineralizing ground water, forced Orleans to construct an impounding reservoir for a water supply. Limited surface drainage, and leakage problems due to the fractured limestone bedrock, made depression storage for water unfeasible. Attempts made to drill shallower wells in order to obtain water of lower mineral content increased the susceptibility of the wells to ground water pollution.

It was observed from dye-tracing experiments on the subterranean system that the effluent from the waste disposal plant at Orleans contaminated both the local ground water and the resurgence at Orangeville. Obviously, health problems will arise whenever a karst watershed is exploited as part of a sewage system. Attempts should be made to regain a higher quality ground water in this area by improvements in waste disposal methods.

KARST OF WESTERN WYOMING: THE SURFACE KARST OF THE TOSI CREEK BASIN, GROS VENTRE MOUNTAINS

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The Tosi Creek basin is located in western Sublette County, Wyoming and contains the headwaters of Tosi Creek. The surface of the area is, essentially, a limestone pavement developed on the Mississippian Madison formation. There is very little soil cover and the details of the surface karst are easily visible.

Two different geologic processes are active in denudation of the basin. The dolomitic rocks weather through frost action, forming felsenmeeren of rock fragments about four inches in diameter. The purer limestones weather chiefly by solution, both on the surface of the pavement and along joints. The limestone beds are first broken up into blocks about one foot in diameter, after which the blocks are completely dissolved.

Karren have developed over the entire surface of the limestone pavement. Where they have formed under snowfields, the karren are enlarged joints. These commonly are one or two inches wide and about six inches deep, although crevices up to two feet wide and 40 feet deep exist. Where the karren have been formed by flowing water, structural lines are generally ignored. These karren are U-shaped in cross-section, about two inches wide and two inches deep, and usually meander, resembling incised streams.

CAVERN DEVELOPMENT IN THE WINDSOR SERIES (MISSISSIPPIAN) OF NOVA SCOTIA

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Gypsum and limestone of the Windsor Series crop out in central Nova Scotia and in parts of Cape Breton Island. Two limestone caves and seven gypsum caves, ranging in length from 250 to 1,250 feet, were investigated during the summer of 1971. Limestone outcrops are highly discontinuous, exhibit poor karst development, and contain few caves. Gypsum is exposed over large areas, but caves tend to form near contacts with less soluble rocks in isolated outcrops. The largest gypsum area underlies much of Hants County. Four major caves are along its periphery.

Most of the caves contain vadose streams and show signs of flooding. Entrances usually occur where streams sink or in karst windows. They occur less frequently in collapse sinks or at resurgences. Stream caves usually have their largest cross-sectional area at the entrance. Entrance collapse during this century, described in historical records, may suggest recent climatic change. More caves exist in the province, but it is doubtful that any of them are large.

MINERAL STABILITY IN THE CAVERN ENVIRONMENT

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Cave minerals deposited by evaporation or de-gassing of percolating ground water have a mineralogy dependent both on the bulk composition of the water and on the temperature, carbon dioxide pressure, and water vapor pressure of the cave environment. The primary mineral constituents of limestone or gypsum ground waters are Ca^{++} Mg^{++}, Na^{+}, HCO_3^{-} and SO_4^{-2}. Less common are K^{+}, Sr^{++}, NH_4^{+}, Cl^{-}, PO_4^{-3}, and NO_3^{-}. Consideration of only the five most common ions gives rise to 21 binary systems and 35 ternary systems, all containing some compounds that could occur as cave minerals.

The problem is to explain the very small number of cave minerals that have been observed. Assembly of the available data for the phase diagrams of the systems shows that the vast majority of possible minerals are excluded by the very restricted range of the variables in the open system of the cavern: T ranges O to 20° C, P_{CO_2} ranges from $10^{-3.5}$ to $10^{-1.5}$, and P_{H_2O} ranges from $10^{-2.5}$ to $10^{-1.5}$ atmospheres. Hydrated carbonates of magnesium are well known, but sodium carbonates and carbonate double salts are not known. Sulfates of all three cations, including double salts and salt hydrates, have been found, but mixed sulfate-carbonate double salts do not occur. In addition to providing an explanation for the occurrence of known cave minerals, the phase diagrams allow a prediction of new minerals that should occur in caves with unusual environmental parameters.

SYMPOSIUM ON BIOGEOGRAPHY OF APPALACHIAN CAVERNICOLES AAAS MEETING, 1972

A day-long symposium on the "Biogeography of Appalachian Cavernicoles" was held at the annual meeting of the American Association for the Advancement of Science, Washington, D. C., 29 December 1972. The symposium was arranged by John R. Holsinger and David C. Culver and was sponsored by the Biology Section of the National Speleological Society, with co-sponsorship by the Society of Systematic Zoölogy and the Systematic Zoölogy Division of the American Society of Zoölogists.

The following abstracts are of the papers presented at this symposium. Some are based partially on previously-published data (papers by Muchmore and by Shear), while others are based on data being published in other journals (papers by Kirk, by Carmody and Peck, and by Culver, Holsinger, and Baroody). The papers given by Carpenter and by Fleming are based, in part, on recently-completed doctoral dissertations (in press) and those by Ferguson and by Hetrick and Gooch are based on current thesis research.

Each of the presentations was followed by a 10-minute discussion, led by Richard E. Graham (Ramapo College, New Jersey), Roman Kenk (Smithsonian Institution), and

Thomas L. Poulson (University of Notre Dame). Thomas E. Bowman (Smithsonian Institution), who originally was scheduled to be a discussant, could not participate and was replaced with Robert W. Mitchell (Texas Tech University).

INTRODUCTION TO THE SYMPOSIUM

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Interest in North American cave faunas has increased dramatically in recent years. With the completion of several regional surveys of cave fauna, detailed information now is available on the species compositions of many of the important cave and karst areas of the United States. One such region is the Appalachians, principally the unglaciated part which extends from the Virginias southwestward through eastern Tennessee to northwestern Georgia and northeastern Alabama. This region contains numerous caves and karst areas and is rich in troglobitic animals (*i. e.,* obligatory cavernicoles). The region has been investigated extensively during the past 10 to 15 years and a significant amount of biogeographic data has been accumulated about it.

The results of these investigations, specifically those concerned with the speciation and geographic distribution of some of the taxa represented in Appalachian caves, are discussed by the participants of this symposium. Attention has been focused on the ecological and geological factors which appear to have influenced the distributional patterns of cavernicolous species. Although most previous studies on geographic variation in cavernicoles have concentrated on morphological differences between populations, the use of electrophoresis to determine genetic differences between populations and even between species now is being employed in research on cave animals. The results of such studies are presented for cave beetles (*Ptomaphagus*) and for amphipods (*Gammarus*). A survey of cave microorganisms (bacteria, Actinomycetes and fungi) also is discussed and the results of a quantitative study of the cave biogeography of a major karst valley are presented.

DISTRIBUTIONAL SURVEY OF HETEROTROPHIC MICROORGANISMS IN OLD MILL CAVE, VIRGINIA

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Plate counts of heterotrophic microorganisms were made on samples of mud, water, dung, and speleothems occurring along a transect through Old Mill Cave, Montgomery County, Virginia. Counts on forest soil and streams outside the cave, also, were made for comparison. Bacteria, Actinomycetes, and microfungi were counted on separate, selective culture media. The disadvantages of such counts as an index of the ecological significance of filamentous microorganisms were noted.

