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Contents

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Discussion of papers published in the Bulletin is invited. Discussions should be 2000 words or less in length with not more than 3 illustrations. Discussions of papers in this issue should be forwarded to the editor by October 15, 1966.

Barometric Wind in Wind and Jewel Caves, South Dakota

By Herbert W. Conn

ABSTRACT

Strong winds blow in and out of Wind and Jewel Caves in South Dakota's Black Hills. Although thought to be barometrically caused, they are stronger than winds of this origin in other caves. The theory of barometric wind in a one-entrance cave is explored. Expressions for calculating wind flow from the barometric records are found for two simple cave forms, the balloon-shaped cave and the tube-shaped cave. A device for recording cave wind velocity was developed, and wind and air pressure measurements were taken over periods of 11 to 16 days at the entrances to both caves. Correlation of the measured and calculated wind supports the barometric theory for these caves, as opposed to other theories such as the chimney effect. From the data, cave volume can be estimated and other characteristics of the caves deduced.

Introduction

When South Dakota's Wind Cave was discovered in 1881, Tom Bingham was attracted to the spot by the sound of wind rushing from the tiny entrance. Story has it that the wind was so strong it blew his hat 20 feet into the air when he leaned over the hole. Returning on another occasion with his brother Jesse, he tried to demonstrate the phenomenon, but this time his hat was sucked into the hole and never seen again.

Wind rushing through a black hole in the earth is awe inspiring, suggesting mysterious forces acting in the underground vastness. Moreover the wind can blow out the explorer's light, chill him to the marrow, and cool his enthusiasm to explore. However, because the wind obviously must be coming from somewhere beyond, it can also stir his curiosity and lure him on.

The Black Hills in South Dakota have a number of these blowing holes. Jewel Cave, 20 miles northwest of Wind Cave, was discovered by the sound of the wind. At Jasper Cave, a mile northwest of Jewel Cave, the wind is not strong enough to attract attention at the entrance, but just inside there is almost always the roar of air rushing through a vertical tube of two square feet cross-section. One can squeeze through to the lower part of the cave, though the wind protests mightily as the spelunker vies with it for passage space. What happens to the wind farther on, though, is a mystery. Below the vertical tube the cave divides into several branching passages, none of which can be followed more than a few hundred feet.

The entrance passages to both Wind and Jewel Caves have been artificially enlarged for easy visitor access, so that in their most constricted places the passage cross-sections are 20 to 25 square feet. There the Jewel Cave wind blows as fast as 15 miles per hour, the Wind Cave wind up to 25 miles per hour. Sometimes these winds change direction many times a day, while at other times they continue to blow in the same direction for three days or more.

Far back in the caves light breezes can be felt, usually one mile per hour or less. They are useful to the explorer in finding passage connections and new areas of cave. In places stronger winds are encountered, where a major part of the total air flow is funneled through a narrow connection. One such place in Jewel Cave, known as Hurricane Corner, served to awaken the writer's present interest in cave winds.

At Hurricane Corner, nearly a straight-line mile from the Jewel Cave entrance and more by devious cave routes, winds usually are strong enough to blow out lights and flap clothing. The wind's roar as it whips around the corner can be heard far down the passage. On several occasions we checked the wind direction here with that at the entrance and found the direction consistently the same. That is, wind flowing past Hurricane Corner toward the entrance continues through the intervening cave passages and out the entrance – or vice versa.

Does the wind at Hurricane Corner indicate a second entrance nearby or does it indicate much more cave beyond? To answer this question it was necessary to answer an even more perplexing question. What causes these winds in the first place?

Local opinion favored the barometric theory. When the barometer rises, air rushes into the cave to equalize the pressure inside. When the barometer drops, air rushes out for the same reason. But to our surprise we found that better informed speleologists questioned, not the theory, but the actuality – the fact that wind of such magnitude could be produced in this way.

In other caves barometer change was thought to be a relatively minor cause of wind. Moore and Nicholas (1964) discuss the various causes of air movement in caves. In regard to barometric air flow, they say, "Usually these air currents are so slow that they can be detected only with instruments. In constricted passages, however, or at small entrances to large caves, air currents caused by surface barometric changes are sometimes detectable as light breezes on the face." Blowing caves, with air currents stronger than a light breeze, are thought to have a different explanation.

In general there are two types of cave wind, the first where wind blows in one entrance and out another, and the second where only one entrance is involved. The first type is the commoner, the two-entrance wind, though sometimes the second entrance is not readily apparent. Usually this type of wind is a convection current caused by temperature difference inside and outside the cave. In winter when the cave is warmer than the outside, the warm cave air flows out the upper of the two entrances, thus bringing cold air into the lower entrance. This is the "chimney effect." In summer the air flow reverses.

Wind of this first type, which flows from one entrance to another, may be caused also by surface pressure difference at the two locations. When there is a barometric disturbance such as a thunderstorm, local pressure variations can occur over a small area. At Lehman Caves, Nevada, the normal chimney-effect wind sometimes reverses direction during a thunderstorm.*

The second type of wind, the one-entrance wind, seems to be less familiar. Besides the barometric effect, one-entrance wind may be produced by the resonance of the cave shape as in Breathing Cave, Virginia (Moore and Nicholas, 1964, pp. 27-30). Another one-entrance wind, studied by Podzimek (1958) in an ice cave in Czechoslovakia, is caused by the presence of relatively warmer cave rooms beneath the ice chamber. Air flows in and out of the warmer rooms much as water flows in and out of a geyser.

Wind of the second type, which requires only one entrance, can also occur in caves with multiple entrances, the wind at each entrance following its own independent pattern. However, such wind might well be masked by stronger chimney-effect wind, and it may be for this reason that the one-entrance barometric wind is seldom recognized.

Jewel Cave has only one known entrance. If Jasper Cave is connected to Jewel Cave, we know that the wind blowing into one cave is not blowing out the other, for a check on October 1, 1965 revealed both caves inhaling continuously throughout the same seven hour period. Wind Cave, besides the main entrance, has an elevator shaft which leaks some air, and two small blow-holes. We have checked the elevator shaft and both blow-holes when the cave is inhaling and when it is exhaling, and in each case the wind direction in all openings is the same. It is unlikely that in country so thoroughly combed by prospectors, hunters, and lumbermen, any unknown holes blowing large quantities of air exist, but the possibility cannot be ruled out.

Resonance does not seem a likely cause of these winds, for they are in no way similar to the wind in Breathing Cave. There is no regular frequency with which they change direction, and the time between changes is often a matter of days instead of minutes. Of the two-entrance wind theories, the chimney effect seems unlikely because the fluctuation is not seasonal. The wind is as apt to flow one way as the other, winter or summer. It is harder to reject the theory of pressure difference between the two entrances. Here one would expect some correlation between wind and barometer at entrance number one, and if this does not explain it all, who can say what the barometer may be doing at unknown entrance number two?

The best course, it seemed, was to see if the wind followed a predictable pattern governed by pressure change at the one entrance. Sooner or later a two-entrance wind would contradict this pattern. So for the present investigation we will assume there is a one-entrance cave with barometrically caused wind and see what happens.

THEORETICAL ANALYSIS

In this analysis we will, for simplicity, neglect the effect of temperature change. Cave air temperature is approximately constant, and only a small percentage of the cave air is exchanged with the outside. However, wind measurements at the cave entrance when the cave is inhaling will be at the outside temperature. As this entering air adjusts to cave temperature its volume will change, so that for strict accuracy an adjustment should be made to the measured wind velocity. During the actual wind measurements on which we base our analysis, the difference between temperature inside and outside never exceeded 30° F., for which the volume adjustment amounts to about 6%. For the present rough figuring we will ignore this correction.

First, let us suppose the cave entrance is large enough and the cave rooms close enough to the entrance so that the pressure throughout the cave will always be virtually the same as the pressure outside. In other words the cave will adjust almost instantaneously to outside pressure change.

If the cave volume is V, the air pressure inside and outside the cave P at the time t, then the mass of air M in the cave at time t equals $\rho_a VP/P_a$, where ρ_a is the density of air at $P=P_a$, the average atmospheric pressure at the cave locality. If P is changing at a rate dP/dt, M is changing at a rate $dM/dt = (\rho_a V/P_a)\, dP/dt$ (assuming constant temperature), so that the wind flow, in mass of air per unit time, is proportional to cave volume and to rate of barometer change. For air pressures in the atmospheric range, wind flow in volume per unit time is approximately proportional to the rate of mass flow. Dividing dM/dt by the density ρ_a gives us the rate of volume flow Q equal (approximately) to $(V/P_a)\, dP/dt$.

In the discussion that follows P_a will be assumed to be unity (one atmosphere of pressure) and the variable quantity P will be in atmosphere units.

Now let us assume some dimensions for this simple cave. Since it must adjust almost instantaneously to pressure changes, we will suppose one very large room 2000 feet long, 100 feet wide, and 100 feet high, connected directly to the outside through a door-sized walk-in entrance with an area of 25 square feet. The barometer, let us say, is rising (or dropping) very sharply, at the rate 0.06 inches of mercury per hour. If the average pressure is 30 inches of mercury, dP/dt will be 0.06/30 in atmospheres per hour. Wind flow Q then equals $V\, dP/dt = 40{,}000$ cubic feet per hour. The average wind velocity at the entrance is obtained by dividing the wind flow by the cross-sectional area of the passage, which gives 1600 feet per hour. This is about 0.3 miles per hour or less than 6 inches per second. Moore and Nicholas are right that such a wind can scarcely be felt.

To increase the wind velocity we must increase the cave volume or decrease the size of the entrance. Either way we are apt to disturb our simple cave system by introducing enough air resistance so that the cave can no longer adjust immediately to a new pressure.

The first step in increasing the complexity of the cave is to assume some air resistance at the entrance. This is the "balloon" cave, again one large room where pressure is uniform throughout the room, but with a more constricted entrance – perhaps a long crawlway, or a tiny hole like the original entrance to Wind Cave. Now there are two pressures to consider, surface pressure P_s, and cave pressure P_c, both functions of time. Our previous derivation for air flow in the simple cave is still valid if we use cave pressure in the formu-

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*Pers. communication, Keith Trexler, naturalist, National Park Service.

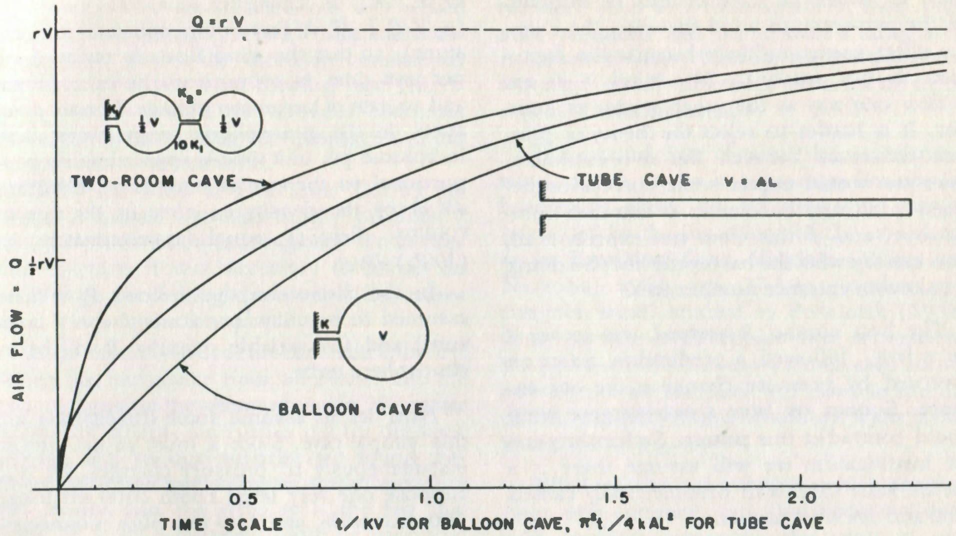

Figure 1.