Counts were considerably higher in forest soil than in most cave samples, exceptions being dung from the entrance room and scrapings from the floor of an aphotic passage which contained decaying arthropod remains. Both samples produced high counts of bacteria and fungi, but not of Actinomycetes. Fungi, but not bacteria, also were abundant on a rimstone dike containing arthropod remains. In general, counts of all microorganisms were higher for the floor than for the walls and the ceiling of the cave. Inordinately high counts in floor samples were associated with deposits of formed organic matter. Petri plates containing low dilutions of this matter sometimes produced fungus-eating maggots during incubation, maggots which later became adult flies in the agar cultures.

Deuteromycetes, including *Trichoderma viride* and *Aureobasidium pullulens,* were common, but mucoraceous molds appeared only in dung samples. Saprolegniaceous water molds were found in streams both inside and outside the cave. A much higher proportion of coremium-forming *Penicillium* spp. and *Doratomyces* occurred within the cave than in forest soil, suggesting that the coremia, which elevate spores into turbulent air, may have special adaptive value in caves.

The ratio of bacteria to Actinomycetes and fungi was greatest for the cave walls and ceiling, where total counts of microorganisms were lowest. It was somewhat less for the cave floor, where some organic matter accumulated, and least for the A-horizon of forest soil, where counts were consistently high. These ratios suggest that heterotrophic bacteria are distributed more uniformly through the cave than are the filamentous microorganisms, owing possibly to the latters' greater dependence upon deposits of formed organic matter. The possible importance of these microorganisms in detrital food webs is discussed and suggestions are made for future research.

SYSTEMATICS AND BIOGEOGRAPHY OF CAVE FLATWORMS

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Individuals representing several species of cave flatworms (planarians and alloecoels) were collected alive from over 50 caves in 11 states. Many of these specimens were photographed while alive and maintained in laboratory cultures. Most sexually mature worms were preserved by a rapid freeze technique. In order to compare the internal morphologies of these worms, serial sections were prepared from about 150 specimens. Nearly all existing type specimens of subterranean flatworms also were examined.

It was concluded from the study of these many specimens that the descriptions of several subterranean species were based on insignificant and variable characteristics. Therefore, the systematics of American cave flatworms was extensively revised. One new species was described. Several species were placed in synonomy and the validity of several other species was seriously questioned. The valid species of *Sphalloplana* were separated into three subgenera. These studies also have resulted in range extensions for several species.

Observations were made on various aspects of flatworm ecology. Definite habitat preferences were noted for some species. Food appears to be extremely variable. Predators probably include fish, crayfish, and salamanders. Sporozoan and ciliated parasites were found occasionally. Cocoons of *Sphalloplana percoeca* and of *S. pricei* were found in spring and summer; cocoons maintained at 13°C. hatched in about 3 months and contained from 2 to 17 young. Observed functions of the adhesive organ included locomotion, food capture, defense and, possibly, chemoreception and mechanoreception. (This study was supported by University of Kentucky grants.)

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THE TROGLOBITIC ASELLIDS (CRUSTACEA: ISOPODA) OF EASTERN NORTH AMERICA

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Studies on the origin, affinity, and distribution of troglobitic asellid isopods (Asellidae) were published by H. R. Steeves, III in a series of papers during the 1960's. Data have continued to accumulate since that time, as a result of extensive collecting efforts by biospeleologists. Analysis of the data obtained since publication of Steeves' reports indicates necessary modifications of some of the species ranges previously given. In addition, several new species are revealed. The affinities of both troglobitic and of epigean (possible ancestral) forms are revised. The reasons for doing so are discussed. The zöogeographical implications of several newly-described species are considered and their ranges are compared with the recently-revised ranges of other species.

ZOOGEOGRAPHY OF THE MILLIPED FAMILY CLEIDOGONIDAE *

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The milliped family Cleidogonidae includes the genus *Pseudotremia* which, with 35 described species, is the most prominent feature of the Appalachian diplopod cave fauna. Species of *Cleidogona* are common in Appalachian caves as accidentals; a half-dozen troglobitic species are found in Mexico. The family Cleidogonidae is closely related to the family Trichopetalidae; both probably originated in the highlands of Mexico and spread northward. Cleidogonids, despite the secondary adaptions to boreal conditions common in species of *Pseudotremia,* are primarily an austral element in the Appalachian fauna while trichopetalids, whose range extends well into glaciated territory, are a predominantly boreal element. Species of *Pseudotremia* occur as troglobites in all major karst regions south and west of Maryland and north and east of the Missouri Ozarks. Troglophilic and epigean species also occur throughout this area. At present, as many as fifteen additional species await description and the distribution of most members of the genus is very incompletely known. The most highly evolved troglobitic species of *Pseudotremia* probably are pre-Pleistocene in age, but there is little evidence to support this contention.

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* Presented in abstract, only.

TOWARD A PREDICTIVE CAVE BIOGEOGRAPHY: THE GREENBRIER VALLEY AS A CASE STUDY

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The distributional patterns of 12 aquatic and 16 terrestrial cave-limited species from 96 caves in the Greenbrier Valley of West Virginia and nearby limestone areas were analyzed. The analogy between islands and isolated karst areas was examined. For terrestrial species, the area effect was greater than on islands, primarily because of low immigration and extinction rates. Aquatic species, on the other hand, showed little or no area effect, due in large part to high immigration rates. The ranges of individual species are determined by a combination of competition and geological barriers.

GENETIC VARIATION IN POPULATIONS OF THE FRESHWATER AMPHIPOD *GAMMARUS MINUS* (SAY) IN THE CENTRAL APPALACHIANS

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The amphipod *Gammarus minus* (Say) in its Appalachian range has 3 morphotypes: (1) a spring form with well-developed eyes, (2) an intermediate cave form with slightly reduced eyes, and (3) an extreme cave form with greatly reduced eyes. This study has the dual objects of comparing the genetic structure of populations in 2 types of karst areas and of analyzing the genetics of populations of the 3 morphotypes within these areas.

Thirteen gene loci were characterized from their stained protein products on polyacrylamide and starch zymograms. Three (23%) are polymorphic in many populations; 2 (MDH-1 and PEP-1) are genotypically determinable in all populations. Genetic data were collected from samples of 14 populations in Huntingdon and Centre Counties, Pennsylvania and from 14 populations in and adjacent to Greenbrier County, West Virginia.

Central Pennsylvania populations principally inhabit springs rising from narrow strike belts of carbonate rock that lack closely-integrated subterranean drainage. These populations are highly polymorphic—11 (79%) are polymorphic at MDH-1 and 14 (100%) are polymorphic at PEP-1. One to 4 alleles per population occur at MDH-1 and 2 to 4 alleles occur at PEP-1. Also, allelic frequencies, or even the alleles present, are notably different in adjacent populations, some of which are as little as 4 miles apart.