Wind curves for linear barometer rise at rate r starting at t = O.

la, for it was based on the amount of air which must enter or leave the cave to change the cave pressure the proper amount. So, with pressure expressed in atmosphere units, we have:

$$Q = V\frac{dP_c}{dt} \tag{1}$$

If P_c is increasing, dP_c/dt will be positive, and the wind direction will be *into* the cave. As a convention we shall consider winds *in* positive, winds *out* negative.

Now Q also depends upon the pressure difference between surface and cave, $P_s - P_c$. If we assume wind velocities sufficiently low, air flow will be laminar (non-turbulent), and flow will be directly proportional to pressure difference. A constant of proportionality K is a measure of the air resistance of the entrance passage.

$$Q = \frac{P_s - P_c}{K} \tag{2}$$

It is possible to equate these two expressions for Q and solve for P_c in terms of P_s, and thus ultimately derive an expression for Q as a function of P_s and of t. However, since P_s is a complex function of time for which we cannot readily find a mathematical expression, the work must be done as a series of approximations. First we need to find the solution of equations (1) and (2) for a linear barometer rise (or drop), $P_s = P_0 + rt$, where r is the rate of surface pressure change, and P_0 is the particular value of P_s when $t = 0$. Equation (2) then becomes $Q = (1/K)(P_0 + rt - P_c)$. Equating these two expressions for Q:

$$V\frac{dP_c}{dt} = \frac{P_0 + rt - P_c}{K} \tag{2.1}$$

This is a linear differential equation of the first order; if we specify an initial wind at time zero equal to Q_0, the solutions are:

$$P_c = P_0 + (rV - Q_0)K \exp\left(-\frac{t}{KV}\right) + r(t - KV) \tag{3}$$

$$Q = (Q_0 - rV)\exp\left(-\frac{t}{KV}\right) + rV \tag{4}$$

As t approaches infinity the exponential term vanishes, and Q approaches rV, which is the wind necessary to adjust completely to a barometer rate of change r, and is the same as we would get for the simple cave investigated earlier. Note $dP_s/dt = r$.

Now it is possible to take an actual barograph record and divide it into many straight line segments, as many as desired for good approximation. If we know the wind at the beginning of one segment the wind throughout the interval of time included by the segment is given by equation (4). At the end of the first segment Q becomes the Q_0 for the second segment, and thus the wind calculation can be continued for the entire barograph record.

It was mentioned above that we are assuming low wind velocities and non-turbulent air flow. Actually there will be turbulence at the cave entrances for any wind velocity we are likely to measure.* Farther into the cave, where passage cross-sections are greater and more parallel paths are available for the wind, the same air flow which produces turbulence at the entrance may produce the slower velocities of laminar flow. As the air flow increases, turbulence will occur throughout an increasing proportion of the cave passages, so that an exact analysis of the problem becomes hopelessly complicated.

For turbulent air flow Q is proportional, not to the pressure difference, but to its square root. The simple proportionality of the equation for laminar flow lends itself much more readily to a mathematical treatment and will be used in the following analysis. In reality the air resistance K in equation (2) is not a simple constant of proportionality, but we can think of it as a mean value which should serve for a rough, semi-quantitative analysis. The error produced by this simplification should become increasingly evident as air flow increases, because the amount of turbulence in the cave will increase correspondingly. As turbulence raises the air resistance, actual wind velocities should prove to be less than those which we calculate whenever air flow is larger than average. When turbulence thus lowers the wind peaks, pressure will not equalize as fast as predicted, and so the wind should be faster and continue longer following such a peak.

If air resistance is an appreciable factor far back in the cave, we can no longer consider it a balloon-shaped cave. Another idealized cave form that may come closer to the truth is the tube-shaped cave. Here we imagine a tube of uniform cross-section A extending a distance L into the earth. The cave volume $V = AL$. Cave pressure is now not only a function of time, but a function of another independent variable x, the distance from the entrance to the point being considered. At this point x, let us picture a thin slice of the tube with length Δx. Suppose the pressure in this slice (holding x constant) is increasing at the rate $\partial P/\partial t$. The mass of air enclosed in the slice is increasing, then, at the rate $(\rho_a A\Delta x/P_a)\partial P/\partial t$. There must be a difference of this amount, per unit time, in the mass of air entering one end of the slice and that leaving the other end. Letting P_a equal one atmosphere, and dividing by the density ρ_a, gives (approximately) the difference in volume flow $\Delta Q = -A\Delta x\,\partial P/\partial t$. The wind as one moves toward the back of the cave (increasing x) must be decreasing, so the sign is negative. Now holding t constant and letting Δx approach zero, we have:

$$\frac{\partial Q}{\partial x} = -A\frac{\partial P}{\partial t} \tag{5}$$

If the air resistance of the tube is k per unit length, the air resistance of the slice will be $k\Delta x$. Air flow through the slice (assuming laminar flow) equals the pressure difference between one end of the slice and the other ΔP, divided by the air resistance $k\Delta x$. The sign is again negative, because wind flows in the direction of decreasing pressure. Holding t constant and letting Δx approach zero, gives us:

$$Q = -\frac{1}{k}\frac{\partial P}{\partial x} \tag{6}$$

The solutions to equations (5) and (6) depend upon the initial conditions in the cave at time zero. In the simplest case, assume at $t = 0$ that P is uniform and Q is zero throughout the cave. At that moment, let us say the outside pressure jumps instantaneously from P_0 to P_1, then remains constant. Another boundary condition that must be fulfilled is that at $x = L$ (the back of the

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*In a smooth round tube of 15 square feet cross-section, air flow enters the turbulent range at about 0.05 miles per hour.

cave), Q remains zero for every value of t. Under these conditions the solutions are given by these infinite series:

$$P = P_1 - \frac{4(P_1-P_0)}{\pi}\sum_{n=1}^{\infty}\frac{1}{2n-1}\exp\left(\frac{-(2n-1)^2\pi^2 t}{4kAL^2}\right)\sin\frac{(2n-1)\pi x}{2L}$$

$$Q = \frac{2(P_1-P_0)}{kL}\sum_{n=1}^{\infty}\exp\left(\frac{-(2n-1)^2\pi^2 t}{4kAL^2}\right)\cos\frac{(2n-1)\pi x}{2L}$$

At the entrance where $x = 0$:

$$Q = \frac{2(P_1-P_0)}{kL}\sum_{n=1}^{\infty}\exp\left(\frac{-(2n-1)^2\pi^2 t}{4kAL^2}\right) \quad (7)$$

It will be noted that for $t = 0$, in other words right at the moment of the instantaneous pressure jump, the wind as given by equation (7) is infinite. Since no pressure jump can be actually instantaneous, it will pay us to examine the situation where the barometer rises at a linear rate r, as we did for the balloon cave.

Let us think of the linear rise as an infinite series of infinitesimal jumps. Each jump dP produces at the entrance a wind component dQ given by equation (7) if $(P_1 - P_0)$ is replaced with dP. If $t = y$ at the time of the jump, we must also replace t in equation (7) with $t - y$. If the jump occurs at a time interval dy following the previous jump, then $dP = r\,dy$. Making these substitutions in equation (7) and integrating from $y = 0$ to $y = t$, gives the total wind at time t:

$$Q = rV\left[1 - \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(\frac{-(2n-1)^2\pi^2 t}{4kAL^2}\right)\right] \quad (8)$$

For shorthand we will write this: $Q = rV[1 - f(t)]$. The infinite series converges rapidly when t is large; when t is small $[1 - f(t)]$ may be approximated very closely by the expression $2\sqrt{t/\pi kAL^2}$, which is derived from consideration of a tube of infinite length.

Equation (8) gives the wind at time t for as long as the outside pressure rises at the rate r, provided that the cave was in equilibrium at time zero. However, we cannot find a single formula for the situation where there is an initial wind Q_0 at time zero, as we did for the balloon cave. Given Q_0 for the balloon cave, the initial pressure condition inside the cave is also determined. But in the tube-shaped cave, for each Q_0 at the entrance there is an infinite set of wind and pressure conditions farther back in the cave. What we must do is figure the wind component due to each pressure segment as if the cave were in equilibrium at its start, then add up the components.

We can show by integrations similar to the one just done that if, starting again with equilibrium at time zero, the barometer rises at a rate r_1 until time t_1, then rises at rate r_2 until t_2, and so on, then at time t_n:

$$Q = V\left[r_n - r_1 f(t_n) - \sum_{j=1}^{n-1}(r_{j+1} - r_j)\, f(t_n - t_j)\right] \quad (9)$$

As can be seen, the mathematics for analyzing cave winds gets fairly complicated even for simple cave forms. The complexity of an actual cave will be impossible to analyze, though we may hope to gain some knowledge of the actual cave form by comparing it with the simple form which produces wind most closely approximating the actual wind. A comparison of wind in the balloon– and tube-shaped caves is shown in figure 1 for a linear barometer rise. The two caves are assumed to have equal volume, and air resistances K and k are so chosen that $KV = 4kAL^2/\pi^2$, thus producing wind responses approximately equal if t is large enough. It can be seen that the tube-shaped cave produces stronger wind when t is small, or in other words, there is a greater immediate response to pressure change.

If we think of a cave shaped like a tapering tube, the diameter increasing as we go in, the wind curve would lie between the two curves for the balloon and the straight-tube shapes. The balloon cave is the extreme case of an infinite taper, and no possible cave form can produce a wind curve below that of the balloon cave. However theoretical cave forms can produce wind curves lying above the curve for the tube cave; in fact the straight tube is the intermediate case between increasing and decreasing taper. If the tube becomes smaller as we go inward, the curves will lie above the straight-tube curve; however, tubes of this sort would require such large entrances in comparison to cave volume that wind would probably be unnoticed.

The third curve on figure 1, which does lie above the tube curve except at the very start, is for a cave with two rooms of equal size, one beyond the other. Air resistance at the connection between the two rooms is ten times as great as that at the entrance. The mathematics of deriving this curve will not be included here, for it has not been used in analyzing actual data. The curve is shown to demonstrate the manner in which wind may vary for different cave shapes.

So much for theory. What actually happens at the real cave entrance?

FIELD DATA

Initial wind measurements (December 1963) were made with a Dwyer hand-held wind gauge, every five minutes at the cave entrance for as long as eight hours. Barometer readings were taken at the same intervals and curves were plotted. It was soon apparent that fluctuations in the cave wind correlated with barometer movement, but also it became obvious (at least at Jewel Cave) that eight hours was too short a span to give conclusive results. A strong wind at the day's beginning, presumably due to a previous pressure change of unknown amount, would not have died out in the evening when we gave up the vigil.

In May 1964, with a recording barometer in the ranger cabin near the Jewel Cave entrance, we were able to check the wind readings on a particular day against the pressure chart for that day and for many days before. The time lag between barometer peak and wind reversal was demonstrated on May 16, when the barometer passed a sharp peak at 6:30 a.m., but the wind did not reverse until 3:30 p.m., 7 hours later.

Similar measurements at the Wind Cave entrance (November 1964 and January 1965) revealed stronger winds and a much shorter

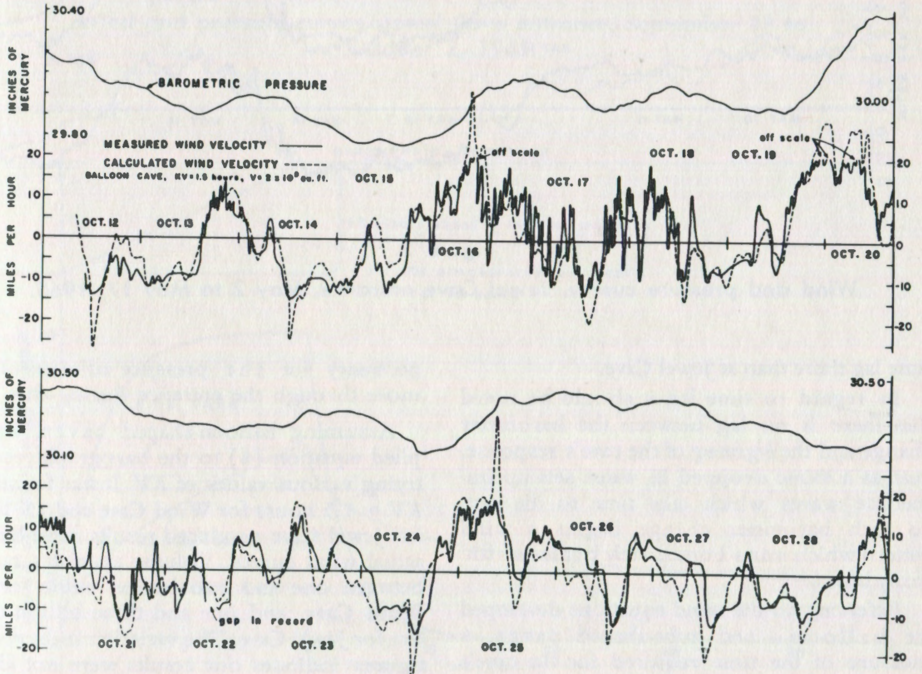

Figure 2.

Wind and pressure curves, Wind Cave entrance, October 12 to October 29, 1965.

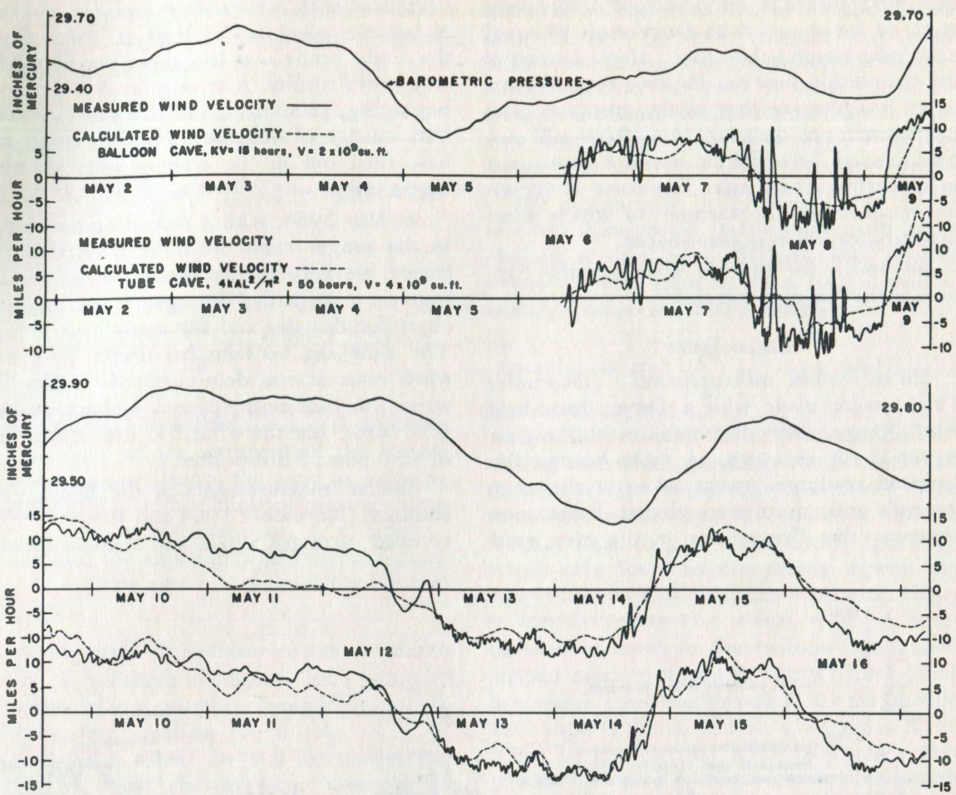

Figure 3.

Wind and pressure curves, Jewel Cave entrance, May 2 to May 17, 1965.

time lag there than at Jewel Cave.

In regard to time lag it should be noted that there is no lag between the barometer change and the *beginning* of the cave's response. Just as a stone dropped in water sets up immediate waves which take time to die out, so each barometer change begins a wind pattern which starts immediately but lasts for many hours.

Referring to the wind equations developed for balloon- and tube-shaped caves, a measure of the time required for the cave's adjustment to a new pressure is given by the constants KV for balloon and $4kAL^2/\pi^2$ for tube shapes. These constants figure out to be in units of time, and it can be shown from the equations that roughly 2/3 of the air necessary for the pressure adjustment will move through the entrance during that time.

Assuming balloon-shaped caves, we applied equation (4) to the barograph records, trying various values of KV. It was found that KV = 1.5 hours for Wind Cave and 15 hours for Jewel Cave produced results most like the actual wind curves. Volume estimates ranged between one and two billion cubic feet for Wind Cave, and one and three billion cubic feet for Jewel Cave. The variation in the volume figures indicates our results were not always consistent, and it seemed probable that our balloon-cave model was not entirely adequate. However there was still insufficient data to try the tube-cave equation, or even to be completely sure we were on the right track. There

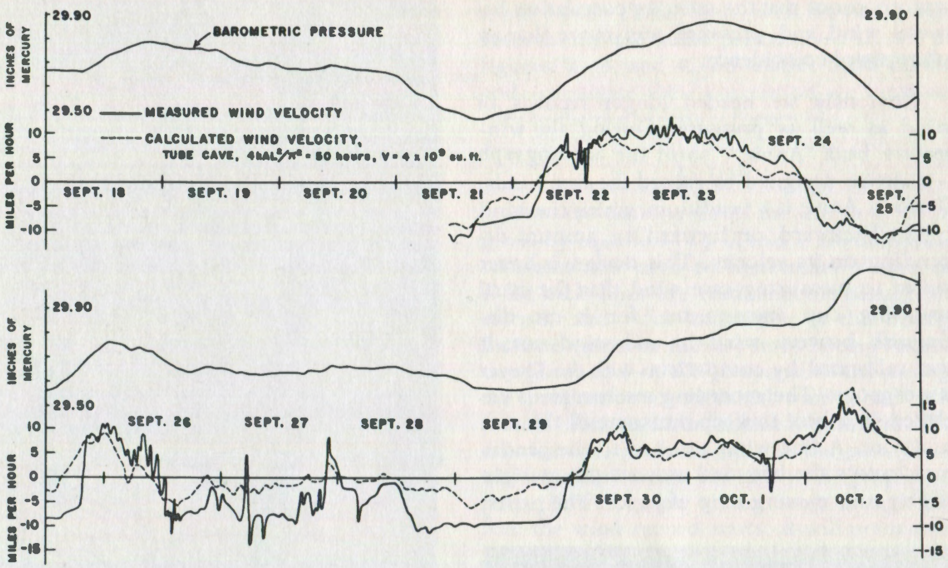

Figure 4.

Wind and pressure curves, Jewel Cave entrance, September 18 to October 2, 1965.

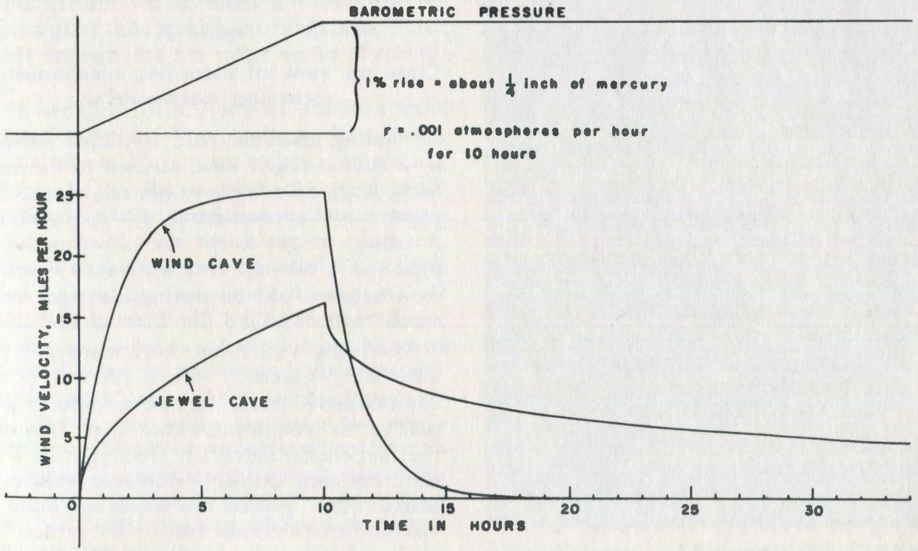

Figure 5.

A comparison of entrance wind, Wind Cave and Jewel Cave, calculated from a theoretical barometer rise.

was no proof that the seeming correlation between wind and pressure was more than an oft-repeated coincidence.

Obviously we needed longer records of wind as well as pressure. During the winter we built "Annie," short for anemograph – a device designed to record the cave winds. Basically Annie is a pendulum, which the wind blows backward or forward an amount depending on its velocity. This design is better suited to measuring cave wind than the usual revolving cup anemometer, for it can distinguish between wind in and wind out. It was calibrated by comparison with the Dwyer wind gauge. The recording mechanism is enclosed in a box to keep out some of the cave moisture. A fine wire, attached to the pendulum, enters the box and moves a pen at right angles to a moving strip of paper. The paper, an adding machine roll, is pulled forward by a rubber-edged disk attached to the hour-hand shaft of a battery-operated clock. The paper moves approximately 3/4 inch per hour. A falling weight keeps the paper pulled up tight on a take-up reel and takes much of the frictional load of moving the paper which would otherwise be the duty of the clock.

Figure 6.

"Annie," the recording anemometer, in operating condition in Jewel Cave, South Dakota.

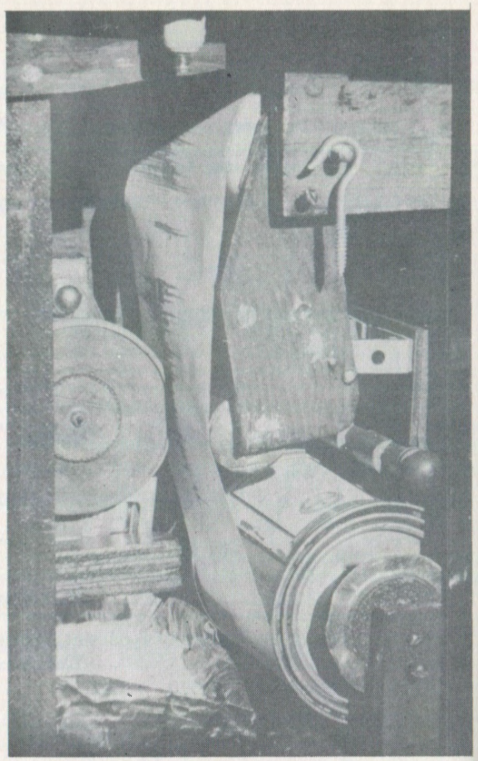

Figure 7.