Eight of the 14 Greenbrier County samples were taken from the Greenbrier Valley, a karst area developed on nearly flat-bedded limestones containing extensive, interconnecting cave passages. Polymorphism here is low, zero percent at MDH-1 and 37 percent at

PEP-1. Also in contrast to those of central Pennsylvania, allele frequencies are nearly identical over all populations.

It is concluded that the populations of central Pennsylvania are at least semi-isolated, due to the discontinuous nature of the subterranean drainage systems. The well-integrated underground drainage of the Greenbrier Valley favors intermittent gene flow among populations which, in turn, tends to keep populations genetically homogeneous.

No systematic genetic differences were found between morphotypes. This indicates that photoreceptor regression has not been accompanied by a major reorganization of the genome.

CAVERNICOLOUS PSEUDOSCORPIONS IN THE EASTERN UNITED STATES

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Representatives of 11 genera of pseudoscorpions have been found in caves in eastern United States. A few are merely accidental or facultative cavernicoles, but most appear to be specifically adapted troglobites. *Chthonius tetrachelatus* and *Microbisium confusum* occasionally occur in caves but these are, doubtless, unusual intrusions of abundant litter-dwelling forms. On the other hand, some species of *Kleptochthonius, Apochthonius, Tyrannochthonius, Microcreagris* and *Chitrella* are highly modified morphologically and certainly are obligate cavernicoles. Of special note in this regard are the troglobitic species of *Aphrastochthonius,* which have no known epigean relatives. Also of particular interest are the guanophile representatives of *Hesperochernes* (formerly placed in *Pseudozaona*). These are not strikingly modified, but are almost certainly confined to caves, nonetheless.

The distributions of these cave adapted forms are quite varied. Most widespread are *Kleptochthonius (Chamberlinochthonius)* and *Hesperochernes,* which are found generally throughout the southeastern cave region; however, the former has not been taken in Alabama or in Georgia and the latter has not been found in West Virginia. Cave-adapted *Apochthonius* and *Mundochthonius* seem to be restricted to the periphery of the area occupied by *Kleptochthonius.* Similarly, cave dwelling *Tyrannochthonius* have been found only in northern Alabama and in southern Tennessee, with little overlap into the range of *Kleptochthonius. Aphrastochthonius* is unique in that it is known only from two caves in Alabama and from several in Mexico and Central America. *Microcreagris* is unusual in that the troglobitic forms are found only in the Tennessee River drainage in Alabama, Tennessee and Virginia while epigean forms are widespread in the southeastern United States.

Explanations of these varied distributions must be sought in complex sets of physical and biological conditions as yet very poorly understood.

PRELIMINARY OBSERVATIONS ON THE GEOGRAPHIC DISTRIBUTION OF CAVERNICOLOUS CAMPODEIDS (INSECTA: DIPLURA) IN THE APPALACHIANS

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Cavernicolous campodeids in the Appalachians are found in caves of the Valley and Ridge Province from Pocahontas County, West Virginia, southwest through Virginia and Tennessee to northern Georgia. They also are found in caves of the Appalachian Plateau and of the Interior Low Plateaus of Kentucky, Tennessee, and Alabama.

In general, there are two forms of distribution: wide ranges, and smaller isolated ranges that are insular in nature. *Plusiocampa cookei* belongs to the former, being found in caves of the plateau regions of Tennessee and Kentucky and in the westernmost part of the Valley and Ridge Province of Virginia and Tennessee. Several other species are restricted to individual, long, linear carbonate valleys in Virginia, West Virginia, and Tennessee. Insular ranges, consisting of one or of several neighboring caves, are also found in the Valley and Ridge Province. Possibly, four species belong to this category. In the tri-state area of Alabama, Georgia, and Tennessee, a *valentinei-henroti* complex of forms intermingle. The exact phylogenetic relationship of these wide-ranging forms is not certain at this time. With the exception of a sympatric species in West Virginia, all species belong to the genus *Plusiocampa.*

GENETIC STUDIES ON THE ZOOGEOGRAPHY OF CAVERNICOLOUS *PTOMAPHAGUS* BEETLES (COLEOPTERA: LEIODIDAE)

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Twelve species of troglobitic *Ptomaphagus* are known in eastern North America. Four of these occur in caves in the Interior Low Plateau Province. A complex of eight species occurs in the caves of a small region at the southern end of the Cumberland Plateau. A model to account for present distribution and speciation patterns already has been presented by Peck. Assumptions and conclusions based on this and other models are now being tested. Data are presented for experiments on: (1) hybridization potential between populations of the same taxon and between populations of taxa differing at the levels of form, subspecies and species; and (2) genetic differentiation and variation within and between populations using gel electrophoresis techniques.

LAVA TUBES AT PISGAH CRATER AREA, CALIFORNIA

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Pisgah Crater lava field is in the Mojave Desert of Southern California, about 175 miles northeast of Los Angeles. Little weathering has occurred since the lava was erupted and almost no vegetation has become established. Because of the excellent preservation of the flow and the numerous characteristic lava features which it contains, the area is an excellent locality for the study of flow structures in basaltic lava.

At least 200 lava tube caves are present. Most of these are small. Only 22 are more than 100 feet in length. The longest are SPJ Cave (about 1,500 feet) and Glove Cave (1,100 feet).

MAPPING THE CAVES OF THE HEADQUARTERS LAVA FLOW LAVA BEDS NATIONAL MONUMENT, CALIFORNIA

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There are 24,524 feet of (surveyed) lava tubes and 1,770 feet of minor collapse trenches open for public visitation beneath the approximately 1.2 sq mi area of the Headquarters Lava Flow, Lava Beds National Monument, California. This system probably was intermittantly continuous over the time span of its formation (which occurred less than 60,000 years ago), but it later was broken into six elements by the formation of lava plugs and of collapse trenches. It has not been determined which is the longest unitary tube (one not intersected or broken by a collapse), but that probably is Catacombs Cave (6,562 feet long). The cave system of the Headquarters Flow is more extensive than indicated above, because caves belonging to the system but not open to the general public, such as Crystal Cave, are not included.

GEOLOGY OF LAVA TUBES IN LAVA BEDS NATIONAL MONUMENT CALIFORNIA

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Lava-tube systems in Lava Beds National Monument are among several that occur in young basalt flows flanking the Medicine Lake Highlands volcano. Mammoth Crater was the source for one tube system (including Heppe, Sentinal, and Dragonhead Caves) which has both a major tributary and numerous distributary tubes. The large tributary (now collapsed) formed where lava was ponded to one side of the main tube before draining into it. More typically, the main channel fed numerous distributary conduits. Complexly-branching distributary tubes at Monument Headquarters are unusually well drained, evidently the result of a high gradient here. The main channel in this area of high gradient (Crystal and Sentinal Caves) is narrow and deep. Evidently, it carried a high rate of flow, as suggested by the evidence of high-velocity gas streaming above the lava river. Modoc Crater was the source of another large tube, whose uncollapsed segments include Bearpaw, Skull, Frozen River, Fossil, and Fern Caves. This was a single channel throughout most of its 15-km length. Unusual features of this tube are a low gradient (less than 0.3° at the downstream end), and a series of collapsed blisters that form non-explosive craters with high, outward-toppled rims. Like the Mammoth Crater tube, this tube generally is deeper than it is wide, is multi-storied, has a thick roof, and is enclosed in several flow units. These complexities, which are typical of large tubes, originated by such mechanisms as successive lava overflow and levee building before the roof completely formed, non-uniform accretion on the tube walls, and local erosion into underlying materials. Except for small features in the tube lining, most layering exposed by tube collapse is believed to represent superposed flow units and not shear layers within the flow.

MAJOR LAVA CAVE SYSTEMS OF OREGON

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Three extensive lava cave systems recently have been mapped and studied in Oregon. These are: the Arnold Lava Tube System, about 12 miles southeast of Bend; the Horse Cave System, about 2 miles east of Bend; and the BLM System, in the Saddle Butte flow northwest of Burns Junction, Malheur County.

The Arnold System, which has been traced for a distance of about 4½ miles, consists of lava cave segments interrupted by extensive collapsed portions of tubes or of collapsed lava ponds. The cavernous sections generally are characterized by large, vertically-elongated cross sections, thick roof sections, and extensive, massive breakdown.

A contrast is offered by the Horse Cave System. Although traceable for 7 miles, it consists of generally smaller cave segments which are branching, parallel, and often disconnected. These also are shallower, having a maximum depth of 33 feet in contrast to a maximum depth of 134 feet for the Arnold System.

The BLM System has been followed for 8.4 miles and is somewhat intermediate in character. It is unitary and its cross sections are of large diameter, like those of the Arnold System. However, it lies at a shallower depth, has a generally thinner roof structure, and exhibits much less breakdown than does the Arnold System.

In general, each of the three long systems possesses distinctive characteristics. It is, therefore, possible that each represents a different type of system with a distinctive mode of formation. It also is possible that each was formed as a result of similar processes and that variations in a parameter such as flow velocity caused the variations in character among these systems.

LAVA TUBE CAVES OF THE SOUTH MEDICINE LAKE HIGHLANDS, CALIFORNIA

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The Medicine Lake Highland is an eastern extension of the Cascade volcanic province in northern California. Situated on the Modoc Plateau, the Highland is formed by a basaltic and andesitic shield volcano about 13 miles in diameter. It has a prominent summit caldera 6 miles long and 4 miles wide; postcaldera lavas include andesites, dacites and rhyolites. Holocene basalt flows, which were erupted predominately from pit craters on the flanks of the shield volcano, contain numerous well-developed lava tubes in the northern region (Lava Beds National Monument) and in the southern region (Siskiyou County). In the southern region, an unnamed series of basalts flowed south down a fault valley and merged with similar flows erupted from the Timbered Crater vent. Extensive lava tubes, many of which are partly collapsed, characterize the flows. One partly collapsed tube (possibly originating from Giant Crater) can be traced for about 14 miles. In some sections, the tube is divided into four distinct levels stacked vertically for a total height exceeding 120 feet. Collapsed wall sections expose pre-flow country rock and the lower surface of the lava flow. Well-preserved sections of the lava tube exhibit multiple flow-levels, lava tube linings, and subsequent flows along the floor. Details of these and other lava tube structures provide additional information on the mechanisms of lava tube formation and on lava tube geomorphology.

HAWAIIAN LAVA TUBES: A PRELIMINARY REPORT

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The Hawaiian Islands are an oceanic archipelago stretching more than 1,500 miles across the mid-Pacific. The western islands are raised coral reefs and shoals resting on remnants of volcanic islands. The 8 eastern- and southern-most islands are the high, major islands of the archipelago and are those most interesting to the speleologist. These are formed by shield volcanoes, a characteristic of oceanic islands. The islands contain a few limestone caves in raised reefs, and numerous sea caves, but their main features of speleological interest are lava tubes.

The oldest main island, Kauai, is something over 5 million years old. Although the youngest lava flows on it are estimated to be 600,000 years old, these still contain extensive lava tubes. Oahu is younger than Kauai and has a number of lava tubes. On Maui, the most recent flow is about 200 years old. Many extensive lava tubes are still extant on Maui. The island of Hawaii holds the most interest for the vulcano-speleologist, because it is there that he can watch new lava tubes form, study extensive young lava tubes still in excellent condition, and visit older lava tubes in order to study the processes of erosion and degradation.

Kazumura Cave, on Hawaii, is presently the longest known lava tube in the state, with about 11,000 feet of passage. It is on the flank of Kilauea Volcano and is relatively young. The cave has several levels and displays many of the speleothems and other phenomena common to lava tubes.

FORMATION AND GROWTH OF LAVA TUBES DURING THE 1970 ERUPTION OF KILAUEA VOLCANO, HAWAII

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A complex, braided, and distributary system of lava tubes developed by the roofing-over of lava rivers and the coalescence of pahoehoe toes during 1970-71 at Kilauea volcano, Hawaii. Lava eventually was transported as many as 7.4 miles underground through these tubes, at average rates of 1.2 to 1.8 mph. Skylights formed at various times during the development of the tube system, allowing events occurring inside the active tubes to be observed. Initially, the tubes were small—generally only 3 to 10 feet deep, but they became at least 50 feet deep, probably as a result of erosion by lava flowing through them. The surrounding lava was an excellent heat insulator, so that the lava cooled very little during its travel through the system. Underground lava falls, multi-storied tubes, lava stalactites, and many other features commonly found in prehistoric lava tubes were observed while in various stages of development.

These events are described in some detail by Swanson (*Geol. Soc. America, Bull.* 84:615-626, 1973) and by Peterson and Swanson (*Studies Speleol.* v. 2, no. 6, 1973).

INTERNATIONALLY SIGNIFICANT LAVA TUBE CAVES OF THE CANARY ISLANDS

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The honor of being the world's longest lava tube cave has been successively claimed for the Cueva de los Verdes system on the island of Lanzarote and for the Cueva del Viento system on the island of Tenerife.

The Cueva de los Verdes system is an impressively spacious, multilevel system having a total of 3.8 mi of passages beneath a surface distance of 2.4 mi. This system, however, is segmented by huge collapse sinks as much as 328 feet in length. The longest intact cavernous segment has about 1 mi of passages. In addition to a notable display of flow patterns, the system is noteworthy for its extensive gypsum deposits, some of which are oulopholitic or acicular in form. A small amount of lateral breakdown has been produced by the growth of gypsum crystals.

The Cueva del Viento system is an elongated labyrinth in which 3.9 mi of passages have been surveyed. It is segmented into two caves by a single small collapse sink. The segments are 2.9 mi and 1 mi long, respectively. Unusual features of the system include SiO_2 microgours and atypical lava speleothems. Exploration is continuing in the larger cave. The possibility exists that the lower, shorter cave may be linked to nearby Cueva de San Marcos, where about 1.3 mi of passages are known to exist. Shorter tubes parallel the Cueva del Viento system and may prove to be parts of a larger megasystem.

TERRESTRIAL ANALOGATES TO LUNAR SINUOUS RILLES

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Lunar sinuous rilles are meandering, channel-like depressions restricted, mostly, to mare areas. Several diverse mechanisms have been proposed to explain their origin. These include: erosion either by volcanic ash or by running water, surface collapse resulting from intrusive stoping, and fluidization of the regolith by gasses escaping through fractures in the lunar crust. It also has been proposed that the rilles are lava channels, collapsed lava tubes, or both.