Close up view of recording mechanism in recording anemometer.

Problems with Annie were many, and they were only gradually solved. A tray of calcium chloride inside the box absorbed a large part of the troublesome dampness. However, alternate condensation and freezing at the Wind Cave entrance during below-zero weather in March 1965 proved too severe for both the machine and its repairman, so the project had to be abandoned awaiting milder weather.

For a writing mechanism we tried various pencils and pens. Pencils required too much pressure to write, creating friction. Ball-point pens which would write on damp paper refused to work in the cold, and vice versa. Pens using a liquid oil-base ink, the non-evaporating type used in other recording instruments, worked best but required daily refilling until we acquired a remarkably designed glass tube and tank arrangement which holds enough ink for many weeks of recording.

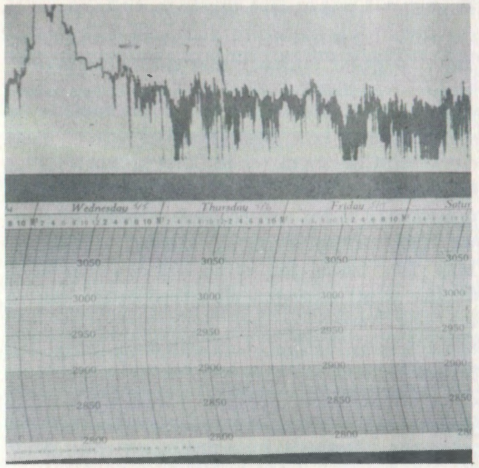

Figure 8.

Specimen anemograph (above) and barograph (below) records.

In her latest form, Annie will run for a week without attention. The pendulum has a wind surface area of 400 square inches at an average distance of 34 inches from the pivot. Adding weight to the pendulum increases the velocity range of wind which can be measured, but at Wind Cave even an extra 25 pounds failed to keep the instrument from going off scale at peak wind velocity. Another problem, still unsolved, occurs at low wind speeds when the wind force is not enough to overcome the frictional drag of the recording mechanism. Below five miles per hour the sensitivity is poor, and occasionally when the cave is exhaling and everything is damp, the pendulum has been found sticking at about the 8 mile per hour position, though the actual wind speed is less.

Two wind records, lasting about 11 days each, were obtained at Jewel Cave, one in May and one in September 1965. A 16-day wind record was obtained at Wind Cave in October 1965. These, along with the barograph records for the same periods, are shown in figures 2, 3, and 4. To analyze these curves and investigate their correlation we must return to the mathematical theory.

ANALYSIS

For the balloon cave, the air flow Q is given by equation (4). K and V are unknown constants we need to determine. Values of P for each hour are read from the barograph record, and r for each hour is the hourly increase (plus or minus) in P. Letting t equal one hour, $exp(-1/KV)$ is a constant expressing the proportion of an initial wind which will remain after an hour of steady pressure. We can assume, at some time in the past, there was equilibrium in the cave with Q equal to zero. If we choose a time long enough before the wind record starts, it will not matter if there was actually a wind at that time, for its effects will die out before we reach the period covered by the wind record.

So we assume $Q_0 = 0$. Then $Q_1/V = -r_1\ exp(-1/KV) + r_1$; $Q_2/V = (Q_1/V - r_2)\ exp(-1/KV) + r_2$; etc. In this way, for various trial values of KV, Q/V can be plotted as a function of time for comparison with the actual wind record. The correct value of KV should produce the same shape of the curves. Then V is determined as the proportionality factor necessary to make Q equal to the measured air flow. (An air flow of 80,000 cubic feet per hour is estimated to correspond, for both caves, to a wind velocity at the entrance of one mile per hour. The effective cross-sectional area of the passage is assumed to be about 15 square feet.)

For Wind Cave we get very good agreement with $KV = 1.5$ hours and $V = 2 \times 10^9$ cubic feet, as shown in figure 2. Wind Cave has a time constant short enough so that differences between the theoretical balloon-cave wind and the actual wind are not obvious on the curves. The chief discrepancy is that the actual wind does not follow when the calculated wind reaches its highest peaks. Here is evidence of our error in ignoring the turbulence of the cave air flow, which increases the air resistance for high velocities and consequently reduces the wind's speed. When turbulence reduces the air flow, pressure inside the cave will not equalize as quickly and the air flow will be prolonged. This effect is well demonstrated following the steep pressure rise of October 19-20. During the rise the wind did not reach its theoretical peak, while afterwards the wind did not decrease as fast as predicted.

This pressure rise of October 19-20 provides a good opportunity for an independent check of the cave volume. Between 2 p.m. October 19 and 9 p.m. October 20 the barometer rose 0.49 inches of mercury. As the average atmospheric pressure at the Wind Cave entrance is about 26 inches of mercury, the percentage rise was 1.9%. At the start of the rise the barometer was at its lowest point in more than three days, so that none of the air which subsequently blew into the cave could have been moved by a previous pressure rise. The area under the wind curve, from 2 p.m. October 19 to 11 a.m. October 21, figures to be about 480 miles of wind through the entrance during that period. Assuming the measured wind velocity to be effective over a 15 square foot cross-section, 480 x 5280 x 15 equals 38 million cubic feet of air which entered the cave. Since the barometer began to drop again before this wind ceased, we do not know that this was all of the air which the 1.9% pressure rise would eventually move into the cave. But we do know, if our basic assumption is correct, that the air volume of Wind Cave is *at least* 38,000,000/0.019, or 2,000,000,000 cubic feet.

Another opportunity to check our Wind Cave figuring was provided by barograph records taken in connection with the 1959 National Speleological Society Wind Cave Expedition. Barometric pressures inside and outside the cave were recorded from July 15 to November 1, 1958. The cave pressure curves are similar to the surface pressure curves except that the amplitude of the variations is a little less and the rough spots are smoothed out. For our balloon-cave model the cave pressure may be calculated from the outside pressure using equation (3). Thus we were able to compare the calculated cave pressure with that actually recorded on the 1958 charts. In general the curves compared well, but with a small consistent error. Using $KV = 1.5$ hours there was not quite enough "smoothing-out." Using $KV = 2$ hours, the peaks were modified more nearly the right amount, but the time lag was a bit more than it should be. Here is good evidence that the balloon cave, while providing an approximate picture, is not the whole story.

Jewel Cave is more difficult to analyze due to the longer time lag. To calculate the time constant KV for an equivalent balloon cave, we chose a point on the curves, 9 p.m. on May 14, when the wind velocity was zero as the wind changed direction from out to in. The barometer had been rising steadily since 3 p.m. of that day, and with $KV = 1.5$ hours (like Wind Cave) the wind would have changed direction between 3 and 4 p.m. The greater KV, the later the wind reversal will occur. In order to delay it until 9 p.m. we must have $KV = 15$ hours.

Figure 3 shows the pressure and wind curves for Jewel Cave for the period May 6 to 16. The upper dashed curve shows the calculated wind velocity based upon the pressure variation, assuming a balloon cave with $KV = 15$ hours and $V = 2 \times 10^9$ cubic feet. At first glance the agreement seems good, but we notice that from noon of May 10 to noon of May 12, the wind remained between 5 and 10 miles per hour, while the predicted curve drops rather quickly to zero. A larger volume and a longer time lag are indicated by this persistent wind; yet if we increase KV further, the lag will become too great at other points of the curve.

The lower dashed curve in figure 3 was calculated using the tube-shaped cave equation (9). Assuming equilibrium in the cave four or five days before, we figured Q/V for 9 p.m. on May 14, trying various values of the time constant $4kAL^2/\pi^2$. However it was found impossible to make Q/V zero. Increasing values of the time constant up to 50 hours decreased the wind at 9 p.m., while above 60 hours it increased again (due to the lingering effect of the barometer rise back on May 9!). Using the 50-hour figure a curve was plotted which shows markedly closer correlation with the measured wind than does the balloon curve. The cave volume has doubled in the process, now about four billion cubic feet.

If cave shapes other than the balloon or tube are used in analyzing the Jewel Cave wind records, it seems certain that the volume figure will always be more than the two billion cubic feet found for the balloon cave. Any other cave shape must have a portion of its volume farther removed from the entrance than in the balloon cave, and this more remote volume will add to that necessary to produce the initial wind peaks.

Figure 4 shows the pressure and wind curves for Jewel Cave for the period September 21 to October 2. The dashed curve is calculated from the pressure curve using the tube-cave equation and the same constants as before. The over-all correspondence is convincing, although there are discrepancies. The most serious one is on September 29, when from the straightness of the wind curve we are suspicious that Annie's pendulum was sticking.

All of the wind curves show short-term oscillations which the calculations do not predict. These are probably due to wiggles too small to see in the pressure curves, as the cave is a barometer more sensitive than the one we were reading.

DISCUSSION

The correlation of measured and calculated wind in figures 2, 3, and 4 is far too close for coincidence. Either our assumption of a one-entrance barometric wind is correct, or else another pressure-caused phenomenon is producing the same results.

The only other wind theory which may conceivably account for this correlation is the two-entrance wind produced by pressure difference between the two entrances, an alternate theory which we need to examine more closely.

Let us assume a cave of somewhat smaller volume with two entrances separated geographically enough so that the barometric pressure at the two locations will differ. If it is a random difference, produced by the whims of the wind and the sun, the cave wind it produces will bear no relation to that we have predicted by the one-entrance theory. However, suppose the difference is produced by the orderly movement of weather from west to east across the country. If the unknown second entrance is to the east of the known entrance, pressure there will always lag by the time it takes the weather system to move between the two entrances.

If we trace the pressure curve on transparent paper and then slide the tracing along the time axis of the original curve, we can see what happens. For any given time lag the curves will cross and recross each other at fixed hours at which the wind should be zero. Maximum wind will occur at hours where the curves are farthest apart.

Trying this experiment on the Jewel Cave records, we find we must displace the curves from 10 to 20 hours to produce wind resembling the actual measured wind. In 10 to 20 hours a weather system normally moves several hundred miles. It hardly seems possible that the second entrance can be that far away, especially as the cave limestone ends in an escarpment just six miles east of the Jewel Cave entrance! Of course it is possible, occasionally, for weather to move much more slowly, but in that event we are back under the influence of random weather variation and cannot expect any consistent correlation of wind with pressure at the known entrance.

The much shorter time lag at Wind Cave prevents our using the same argument there. If there is a second entrance, it need not be so far away. However to accept the two-entrance theory for Wind Cave, we must suppose that the weather movement was incredibly constant in both speed and direction during the entire 16 days of our record.

We believe, therefore, that the major part of the wind in both Wind and Jewel Caves is the result of the cave's adjustment to outside barometric changes, and that neither cave has a second entrance always blowing in the opposite direction. It is likely that one-entrance barometric winds of this magnitude are fairly rare. It takes a big cave to produce such winds, but there are other big caves. However, other caves may have more or larger entrances, so that there is not as much air flow per square foot of entrance area. Deal (1962) concludes that erosion in the Black Hills has filled more potential cave entrances than it has opened. In the Black Hills, too, much of the cave-bearing limestone is far underground, buried under other kinds of rock. Whereas other caves may breathe through frequent cracks and pores throughout their area, these caves may have almost no connection to the outside except at the known entrances.