Consideration of the composition of lunar mare lavas and of geomorphic evidence supports the hypothesis that at least some sinuous rilles developed from lava tubes and channels. Lava tubes and channels on Earth commonly (and almost exclusively) form in basaltic flows. Because lunar mare lavas are predominantly basaltic, it is reasonable to assume that these features also will be present in the maria.

Lunar sinuous rilles generally pass around topographic highs. They often are composed of discontinuous segments, have pronounced lateral levees or a broad topographic high along the rille axis, originate in irregular craters, and may have distributary (rather than tributary) structures. Nearly all aspects of rille morphology are analogous to terrestrial lava tubes and channels except that of size: Sinuous rilles are considerably larger than are their terrestrial analogates. However, differences between the lunar and earthly environments may account for the difference in size. Laboratory determinations obtained independently for Apollo II samples indicate that at least some lunar lavas have a much lower viscosity and thermal conductivity than have terrestrial lavas; thus, the lunar lava flows could be longer. Lava tubes and channels, therefore, could be correspondingly larger on the Moon. Although these interpretations may explain certain lunar sinuous rilles (*e. g.*: Hadley Rille and rilles near Herigonius), it is possible that other rilles were formed by other mechanisms.

UNUSUAL MINERALOGY OF THE CRYSTAL PIT SPATTER CONE, CRATERS OF THE MOON NATIONAL MONUMENT, IDAHO

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Crystal Pit Spatter Cone lies on the Idaho Rift System of the Snake River Basin Lava Plateau, in south-central Idaho. Under the spatter cone, the former magma chamber, about 80 feet long and 35 feet wide, is still open for examination. A descent of 90 feet through the narrow spatter-cone throat is necessary in order to reach the magma chamber. The chamber contains large quantities of the secondary sulfate minerals gypsum, mirabilite, and jarosite, all of which seem to be scarce or absent in caves in other volcanic regions. The gypsum and mirabilite probably were deposited from mineralized capillary groundwater seeping into Crystal Pit, rather than by condensation from mineralized volcanic gasses. However, the basaltic rocks overlying Crystal Pit seem to be poor in calcium-, sodium-, and sulfur-containing primary minerals that could be leached by the capillary groundwater. This extensive mineralization has occurred within the past 1,000 to 2,000 years.

A DRAFT CAVE LAW FOR ALABAMA

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Members of the Huntsville Grotto got their heads together several years ago and decided to "go for broke" on a cave law that would be quite comprehensive in nature. Their prime motivation probably was conservation, but discussion soon led to a number of other topics.

A key issue in the proposed law is the establishment of a State Speleological Committee, which would arbitrate many of the features of the law. It would be essential to assure a favorable Committee membership. Private property rights would be re-inforced by establishing procedures for controlling access to caves. Cave-owner liability would be limited, in the event of caver injury or accident. Vandalism would, of course, be unlawful and we would forbid the indiscriminate sale of speleothems. Water pollution prevention would get an assist from this law by a prohibition against dumping in sinkholes. A state policy on cave biology would be instituted. Possibly, we could reverse the trend toward extinction of bats. Commercial caves would come under a licensing provision, for the protection of the public. Archaeological, paleontological, and historical cave sites would be protected. Finally, the law would provide for enforcement by a system of fines. A procedure for making exceptions, principally through the State Speleological Committee, would be provided.

FEATURES OF LIMESTONE SOLUTION, EROSION, AND PRECIPITATION ALONG THE SOUTHWEST COAST OF PUERTO RICO

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The southwest coast of Puerto Rico, from Guayanilla Bay westward, is composed of a series of alternating cliffs or hills of limestone and low alluvial valleys. It is climatically unusual in that it supports a subtropical dry forest similar to that of southwestern United States. The principal limestones are the Juana Diaz and Ponce formations of Mid-Tertiary age; they are relatively undisturbed and dip gently southward. Most of the limestones are poorly consolidated. The more resistant beds cap the uplands. The Caribbean Sea here has normal tropical temperatures (27-28°C) and salinity (36 ppt). Waves driven by the daily seabreeze are moderate (0-3 m) in height. The coast is protected by a shallow (0-18 m) shelf 8 km wide at the western end narrowing to 2 km eastward. An undercut notch has developed generally on limestone in the intertidal wave zone, probably by solution. This is enhanced in areas with high waves. At many localities, a tidal platform occurs in the middle of this notch. A visor overhangs the notch on sloping portions of the coast. The upper surface of the notch is marked by irregular blades of limestone. These blades separate circular depressions of varying size which, apparently, are analagous to raindrop pits. Larger, flat-bottomed solution pans usually interconnected by undercut solution runnels drain the visor surface downslope. The solution pans may become dissolved through the visor, resulting in features similar to blowholes. On cliffs, the limestone face above the notch usually is marked by vertical solution flutes and runnels. All of these features are similar to those found on bare karst, but they are more exaggerated in their development due to the frequency of spray inundation.

The resistant limestone beds capping the hills are divided by grikes into an irregular pavement of raindrop-pitted clints. Layers appear to be retreating headward, the meanwhile uncovering a smooth bedding surface below. Since the limestone generally is in place, these features have had considerable time to develop.

The more protected shore west of Guanica has a smoother coastline than has the eastern, narrow-shelf, high-wave area. The coast east of Guanica consists of irregular points and bays and of high cliffs with large sea caves undercutting their bases. The caves probably were eroded into the poorly-indurated limestone by waves laden with coral cobbles such as those which now form the floors of the caves. Some caves penetrate completely through points, forming natural bridges. In some cases, these show lithologic control. The eventual collapse of the bridge leaves isolated stacks and pinnacles forming small islands.

Several shallow sea caves in the protected western area occur approximately 2 to 2½ m above sea level. These probably indicate a former, higher stand of the sea. A window in Punta Ventana may mark a previous level 12 to 15 m above that of the present.

Both cementation of beachrock and solution of limestone occurred at several localities on the southwest coast. That they appear to have taken place concurrently demonstrates the complexity of carbonate solution and precipitation. Diurnal or, possibly, seasonal fluctuations may cause these phenomena.

CO_2 CONCENTRATIONS IN SOME LIMESTONE SOILS OF THE EASTERN SIERRA MADRE ORIENTAL, MEXICO

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The eastern Sierra Madre Oriental from Xilitla, S. L. P. to Ahuacatlán, Qro. contains some of the most varied and well-developed karst features in central Mexico. Large-scale karst landforms such as integrated solutional valleys, large dolinas, and haystack hills predominate on the front-range. This area receives about three meters of rainfall annually and has a sub-tropical to tropical vegetation. Karst towers, blockfields, pavements, and small closed valleys are more common in the ranges to the west. Rainfall there is less, vegetation in thinner and of a more temperate nature, and bedrock commonly is exposed. Deep pits and vertical cave systems are common throughout the region.

CO_2 concentrations have been measured in various limestone soils from Xilitla to Ahuacatlán and found to range from 0.15 to 4.12%. Distribution patterns suggest that soil CO_2 concentrations are a function of vegetation (rainfall). Thus, they ordinarily decrease westward from the front range and increase with elevation within any specific local area. The high CO_2 concentrations observed, the nature and distribution of rainfall, and the type of karst features present in the region indicate that the solution of limestone occurs primarily at the base of the soil zone and that limestone solution is the dominant process in the development of the present topography of the region.

CONTROL OF VERTICAL POSITION OF CAVE LEVELS BY PERCHED GROUNDWATER BODIES

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Cave levels may be controlled by stratigraphic or lithologic factors which fix the altitude of ground water bodies for long periods of time. In Cloverlick Valley, Pocahontas County, West Virginia, cave streams are graded towards the intersection of a thin, horizontal layer of impure limestone with the land surface, rather than towards any recognizable past or present surface base level. It is postulated that the solution rate, rather than the absolute solubility, of the rock is the controlling factor. The filling of original joint openings with insoluble residue, as well as a low rate of solution within the impure limestone layer due to the coating of individual grain surfaces by insolubles, distorted the Rhoades and Sinacori type of ground water flow pattern.

Levels in cave systems elsewhere may be controlled by the same mechanism. Beds of insoluble or poorly soluble rocks can control spillover levels (both surface and subterranean) of ground water bodies for considerable periods of time.

CHEMICAL CHARACTERIZATION OF VADOSE WATERS IN THE CENTRAL KENTUCKY KARST

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Vertically-moving waters intersect the cave systems of the Central Kentucky Karst. Some deposit travertine, some cut vertical shafts, and some enter through fractures and joints without obvious solution or deposition. Water samples from many systems have been analyzed for Ca, Mg, bicarbonate, and pH. A computer calculation allows the waters to be characterized by a saturation index and an equilibrium CO_2 pressure. The resulting parameters form a bimodal distribution in agreement with Thrailkill's classification of "vadose seeps" and "vadose flows."

Shaft waters are highly undersaturated, $\langle SI_c \rangle = -0.83$, and would be in equilibrium with a gas phase of log CO_2 pressure $= -2.33$. Dripwaters are somewhat supersaturated, $\langle SI_c \rangle = +0.18$, and have a (slightly higher) CO_2 pressure of $\langle \log P_{CO_2} \rangle = -2.29$. The base-level springs, the discharge of which presumably is a composite of the different input water types, remain undersaturated ($\langle SI_c \rangle = -0.58$) but have a surprisingly high CO_2 pressure ($\langle \log P_{CO_2} \rangle = -2.14$).

FIRN CAVES IN THE VOLCANIC CRATERS OF MOUNT RAINIER, WASHINGTON

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Extensive cave systems exist in both of the ice-filled craters of Mount Rainier. The caves develop in ice having a density of 0.5 to 0.6 g/cc, thus the term firn cave seems appropriate. Heat and steam rising between the crater floor and the overlying ice has melted out over a mile of passages in the east crater and 1000 ft in the west crater. Both craters have numerous passages leading from the surface down to a relatively horizontal perimeter passage. Fumarole activity along arcuate fractures causes the horizontality of the perimeter passage.

The lowest accessible point in the east crater lies 330 ft below the north entrance in a room 120 ft by 120 ft by 70 ft high (elevation 13,870 ft). The largest room yet discovered lies approximately 150 ft below the surface of west crater and is 170 ft by 130 ft by 25 ft high. A small crater lake 13 ft deep, 27 ft wide, and 130 ft long occupies the lower part of this room.

Bouldery, moraine-like ridges often occur against or near the downslope ice wall in the east crater. These ridges form when gravity carries debris to the ice wall at the bottom of the passage. Ice walls characteristically are fluted. Ice stalactites, stalagmites, columns, and needles occur close to entrances where temperatures are at or below freezing.

Subsidence of the crater ice and melting of the cave ceilings results in the replacement of crater ice once in 50 to 80 years in the east crater and once in 15 to 25 years in the west crater. Changes in ablation rates or in morphological features of the caves should be carefully monitored because of their relation to thermal changes in the dormant volcano.

TWO TYPES OF SPELEOGENESIS IN COMAL COUNTY, TEXAS

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Comal County, Texas lies on the southeastern margin of the Edwards Plateau; the Balcones Fault Zone passes through the southern portion of the county and that small area of the county south of the fault belongs to the Gulf Coastal Plain. The Plateau area is underlain by limestones of the Fredericksburg and Trinity groups (principally the Edwards and the Upper and Lower Glen Rose formations), and by younger rocks near the fault zone. The climate is semi-arid. Soils are thin and vegetal cover generally is sparse.

Comal County contains many small caves and springs characteristic of the Edwards Plateau area and, also, some larger springs associated with the Balcones Fault Zone. Study of the origin of the caves in this area shows certain geologic, hydrologic, and physical similarities among the caves and suggests that most probably have been formed under similar circumstances.

Bartel's Cave, Jordan's Cave, Honey Creek Water Cave, and Wolle Cave all occur within a massive artesian aquifer at the base of the Lower Glen Rose Formation. All four are active cave-spring systems and are the sources of small, perennial streams. All four, also, are joint controlled and are oriented approximately down dip. In general, all of these caves are linear. They have one principal passage, few side "feeder" passages, and little vertical development. These caves approximately illustrate the conditions which Gardner specified in his earlier theory of speleogenesis and they appear to demonstrate the validity of that theory under appropriate geologic circumstances.

Natural Bridge Caverns and, apparently, Dinosaur Cave, formed primarily under phreatic conditions. Their main passages are large in cross section (on the order of 15 m by 15 m) and still conduct water in their lower levels. Both caves generally are linear and have only a few small side passages; entrances probably are secondary. Both caves appear to be developed in the relatively thick, dolomitic limestone beds of the Upper Glen Rose Formation.

Natural Bridge Caverns is hydrologically down-slope from a large groundwater confluence. Dinosaur Cave appears to be similarly situated. Natural Bridge Caverns terminates down-gradient in a fault associated with the Balcones Fault Zone, well known as a major groundwater channel. The origin of Natural Bridge Caverns, and possibly the origin also of Dinosaur Cave although less information about it is available, is hypothesized to have been caused by a groundwater convergence and by the subsequent large volume and high flow-velocity of water passing through the joints of this area. The downstream termination of Natural Bridge Caverns probably was controlled by the fault zone, which readily carried this water away.

SKULLITES—UNUSUAL NEW SEDIMENTARY FORMATIONS DISCOVERED IN SKULL CAVE, NEW YORK

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New sedimentary cave formations were discovered on 13 November 1971 by Frank Mullett and Ernst Kastning in the Stony Brook Section of Skull Cave, Albany County, New York. This area consists of approximately 1.3 km of highly joint-controlled passageways and had been discovered only a few months before by Michael Queen and others. The sedimentary formations, named "skullites" after the cave, are reported here as a new cave formation. To the authors' knowledge, they have not been described previously in the literature.

Skullites are spherical in shape and range in diameter from 10 mm to 20 mm. The interior of one specimen was found to contain concentric laminations similar to those in cave pearls. The laminations are composed of alternating layers of sand- and silt-sized particles. The most unusual and obvious feature of each skullite is the presence of numerous protrusions (up to 25 in number) spaced uniformly around the exterior of the sphere. These also are composed of sand and silt. The protrusions average approximately 4.5 mm in length and 3.0 mm in diameter.