Our analysis provides an interesting comparison of the two caves. Wind Cave has strong wind which dies out quickly after a pressure change, indicating that much of the cave volume is close to the entrance. The cave may resemble a balloon, or more likely a sponge, with intimately interconnected passages fanning out in all directions from the entrance. We would expect to find high wind velocities only near the entrance. Within a few hours an outside pressure change should reach most, if not all, of the cave.

Jewel Cave, on the other hand, has wind less strong which persists for many hours after the barometer becomes steady. Much of Jewel Cave must lie far from the entrance, separated perhaps by many constrictions. At these constrictions the wind may be fast, even far within the cave, as it is known to be at Hurricane Corner. We know now that the Hurricane Corner wind indicates much cave volume beyond, rather than a nearby entrance. If the cave resembles a tube, it is certainly not apparent in the known part of the cave, where the passages form a network almost as complex as in Wind Cave. Moreover, since the volume has been calculated as several billion cubic feet, the tube would have to be unbelievably wide or fantastically long. More likely the cave occupies a zone of limestone which is roughly tube-shaped, a zone filled with interconnected passages.

Because Wind Cave reaches equilibrium more quickly after a pressure change than does Jewel Cave, the wind at Wind Cave reverses more often. During the 16 days of our record at Wind Cave, the wind changed direction an average of four times a day, and on one day it switched 17 times. On the Jewel Cave records wind changes per day averaged $1\frac{1}{2}$.

After a pressure jump at the Jewel Cave entrance it will take about 24 hours for *one-half* of the air necessary to equalize the cave pressure to enter the cave. If the mercury rises $\frac{1}{4}$ inch and then steadies, Jewel Cave will continue to blow for over three days before the wind velocity drops to one mile per hour.

Figure 5 shows a comparison of the calculated wind for the two caves, assuming the same theoretical pressure rise.

Our figures show a volume of roughly two billion cubic feet for Wind Cave, based on wind which blows through the main entrance. An undetermined, but probably much smaller, volume should be added to this to account for the air flow through the elevator shaft and the blow-holes. The volume of Jewel Cave is at least two billion cubic feet, and may well be as much as four billion. These are air volumes, including of course small spaces inaccessible to the explorer. If we picture four billion cubic feet of cave space underlying one square mile of surface area, vertical holes drilled at random throughout the square mile would each, on the average, encounter 140 feet of cave. If we reduce the "cave density" by a factor of ten, each hole would then average 14 feet of cave throughout a surface area of 10 square miles.

While mentioning vertical holes, it is interesting to note that a well was drilled about 800 feet from the Jewel Cave entrance in 1959. As described by Dyer (1961) this hole encountered 20 feet of cave fill but no open cave passages in the 432 foot thickness of the Pahasapa limestone. However, in talking to local well drillers, we learned of another deep well four miles to the southeast which struck nine feet of cavern and blew in and out with a strong wind. In another blowing well 15 miles southeast of Jewel Cave and 10 miles west of Wind Cave, valuable drilling equipment was swallowed up in a cave space of unknown depth. The well drillers with whom we talked are not eager for work in this area.

Our investigation can be continued in several ways. Particularly we would like to compare pressure readings at the Jewel Cave entrance to those at or near the back of the known cave. Such a comparison will either confirm or contradict the idea of a tubular shape. If it confirms this idea, it should also tell us where in the tube the readings were taken and what proportion of the tube still lies ahead. If it contradicts the tube notion, it may indicate some other shape or pattern for the cave.

The question arises whether investigations of this nature would yield worthwhile information at other blowing caves. The first problem at any cave is to determine the true cause of the wind, a problem that will probably require collecting wind records over an extended period. If anyone wishes to begin a serious investigation, the author will consider loaning the vital parts of "Annie," those that cannot readily be improvised to suit the requirements of another cave.

ACKNOWLEDGMENTS

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REFERENCES

Deal, Dwight E.
1962 Geology of Jewel Cave National Monument, Custer County, South Dakota, with special reference to cavern formation in the Black Hills: Masters thesis, Univ. of Wyoming, 182 p.

Dyer, C. F.
1961 Geology and occurrence of ground water at Jewel Cave National Monument, South Dakota: U.S. Geol. Survey Water-Supply Paper 1475-D, pp. 139-157.

Moore, George W., and Brother G. Nicholas
1964 Speleology, the study of caves: D.C. Heath, Boston, 120 p.

National Speleological Society
1958 Wind Cave meteorological studies: unpublished records in National Park Service files, Wind Cave National Park, South Dakota.

Podzimek, Josef
1958 An attempt at explaining the "breathing" of spaces in ice caves: Studia geoph. et geod. 2, Czechoslovak Academy of Sciences, pp. 165-173.

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Cave-to-Surface Magnetic Induction Direction Finding and Communication

By **Royce E. Charlton, Jr.**

ABSTRACT

Wireless communication between cave and surface is now practical by the use of transistorized magnetic induction equipment. The equipment also has directional characteristics which are particularly suited to cave-to-surface correlation in the more complicated cave systems. Accuracy of cave maps can be checked, proximity of adjacent caves determined, and depth of overburden can be measured. The feasibility of digging artificial entrances or re-excavating collapsed entrances can be determined. The equipment is within the construction capability of anyone with electronic construction experience.

INTRODUCTION

The need for subsurface communication equipment is only partly fulfilled by conventional communication equipment. The telephone gives excellent results but laying telephone wire for any distance is a costly undertaking suited mainly to permanent installation. However, portable telephones have been successfully used between the surface and the bottoms of deep pits for many years. Radio operation within caves is poor and unpredictable. Minature radio transceivers (Citizens band, 29-30 mc) have been used with some success in pit work.

Cave communication by magnetic induction is feasible because a magnetic field has excellent ability to penetrate limestone. Communication by magnetic induction is not new. Morgan (1913) described voice communication in excess of 300 feet. Although this was done above ground, half the magnetic path was through the earth. As applied to cave communication, feasibility studies were conducted during 1950-51 by the author. Subsequently, vacuum tube equipment was constructed. However, because of size, weight, and fragility, experiments were shelved. The advent of inexpensive power transistors made possible the construction of lightweight Magnetic Induction Direction and Communication (MIDAC) equipment for use between cave and surface. Roeschlein (1960) described transistorized equipment with a range in excess of 400 feet and employing a frequency of two thousand cycles. Keith and Nixon (pers. comm.) designed a set with a range of 700 feet which operated satisfactorily but needed improvement. Oscillator frequency varied with battery voltage. Increased range, and an automatic beep circuit were desirable. There was a feed-back problem between the headset and the receiving coil. The oscillator, being separate from the transmitting coil, required a matching transformer that was difficult to find. The fact that the oscillator and coil were separate resulted in problems in tuning the oscillator and the coil to the same frequency.

PRINCIPLES OF OPERATION

The transmitting equipment consists of a transistorized oscillator, generating an alternating electric current, connected to a large diameter coil of wire which in turn produces an oscillating magnetic field. A frequency of 2000 cycles per second seems to be the most satisfactory. As frequency is raised above 2 kc, signal strength through limestone falls rapidly. As frequency is lowered, the reactance-resistance ratio of the transmitting coil decreases and the battery drain increases. At 2kc the frequency is so low there is practically no radiation of electromagnetic waves – radio waves. To produce any useful radio waves the frequency would have to be at least five times greater. The 2kc frequency simlifies receiver circuitry. Because it is within the audio range, only an audio amplifier and an earpiece are needed in conjunction with a receiving coil.

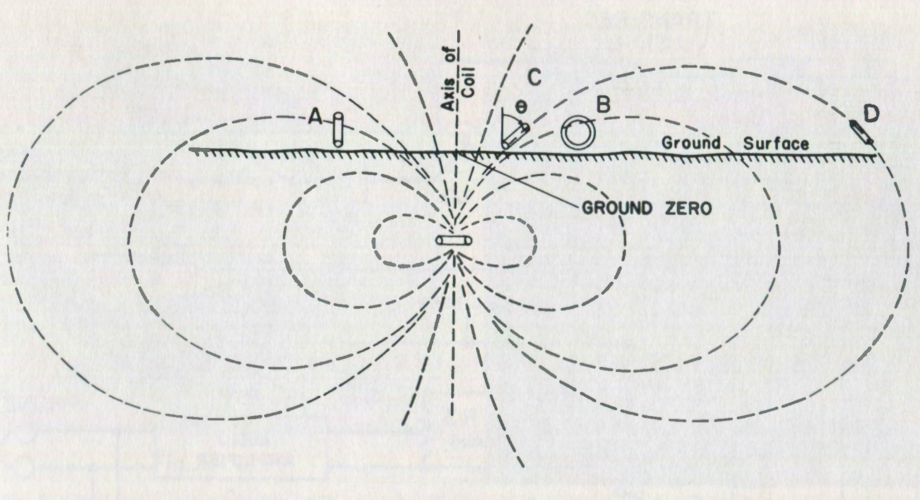

Figure 1.

Cross-sectional view of the magnetic field surrounding MIDAC transmitter.

The magnetic lines of force (dotted lines, figs. 1 and 2) pass through the center of the transmitting coil, follow a fan shaped path, and return to the opposite side of the coil. When the receiving coil is placed within this oscillating magnetic field and oriented perpendicular to the lines of force (A, figs. 1 and 2), a maximum number lines of force pass through the coil thus inducing a maximum signal for that location. If the receiving coil is rotated until it is parallel to the lines of force, none pass through the coil and no signal is received. This is a null position (B and C, fig. 1). In respect to the total magnetic field there are two types of null positions. The first is the radial null (B, figs. 1 and 2), in which the null plane of the receiving coil points to the axis of the transmitting coil and its ground zero. The second type is the tangential null (C and D, fig. 1) in which the null plane of the receiving coil follows the curve of the magnetic lines of force. The radial null is the easiest to use since it follows straight lines. Care must be taken when making a null reading to rotate the receiving coil on the proper axis.

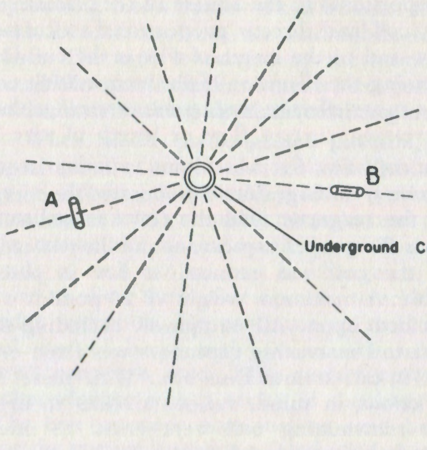

Figure 2.

Vertical view of MIDAC transmitter magnetic field.

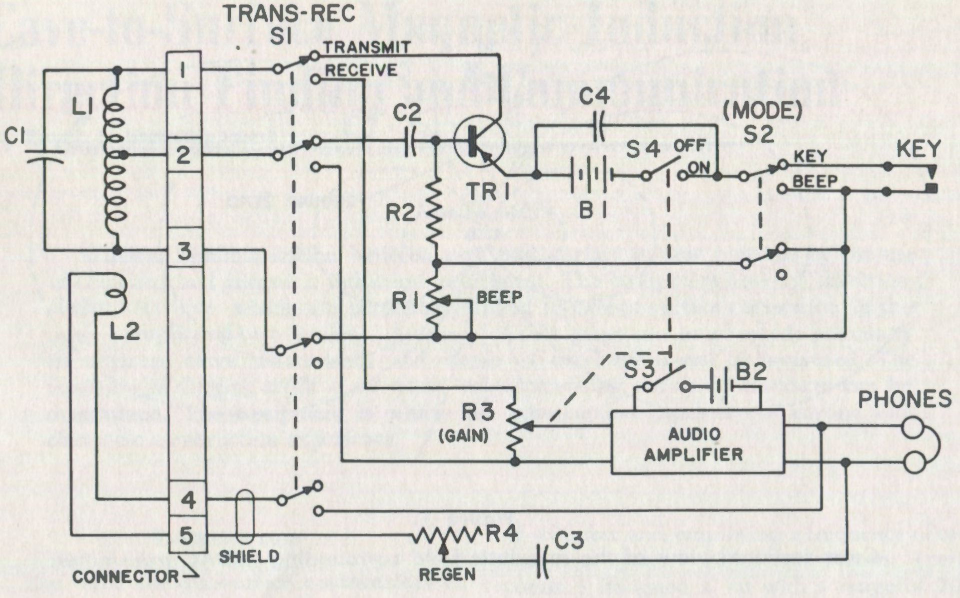

Figure 3.

Schematic diagram of MIDAC equipment.

Construction Considerations

Field strength of the transmitting coil at a distant point from the transmitting coil is proportional to the square of the diameter of the coil and directly proportional to current flow and to the length of wire in the coil. Increasing the diameter of the transmitting coil is a more effective way to increase range than increasing current flow or length of wire in the coil. Five feet was found to be the largest diameter manageable. To conserve the energy in the magnetic field the coil was resonated with the proper capacitance and the resistance of the coil was reduced as low as practicable. A maximum weight of 20 pounds was decided upon. All equipment excluding the coil and resonating capacitors was fitted into a 30 cal. ammunition box. With these restrictions in mind, various circuits to drive the transmitting coil were tested to determine which produced maximum field strength per watt of battery drain. Experiments were also conducted to increase the range of the receiver.

High powered oscillators and amplifiers were not needed for a transmitting coil drive. By center tapping a resonant coil and using it in its own oscillator circuit, the matching transformer and tuning of the coil to the oscillator were eliminated. Frequency was stable over a wide range of supply voltages. Sufficient current flow was obtained. With a coil of five foot diameter, 0.25 ohms resistance, 11 ohms reactance at 2 kc, and 30 volts supply, battery drain was 130 milliamperes (4 watts) at continuous signal and 25 to 50 milliamperes on automatic beep.

It was found that the transmitting coil functioned quite satisfactorily as a receiving coil. The resonating capacitor increased reception as well as reducing noise-mainly 60 cycle hum. The addition of positive feedback aided fringe reception. Because of its small size a commercial transistor amplifier was used in the receiver. This amplifier has two audio stages followed by a push-pull output stage. The gain is one millivolt input for 100 milliwatt output into an 8-12 ohm load. Input impedance is 2500 ohms at 1 kc. Battery voltage is 9 volts. Current drain at zero signal is 7½ milliamperes, maximum signal 45 ma. Frequency response is ±3 db, 200-7000cps.

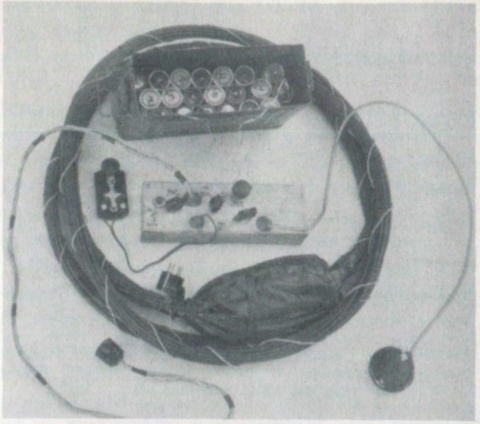

Figure 4.

Underground tranceiver with coil wrapped for shoulder carrying. Chassis and insulation sheet have been removed from ammunition box to show the transmitting batteries.

Coils 12 inches in diameter were designed primarily to provide initial experience in equipment operation. These coils are electrically interchangeable with the larger coils and can be used with the 31½ volt batteries when a range of over 200 feet is not required.

The finished equipment combines the transmitter and receiver into a single unit which weighs 21 pounds. It has a useful range of over 1200 feet. This is not excessive but allows for strong signals, sharp nulls, and a wide radius of operation. The schematic diagram of the equipment is shown in figure 3. A chassis layout (fig. 7) and parts list are included in the appendix. Figures 4 and 5 show completed equipment.

Operational Procedures

Initial experience with the equipment can be gained by using the practice coils. Experience in all phases of operation can be gained by using them in a multi-story building simulating a cave-to-surface situation. Valuable field time can be saved by such practice.

Figure 5.

Operator using surface transceiver to make a depth-determining tangential null (note wooden frame used to stiffen coil).

The operational coils are flexible for convenience in storage and transportation. The underground coil is formed into a smaller coil by folding it over and twisting it into a coil of three turns of the original. This is carried over the shoulder with a wide strap supporting the ammunition box. The surface coil is converted into a rigid unit by lashing it to a framework of wooden strips with bands cut from an automobile inner tube. The coil is carried by the frame. A small non-metallic inclinometer is incorporated to facilitate making depth-determining nulls.

When at the predesignated position, the cave operator unfolds his coil and places it in a circular, horizontal position (using a small spirit level), connects the jacks, and puts the transmitter on automatic beep. Ten seconds of each two minutes he changes to receive to allow the surface operator to acknowledge reception. He continues to send two minutes of beeps with 10 seconds receive until contact is made. The surface operator acknowledges with a series of the letter B. The cave operator continues to send beeps for the surface operator to find ground zero. The surface operator holds his coil in a vertical plane and rotates it on the vertical axis to determine the radial null. His assistant takes a compass bearing of the coil plane during null. The surface operator moves 30 paces at a right angle to the bearing and finds null again. His assistant takes a compass bearing. The convergence of these bearings is ground zero. At approximately ground zero the operator circles the area taking six or eight nulls. His assistant draws lines on the ground through the plane of the coil during each null. The intersection of these lines is exact ground zero.

Once exact ground zero is found, a depth measurement can be taken. If possible the surface operator picks a compass bearing which allows him a level traverse for several hundred feet. (If a level traverse cannot be made, difference in elevation of null site and ground zero must be measured and added or subtracted from depth). He communicates this bearing to the cave operator who acknowledges and with his assistant's help, holds their coil vertically and circular on this bearing. The surface operator measures 100 feet along the bearing and dips his coil to null, rotating it on a horizontal axis perpendicular to the bearing. The assistant records angle of dip. Similiar proceedings are taken at 200 ft, 300 ft, etc., until the dip is less than 45°. They backtrack until a 45° dip is reached. This point is the same distance from ground zero as the cave coil is vertically. All measurements are recorded and calculated using trigonometric tables or a slide rule.

A log of all transmissions with the time and complete messages is kept by both parties. The messages must be clear, concise, and devoid of double meanings. It is suggested that for those operators not proficient with Morse code, letters be formed slowly, distinctly, and repeated twice. At first the letters may be recorded by sound and then translated to the alphabet; when more proficiency is gained the operator can record the message directly.

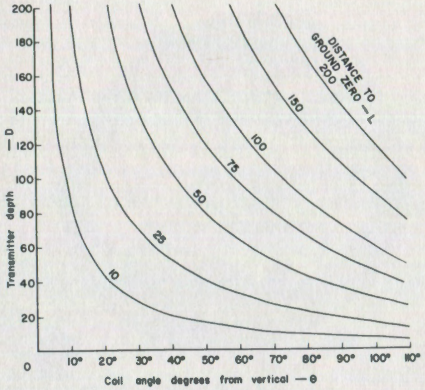

Figure 6.

Depth curves.

ALTERNATE PROCEDURES

When locating ground zero, a brisk walk along the direction of radial null (cave coil is always horizontal in these alternate methods) will quickly determine the direction of the strongest signal. Holding the coil vertically and perpendicular to the radial null, then dipping it toward the horizontal plane, the tangential null will be found. Progressing in the direction of the strongest signal, this null will become more vertical. If the signal is weak and does not increase in volume the tangential null should point away from the transmitter. At the point where it becomes vertical the coil should be able to be rotated on a vertical axis and remain in null. If not, by dipping the coil side to side in an east-west direction and then a north-south direction, the direction to move to get a vertical null in both planes will be shown. This point when reached is ground zero. This method requires no assistant. The preceding assumes the surface operator is always at a level above the underground operator. If by travelling down a hillside the same level as the cave operator is reached, a vertical tangential null will be found that can be followed around the hill on the contour. The radial null will be at right angles to the tangential and when the coil is rotated on a vertical axis the two nulls tend to appear as a single null for the entire 360° rotation.

An alternate method for determining depth is described by Blenz (1964) and also by Plummer (1964, 1965). The cave coil is left in a horizontal plane. On a line level with ground zero, distances are measured and the coil dipped to determine angel of tangential null. Blenz uses the formula $\theta = \mathrm{TAN}^{-1} \frac{3LD}{2D^2 - L^2}$ construct a graph of a family of curves having depth of transmitter D on one graph axis and angle of null from vertical on the other graph axis. The curves show distance from ground zero L. The curves (fig. 6) show when $\angle\theta$ is small, a small change of $\angle\theta$ gives a large change in D. When $\angle\theta$ is large a small change in $\angle\theta$ gives a small change in D making accuracy in measuring $\angle\theta$ less a factor in obtaining an accurate D.

Plummer rearranges the formula and uses it to construct a protractor which reads not in degrees but in depth to transmitter when determining tangential null at given distances from ground zero. The protractor is incorporated into an inclinometer which is mounted on the surface coil. Table 1 gives a series of factors which can be used to construct such a protractor. The factor multiplied by distance from ground zero will give depth to transmitter.

Table 1.

Protractor Construction Factors

Degrees dip from vertical	Multiplying factor
10	8.40
15	5.65
20	4.20
25	3.35
30	2.78
35	2.36
40	2.04
45	1.78
50	1.58
55	1.40
60	1.26
65	1.13
70	1.02
75	.93
80	.85
85	.77
90	.70
95	.64
100	.58
105	.53
110	.48

These methods are quicker, reduce communication with the cave party, and eliminate the possible error of placing the cave coil in a wrong plane.

ACCURACY

Accuracy depends mainly on the skill of the operators. Most errors will be due to (1) cave coil not in the correct plane; (2) ground zero not determined exactly; (3) nulls not accurately measured; (4) distances from ground zero incorrectly measured; (5) effect of hill-slope not compensated for properly; and (6) errors in calculations. All of these sources of error can be minimized by careful work. Also, increasing the number of measurements taken for a given location and averaging the figures will give a better result than for just one or two measurements.

During 1962 Wightman and associates (pers. comm.) using magnetic induction equipment with 19 inch coils located two air shafts for Meramec Caverns in Missouri. The depth measured was 40 feet. The shafts hit within inches of the indicated points. In 1964 they located a shaft at Jewel Cave for the National Park Service. The depth was approximately 200 feet. The shaft missed by about seven feet but a careful check showed that the drill had drifted six feet!

VOICE OPERATION

Using magnetic induction to obtain an adequate range of voice transmission, the experimenter must increase power and/or diameter of the transmitting coil. Since voice consist of a range of frequencies and volumes, not a steady frequency, the energy in a magnetic field driven by an electrical current of voice frequency cannot be conserved by a resonant capacitor. To get a range comparable to the 2 kc transmission of the five foot coils, they must be driven with over 100 watts of audio power. At present this requires excessively heavy power supplies and amplifiers.