A "nest" of skullites was found in the floor of an alcove within the cave. Ninety to 100 specimens were observed to be lying within this nest. Most were unattached, but some were partially buried. The nest is about 85 cm by 20 cm in width and is several cm deep, being simply a depression in the alcove floor. This is the only occurrence of skullites known at the time of writing (Aug '72).

The origin of these formations currently is under study by the authors. Initial results indicate a concretionary origin attributable to variations in local flood-water currents. Organic processes, such as fixation of the sediment by bacterial action, also may contribute to their growth.

DECORAH'S DEFINITIVE ICE CAVE

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The Decorah Ice Cave is the largest glacière in eastern North America. While the exact date of its discovery is unknown, the cave has figured prominently in the literature on glacières since 1860 and, during the last quarter of the 19th Century, enjoyed an international reputation.

Ice deposits underground were the subject of much speculation from 1586, when Benigene Puissenôt suggested that the cold of winter produced the ice at Chaux-les-Passavant, France, until 1898. In the latter year, Alois F. Kovarik, an instructor at the Decorah Institute, Decorah, Iowa, published the results of an extended series of meteorological observations at the Decorah Ice Cave which clarified the mechanics of static glacières and rationalized the seemingly incongruous features of such caves. The endorsement of Kovarik's work by E. S. Balch in his monumental "Glacières or Freezing Caverns" (1900) assured its acceptance and established the Decorah Ice Cave as the type example of static glacière in North America.

The Decorah Ice Cave was developed and shown to tourists by Stanley Scarvie and others from 1929 until 1941. Despite its scientific importance, however, the cave was found to be too small to support a commercial venture after larger and more scenic caves were discovered nearby. The cave now is included in the Decorah park system and, although described in many regional tourist handbooks, seems largely to have been forgotten.

THE FINGER OF GEOLOGY—THE SEARCH FOR LESTER HOWE'S GARDEN OF EDEN DURING THE LATE 1920'S AND EARLY 1930'S

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Lester Howe discovered Howe's Cave, now known as Howe Caverns, in 1842. News of this discovery spread and people came to visit Schoharie County, New York and the new natural wonder. The popularity of the cave increased, but Howe later relinquished control of the cave to the Albany and Susquehanna Railroad. Embittered by this event and by the continued success of the cave as a tourist attraction, he retreated to his farm, which he had named the Garden of Eden, and became a recluse. It was during his hermitage that he was heard to say that he had discovered a bigger and better cave, but, in light of his misfortune in the Howe's Cave venture, he chose not to reveal its location, lest someone take advantage of him once more. He supposedly died without either revealing the location of the cave or whether his story was indeed true.

During the late 1920's and early 1930's, a local group, including Arthur H. Van Voris and Col. Edward A. Rew of Schoharie County, were exploring caves in the area when they chanced upon early accounts of Howe's secret. They eagerly sought his Garden of Eden Cave and believed that they had found it in Van Vliet's Cave, near the village of Schoharie. This cave they thought to have been a linear extension of Howe's Cave prior to its having been severed by the deepening of the Cobleskill Valley. Newspaper accounts, personal communication with Mr. Van Voris, and subsequent exploration of Van Vliet's Cave indicates that Lester Howe's Garden of Eden Cave was not rediscovered by Van Voris' party, but that Van Voris and his group had penetrated beyond known cave passages in Van Vliet's Cave.

CAVERNICOLOUS MODIFICATIONS OF A MALHEUR CAVE PSEUDOSCORPION

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Malheur Cave, a Pleistocene lava tube in southeastern Oregon, provides a mesic habitat in an otherwise fairly xeric environment. A series of Berlese samples of debris from the cave floor yielded information about the microfauna within the cave and revealed a new species of pseudoscorpion, *Apochthonius malheuri*. Although the genus is widespread and common throughout the United States and is represented by a number of epigean species in Oregon, this manuscript species is the first example reported from a cave west of Missouri and Arkansas. Pseudoscorpions, small duff-inhabiting arthropods, require a minimum of adaptive change to exploit cave environments. In common with many other cave-dwelling forms, these animals typically exhibit decreased pigmentation, reduction of photoreceptors, and attenuation of appendages. In addition, elongate setae and giantism frequently are observed.

In contrast to epigean members of the genus, *Apochthonius malheuri* has little brown pigment and, therefore, is a delicate reddish tan in color. Although most species of the genus are four-eyed, the new species possesses only one pair, which are very weakly developed. Statistical analysis confirms the supposition that this species does show significant degrees of giantism and of attenuation. The setae do not appear to be especially elongate. The total specialization of this species for cavernicolous existence is not as marked as is that exhibited by many species found in the limestone caves of the eastern United States.

TEMPERATURE PREFERENCE RESPONSES OF SOME AQUATIC, TROGLOBITIC CRUSTACEANS FROM CENTRAL TEXAS AND MEXICO *

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The purpose of this study was to determine the preference responses of five species of aquatic, troglobitic crustaceans to a temperature gradient. I studied two gammarid amphipods, *Stygonectes hadenoecus* (Holsinger) and *S. russelli* (Holsinger), an unidentified asellid isopod, and two cirolanid isopods, *Cirolanides texensis* (Benedict) and *Speocirolana bolivari* (Rioja).

* This study was supported, in part, by a grant from the American Museum of Natural History.

The temperature gradient apparatus was an aluminum channel, housed in an insulated case. The gradient was established by means of heating strips and circulating coolant. Proportional temperature controllers actuated this antagonistic system, so that a stable gradient of 15° to 30°C resulted. Forty-eight individuals of each species were kept in the laboratory under cave conditions (constant temperature and darkness) and were tested in six or eight replicates under both constant and gradient conditions. The animals were introduced randomly into a gravel-floored, water-filled tray which precisely fit the aluminum channel. Thirteen thermistor sensors, spaced at 10 cm intervals, delimited twelve areas in the tray. The positions of the animals in these areas were recorded at five minute intervals for two hours, yielding 1,152 observations for each species. Temperatures fluctuated no more than ±0.5C°.

The results were analyzed by contingency-table analysis and by linear-regression analysis. Only one species, *Cirolanides texensis,* had a well-defined preferendum, and it preferred temperatures 2 to 12°C higher than its natural habitat. The weak temperature preferenda of the other four species are best explained by Mitchell's hypothesis (1968), that imprisoned troglobites should lose their ability to respond to environmental conditions which in the cave are constant. The preferendum of *C. texensis* can be explained by the hypothesis that it is recently descended from a tropical, epigean, freshwater ancestor.