Experiments have been conducted to add voice to the MIDAC equipment described. The switching was re-arranged (Appendix 1 fig. 8) so the headset could feed the receiving amplifier powering a 100 foot diameter coil. The coil consisted of a single no. 16 plain enameled copper wire 320 feet long laid in a circle on the ground. An understandable signal was received on the five foot coil at a distance of 250 feet from the edge

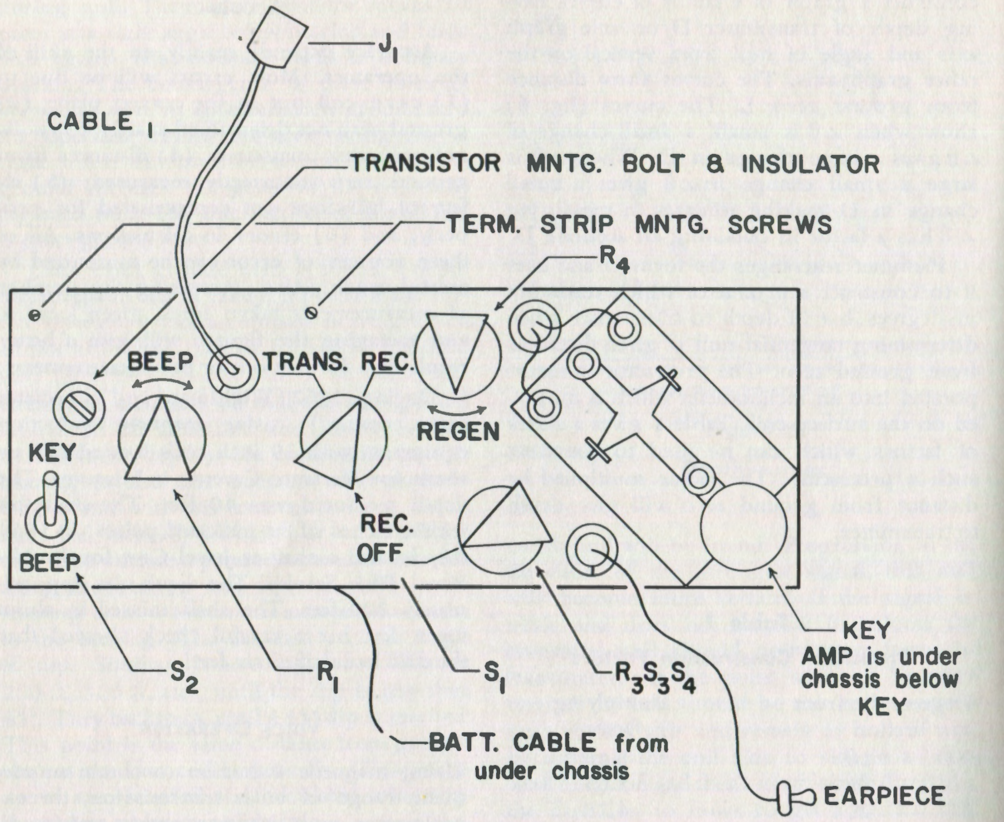

Figure 7.
Chassis layout.

of the 100 foot coil. To simulate a long narrow cave passage the wire was laid in a 155 feet by four feet rectangle which had a range of 120 feet. A rectangle 150 ft by nine feet had a range of 150 feet. Disadvantages in converting to voice were (1) headset not in receive position when transmitting code, (2) difficulty in setting amplifier gain to optimum point when transmitting voice, (3) increased drain on amplifier battery, and (4) additional time and effort to lay, retrieve and carry 320 feet of wire. Later improvements were made by the addition of S_5 and substituting the No. 16 P.E. wire with a twisted pair of No. 22 plastic-insulated wire 300 feet long, to form a two-turn coil 96 feet in diameter.

COMMENTS

MIDAC equipment was designed with range as the foremost consideration. Its size and weight restricts its use primarily to mapping. Those who do not require the present range can design smaller coils without changing the electronic circuitry. Plummer's equipment uses iron-cored coils that are lighter and less bulky than open coils of equivalent range. Lighter batteries of lower voltage can be used with reduced range. A 9-volt transmitting battery with the five foot coils has a range of 500 feet. New size D flashlight cells in a 31½ volt battery, weight 4½ pounds, should give 100 to 150 hours of slow beeps. A 22½ volt Burgess No. 4156, weight one pound, should give 15 to 20 hours of slow beeps (with slight reduction of range).

A higher gain receiving amplifier can increase range but has two problems, (1) feedback from amplifier and headset to pickup coil, and (2) pickup by receiving coil of excessive background magnetic fields. Plummer solves the first problem by eliminating the amplifier output transformer and using a crystal earphone. Budreau (pers. comm.) mounts the headset rigidly to the amplifier chassis and encompasses the entire unit with a degaussing coil. The second problem requires the use of a narrow bandpass amplifier. Each stage could be tuned to 2kc by slug tuned coils or the amplifier could employ one or more regenerative stages using feedback through a resistance-capacitance, "Twin Tee," phasing network (Kyle, 1965).

Those who are not interested in the directional characteristics of MIDAC may be interested in Wightman's voice transmission work using the earth as an electric current conductor. Equipment is described in *Electronics Illustrated.* Wightman has combined both principles of transmission into a single instrument. However, he states that it is far from perfected.

The author and party have used MIDAC to tie cave locations to the surface to check the accuracy of the cave surveys and check for possible dug entrances in Windy Mouth Cave, West Virginia; Organ Cave, West Virginia; and Butler Cave, Virginia. The equipment has given outstanding performance even at working depths of 450 feet. MIDAC should prove useful in other large cave systems and also in rescue work.

REFERENCES

Blenz, Richard, and William Mixon
1964 Windy City Speleonews, December, pp. 47-53.

Kyle, Jim
1965 Electronics World, July, pp. 84-88.

Maynard, Fred
1961 Electronics Illustrated, September, pp. 41-44.

Morgan, Alfred P.
1913 The Boy Electrician, pp. 290-295.

Plummer, William T.
1964 Baltimore Grotto News, pp. 162-171.
1965 Baltimore Grotto News, pp. 357-359.

Roeschlein, E. R.
1960 Electronics Magazine, September.

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APPENDIX 1

Item	No. Required	Remarks
Amplifier	2	Four transistor Radio Shack 27m1240 or Lafayette PK 543 (see text)
Battery 1	2	21 flashlight D cells, series connected, standing vertically in bottom of box; sheet of heavy rubber (auto inner tube) above and below layer cells
Battery 1 Practice	2	Three D cells, series connected
Battery 2	2	2U6 9-volt transistor radio battery
Box	2	Metal box 2½x7x10 inches (30 cal. ammo) with shoulder straps
Cable 1	2	4 feet of shielded microphone cable with 3 pieces of stranded, plastic insulated wire taped on
C1	2	Each consisting of approximately 3-2mfd, 1-1mfd, 1-0.5mfd,1-0.1mfd, 1-005mfd, and 3-0.1mfd wired parallel, frequency adjusted to 2 kc by changing number of parallel capacitors (tone from a closed end pitch pipe 1 5/8" long is sufficiently accurate as a frequency standard) adjust second set by beating received signal from first set against regeneration, capacitor leads soldered to ends of coil wire, avoid strain on leads, coil and capacitors wrapped (in area of capacitors) with padding and sheet plastic, capacitors 100 to 200 volt Mylars
C1 Practice	2	Consisting of several capacitors in parallel to tune to 2 kc 100-200 volt Mylars
C2 &	4	40mfd 100 volt electrolytic
C3	2	0.05mfd 100-200 volt Mylar
Chassis	2	Formed from 13"x6¾" galvanized 22 gauge sheet metal, 9½" long, 3¼" wide, 1½" deep, and ¼" folded under bottom parallel to top
Grommets	8	Rubber grommets 3/16" inside diameter for cable holes in chassis
J1	4	Five prong jack Amphenol 78PF5 or equivalent
Key	2	Skillman key, Radio Shack 20K1085, lever shortened 1½ inches, drilled, threaded, and knob replaced; or home made key to fit space available
Knobs	8	Pointer knobs for switches and pots
L1	2	Each consisting 250 feet No. 10 stranded copper wire, TW insulated, 16 turns, center tapped, 5 feet in diameter
L1 Practice	2	110 turns No. 22 plastic insulated center tapped, 1 foot diameter
L2 all	4	One No. 22 wire, stranded, plastic insulated, wrapped around L1 to bind L1 together, wraps spaced 3 inches apart, reverse leads if fails to regenerate
Phone	2	2" speaker in home made case or a 10 ohm transistor radio earpiece
PL	4	Five prong plug, Amphenol 86PM5 or equivalent, underground plug protected when not in use by dummy jack fastened to coil
R1&4	4	500,00 ohm ½ watt potentiometers; see fig. 8 for addition of S5
R2	2	3500 ohm ½ watt, if key tends to beep or is slow to key – reduce value slightly
R3	2	500,00 ohm pot with dpdt switch
Rubber Bands	12	to lash surface coil to wooden frame, cut from auto inner tube, ½" wide
S1	2	4P2T rotary switch
S2	2	2P2T lever switch
S3 & S4	–	On R3
Tr1	2	2N158 (Radio Shack 27M1230) or GE-3, 2N301, 2N176 or equivalent, value of R2 and C2 may vary slightly with other than 2N158
Term	2	Barrier terminal strip, eight screw terminal
Wooden strips	4	¾"x1¼"x 5 feet to form frame of surface coil

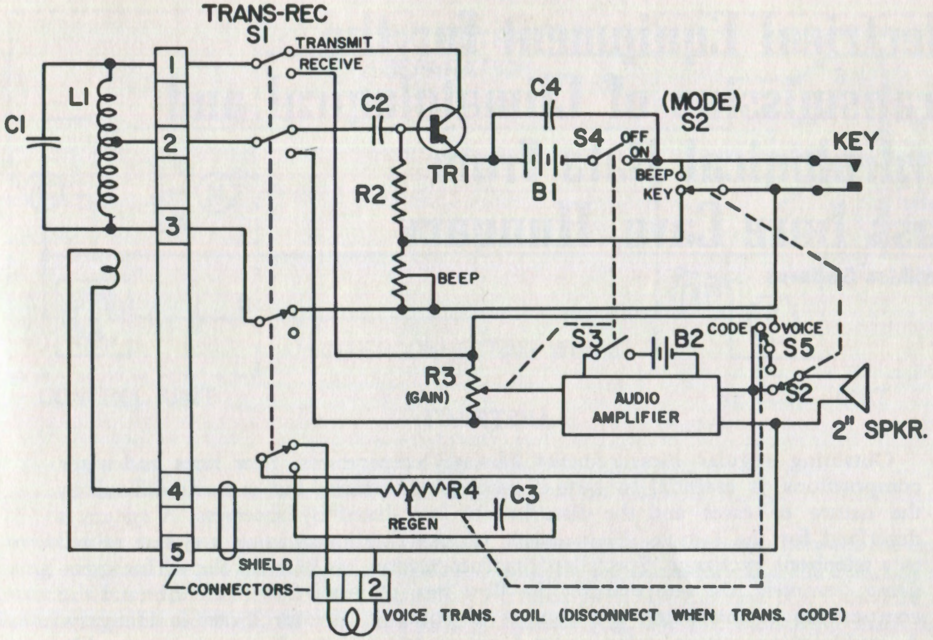

Figure 8.

Schematic diagram of MIDAC equipment with voice capability.