FAUNA OF HAWAIIN LAVA TUBES

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The Hawaiian Islands are a string of oceanic volcanic islands extending more than 1,500 miles across the mid-Pacific. The western islands are raised coral reefs and shoals resting on seamounts. The seven inhabited islands total 6,450 square miles in area and are relatively young, geologically. Ages of the islands range from 5+ million years for the island of Kauai to 1 million years for the largest island, Hawaii. The native fauna and flora is composed of those groups which dispersed across upwards of 2,500 miles of open ocean, or island hopped, and became successfully established. Thus, the fauna is remarkably disharmonic. Among the vertebrates, there is but one terrestrial mammal, a bat. There are no reptilians. Among the insects, only 12 (37%) of the orders are represented, and those orders are represented only by a few families. Approximately 250 introductions gave rise to our entire native insect fauna, 5,000+ species, with better than 99% of these endemic. The aquatic, soil, and cave arthropods of the continents are poorly represented, most likely because of their lack of dispersal ability.

What Hawaii does have, though, is incredible! Those insects which won the dispersal sweepstakes have become adapted to fill the empty niches. Thus, we have such anomolies as terrestrial damselflies, flightless beetle-like lacewings, flightless flies, and aquatic moths. Endemic to these islands are 700 species (approximately one-third of the world's known fauna) of Drosophilidae (vinegar flies). These evolved from just 1 or 2 introductions. To this now must be added a remarkable cavernicolous fauna. Some of the cave species are closely related to speciating surface groups and display the remarkable adaptive shifts characteristic of our successful endemic complexes; for example, the 2 species of troglobitic planthoppers, Cixiidae, and the world's first troglobitic lycosid spiders. Other cave anthropods are not related to anything known in the surface fauna and may or may not be relict. Among these, are the world's first troglobitic bug, Mesoveliidae, and the first troglobitic terrestrial amphipod. The potential for evolutionary research in Hawaiian caves is

significant. The 2 favored biomes of evolutionary biologists are oceanic islands and caves. Now, for the first time, these have been combined.

The main source of energy in shallow lava tubes is tree roots. These are fed on directly by phytophagus cavernicoles, which are in turn fed upon by predators and scavengers. To date, some 25 new species of native insects have been discovered in Hawaiian lava tubes, of which 12 are considered to be troglobites.

BATS OF OREGON, WITH EMPHASIS ON A BAT BANDING PROGRAM IN CENTRAL OREGON

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Oregon has seventeen separate species of bats, many of whom are transient or migratory by nature. Seven of these species are divided into fourteen subspecies which typically are separated, geographically, by the Cascade Range. The Cascades trend from north to south and separate Oregon into two distinct environmental regions. A limited bat-banding program, involving nearly 200 bats, has been carried out in central Oregon beginning in 1963. The predominant species among those studied has been *Plecotus townsendii*, the Long-Eared bat. Seven lava tubes in the High Lava Plains of central Oregon have served as our principal study localities. In at least one of these caves, our data has indicated seasonal occupancy, from October to May, for hibernating bats. However, an almost total absence of members of the genus *Plecotus* from most of the study caves was noted during the summer months.

SURVIVAL AND MOVEMENT OF BIG-EARED BATS *(PLECOTUS TOWNSENDII)* IN LAVA TUBES IN SOUTHWESTERN WASHINGTON

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Winter hibernation colonies of the western big-eared bat, *Plecotus townsendii*, occur in the lava tubes south of Mt. St. Helens in Skamania County and west of Trout Lake in Klickitat County, Washington. The bats are found alone or in small clusters, on the ceiling or on the sides of certain tubes. Preferred sites seem to have less air circulation and to be cooler than nearby unused sites and caves. The preferred temperature seems to be less than 5°C. The bats seem to come to the sites starting in October and to leave by March, but movement into caves is noted all during the winter. The bats at Mt. St. Helens move south and west to lower elevations during the rest of the year and have been recovered both at Woodland and at Vancouver, about 30 miles away. The ones near Trout Lake are found in the same area during the summer, but also have been found near White Salmon.

About 60% of the banded bats survive each year, to be recaptured later. The decline in colony size is felt to be due partly to banding and partly to disturbance during the winter hibernation period.

Several species of *Myotis* are found roosting in the caves during the summer and, also, feeding about the mouths of the caves, but these rarely are seen during the winter.

INFORMATION FOR CONTRIBUTORS TO *THE NSS BULLETIN*

Papers discussing any aspect of speleology are considered for publication in *The NSS Bulletin.* We particularly welcome articles describing important caves and cave areas, on the history of caves and of speleology, on problems and techniques of cave conservation, and critical reviews of current literature, in addition to papers on the more traditional subjects of cave geology, geography, fauna, and ecology. The material presented must be original and of lasting interest. Authors should demonstrate the significance of their work to speleological theory and should elucidate the historical antecedents of their interpretations by reference to appropriate literature. Presentations consisting of raw data, only, will not be accepted.

A narrative style of writing is preferred. Fine prose is terse yet free from lacunae, sparkles without dazzling, and achieves splendor without ostentation. Data and interpretations blend effortlessly along a logical continuum so that the reader, having read, neither knows nor cares how many pages he may have turned while following the author's exposition.

As written language must communicate through time as well as across space, neologisms should be introduced only if needed to express new concepts or to record new percepts. This is especially important in an archival journal such as *The NSS Bulletin.* Standard usage, therefore, is required of all authors. For general style, refer to papers in this *Bulletin* and to the following handbooks: "Suggestions to Authors" (U. S. Geological Survey), "Style Manual for Biological Journals" (American Institute of Biological Sciences, Washington, D. C.), and "A Manual of Style" (The University of Chicago Press).

Articles on earth sciences (including pseudokarst), life sciences, conservation, history, and exploration should be sent directly to the appropriate specialist on the Board of Editors (see masthead); articles not clearly falling into any of those categories may be sent to the Managing Editor. Potential contributors, especially those not professional scientists or writers, are invited to consult with the editors for guidance or aid in the presentation of their material.

Two double-spaced, typewritten copies of each manuscript, including all illustrations, are required. Manuscripts should not exceed about 10,000 words in length (approximately 40 pages of typescript), although this limit may be waived when a paper has unusual merit. Photographs must be sharp, high in contrast, and printed on glossy paper. All line drawings should be neatly rendered in "india" ink or its equivalent; the smallest lettering must be at least 2 mm high after reduction. Typed lettering is not satisfactory. Captions will be set in type and added in proof. The dimensions of original drawings and of cropped photographs should be made some multiple of the length and width of a column or of a page, when possible, in order to avoid problems with the layout. In case of doubt regarding length or illustrations consult with the editors.

Abstracts are required of all papers; these must be brief and must summarize the author's discoveries and conclusions, not merely tell what he did. Captions are required for all illustrations. All unusual symbols must be defined. References to the literature must be by author and date, with specific pages where desirable. Literature cited must be listed in an end bibliography with entries arranged alphabetically by the author's surname, typed in the format employed in this *Bulletin*.

Contributed papers will be refereed by one or more authorities in the appropriate specialty and will be edited for style before publication. After being refereed and again after being edited, papers will be returned to the authors for inspection and for any revisions which may be necessary.

Reprints may be ordered when galleys are returned by the authors to the Managing Editor; these will be supplied at cost.

INFORMATION FOR CONTRIBUTORS TO THE NSS BULLETIN

CONTENTS—Continued

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Discussion of papers published in the BULLETIN is invited. Discussions should be 2,000 words or less in length with not more than 3 illustrations. Discussions should be forwarded to the appropriate editor within three months of publication of the original paper.

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CONTENTS