Electrical Equipment for the Transmission of Climatological and Hydrological Data from Vass Imre Cave, Hungary

By Miklos Gadoros

ABSTRACT

Obtaining regular measurements of cave temperatures, flow rates and water compositions is essential to cave climatological studies, but is made difficult by the nature of caves and the disturbances introduced by observers. A system is described for the remote measurement of cave conditions using a system related to a telephone exchange. Specialized instrumentation has been developed for measuring, remotely, the temperature, the flow rate of water from stalactites and the composition of this water, at a number of points in a research cave in Hungary. A multiplexing station selection and transmitting network permits measuring all of these quantities from a Research Station on the surface as electrical signals. The system promises to be of great value in collecting consistent climatological records.

INTRODUCTION

The Speleological Group of the Technical University of Building and Transport (Budapest, Hungary) started regular scientific investigations on the Karst of Aggtelek in 1954. The first important result of their work was the exploration of the one kilometer long Vass Imre Cave, near Jósvafő. To improve the scientific work of this research group, the Department of Minerals and Geology of the Technical University built a research station about 300 meters from the cave entrance in 1957. This made it possible for us, in the spring of the following year, to set up a meteorological station in the cave consisting of a barograph and a hygrothermograph. These instruments were current types for meteorological purposes.

However, it soon became evident that these recording instruments were not suitable for our purposes. The barograph gave utilizable data but its value was greatly reduced by the inexactitude of synchronism with a surface instrument, while the hygrothermograph was insensitive to the slight fluctuations of temperature and humidity in the cave. Moreover, the clock mechanisms of these instruments could not stand the corrosive effect of the humid atmosphere.

Travel in the cave is very difficult so it was not easy to make regular observations underground, all the more so as the presence of a person taking the readings greatly disturbs the microclimate. The annual fluctuation of temperature and humidity in the cave is so slight, except in the immediate vicinity of the entrance, that approaching the instruments may produce a disturbance as great as the annual fluctuation.

In view of the above, an electrical telemetering system was put into operation in the summer of 1959. By means of a four wire connection from the Station to the cave, it permitted the selection of 11 measuring stations and the maintenance of a telephone circuit. Dry and wet thermistors for measuring temperature and humidity and two flow meters and conductivity instruments were also branched to this network. In 1961 the capacity of the network was increased to 28 stations. The underground units can be selected by dialing and the survey data can be read in the laboratory of the Research Station. When constructing this remote measuring network we had to develop new techniques because we could not find any description of a similar set of instruments in the literature. The switching systems, although made from telephone type components, differ greatly from those used in automatic telephone exchanges, mainly in the use of operating current pulses. The various remote stations are also brought into step in a new way. As far as we know, the flow meter used for measuring volumetric discharge from dripstone (together with the so-called "robot stalactite") is an original idea and device.

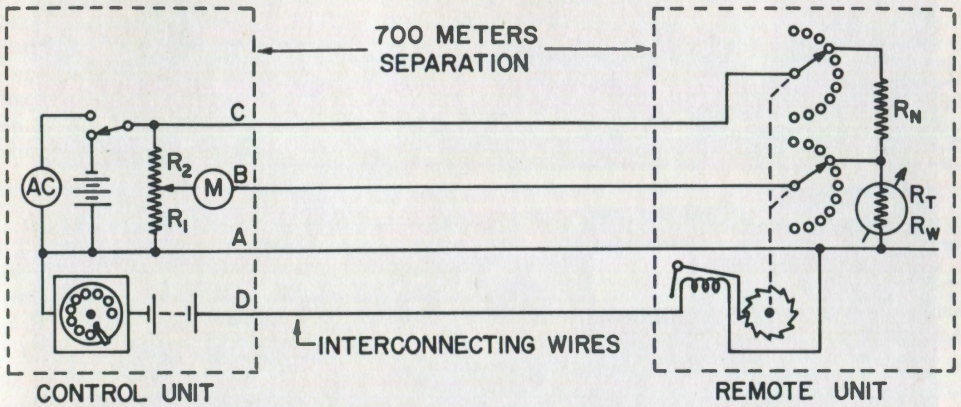

Figure 1.
Schematic circuit of the system.

PRINCIPLES OF MEASUREMENT

Measurement of all physical and chemical characteristics is based on electrical resistance. The sensing devices produce a definite resistance corresponding to the value of the quantity to be measured. The resistance thus obtained in the cave is then measured with a Wheatstone-bridge in the surface laboratory. Two arms of the bridge are formed with a balancing potentiometer. Between the central unit in the laboratory and the remotely controlled switch in the cave is a four wire connection (fig. 1). The measuring instruments at different points in the cave are connected to the remote control switches by three wires each in order to reduce the effect of conductor resistance. The fourth wire leading to the remote control switch, together with one of the measuring wires, serves to control the switch.

CENTRAL UNIT

The central unit contains all the elements necessary to balance the bridge, to choose and to change the measuring ranges and to control the remote switches. A built-in center-position Deprez meter (fig. 2) with a range of ±25 μA (1800 ohm, 5x10^{-7} A/microamperes sensitivity) is used as a DC indicator. The same meter can be used for general AC-DC measurements. A sensitive external galvanometer (200 ohm, 1x10^{-7} A/mm) can be switched into the circuit by pressing a button. For AC bridge measurements there is a separate detector (see Conductivity Measurements). The three indicators, internal, external and AC, can be chosen by a push button and two relays. In the disconnected state, or when dialing the conductivity measuring stations, the oscillator and AC indicator are also automatically switched on.

To select the type and required range of

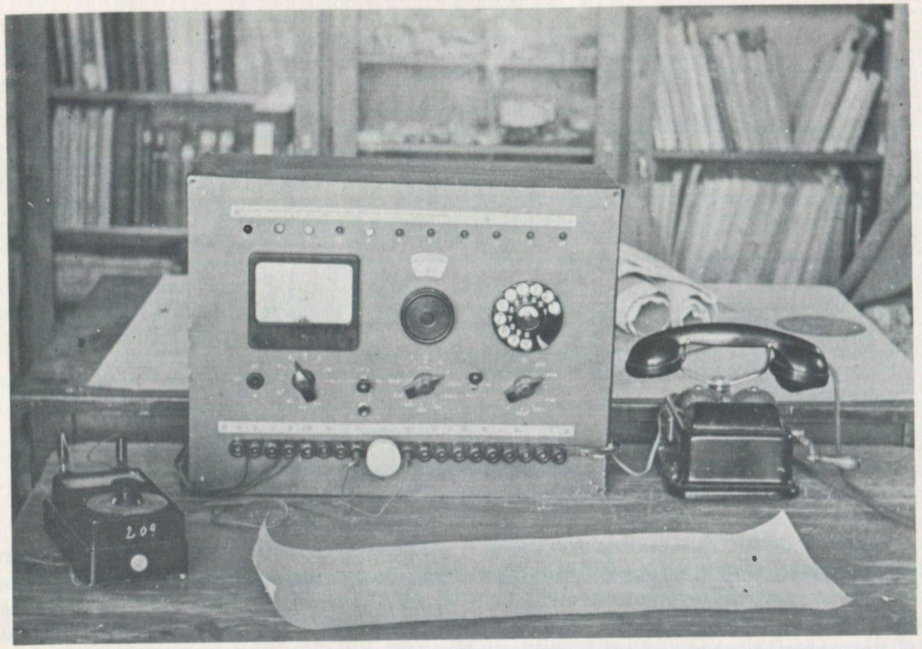

Figure 2.
Central unit for the remote measuring equipment, located in the laboratory of the Research Station.

bridge operation there are three rotary switches. The left hand rotary switch (fig. 2) selects the required mode of operation (remote measurements, resistance measurements in the laboratory, etc.). The middle switch is used to set the range of ratios R_1/R_2 which may be produced by the balancing potentiometer. The right hand switch selects reference resistances (100, 500, 2K 10K, 1M ohms, or "external") for the bridge.

For direct current measurements either 0.7 or 4.5 volts may be applied to the bridge with the three position switch on the far left. The dial of the balancing potentiometer is graduated in degrees. Temperature, flow discharges, etc., corresponding to the values given in degrees, are obtained from calibration charts.

The measuring wires were also used originally for the telephone circuit. This had the disadvantage that sometimes the sensitive thermistors received the ringing voltage, which destroyed their original calibration. Therefore we put the telephone on an independent circuit as soon as possible. The remote control switching system will be described in a later section.

Temperature Measurement

The equation relating the resistance RT of a thermistor to the absolute temperature T is, to a good approximation,

$$R_T = A \exp(\frac{B}{T})$$

where *A* and *B* are constants. From this it follows that the temperature coefficient is $\propto = -B/T^2$. For thermistors from the Tungsram Works (Hungary) this is, at 20° C, $\propto = -0.032$ $°C^{-1}$.

Thermistors have a double advantage over metal resistance thermometers. Their greater sensitivity allows more exact measurements and their greater resistance reduces considerably the effects of the long connecting wires (there are thermistors available with 10^5 to 10^6 ohm basic resistance). On the other hand, their aging is rather intensive and, in the case of great temperature changes, the disagreeable phenomenon of hysteresis appears. Fortunately, there are never great temperature changes in a cave, and the effect of aging can be corrected from time to time by recalibration.

We use glass-covered thermistors (Type 1-TH–4). Their resistance in the cave (at about 10°C) is about 5000 ohms. The resistance values for R_N (fig. 3) have been chosen so that $R_N = R_T$ at 10° C.

Using a potentiometer to balance the bridge, the bridge ratio (R_1/R_2) may be varied from zero to infinity. For ordinary measurements we limit this variation to from 0.1 to 10 by a series of resistors. Higher precision is required for measuring temperature and therefore, for that purpose, the bridge ratio is narrowed further to between 0.9 and 1.1. This covers a range of about 5° C, which is more than sufficient. One degree on the potentiometer dial equals about 0.02° C, giving an accuracy of ±0.05° C.

In choosing the supply voltage for the bridge, opposing factors must be considered. The accuracy of measurements is proportional to the applied voltage but the thermistor is heated by the current flowing through it, causing errors in measuring. The admissible power dissipation depends not only on the admissible error for temperature measurements but on the circumstances of cooling as well. The values indicated for a particular thermistor are, therefore, only partly helpful. Our test results found 0.7 volts a good compromise. Half of this is applied to the thermistor, causing a dissipation of about 0.025 milliwatts or a nominal 0.05° C temperature rise according to the thermistor specifications.

With remote measurements the resistances of the connecting wires (about 35 ohms each) are connected in series with the thermistor and reference resistances. The 400 meter underground cable is at constant temperature but the 300 meters of aerial wire between the cave entrance and the Research Station is exposed to the strongly fluctuating thermal conditions of the surface. If only the thermistor were in the cave, the wire resistance changes would be read as significant cave temperature changes. This error is reduced by using thermistors with sufficient resistance, but too large a resistance leads to a fall in sensitivity and the problem of insulation becomes more difficult (difficult enough in caves, in any event). Several methods have been used to compensate for the temperature dependence of the conductor resistance. The simplest is a balanced three-wire circuit where similar lines are connected in series with the remote thermistor and standard resistance (fig. 3). In this case there is no conductor temperature effect when the ratio of the bridge is exactly 1:1. However since temperature is measured in terms of the bridge ratio R_1/R_2, an error, although attenuated, necessarily appears. When the conductor resistances (R_V, fig. 3) are equal, this may be shown to be

$$\Delta T = \frac{(a-1)\Delta R_V}{\propto R_{T_o}}$$

where *a* is the bridge ratio, R_{T_o} the resistance of the thermistor at a reference temperature, ΔR_V the variation in conductor resistance caused by temperature changes, and ΔT the change in thermistor temperature, equivalent to ΔR_V, such that the bridge remains balanced.

In our measurements the maximum change in line resistance caused by temperature is about 5 ohms, $\propto = -3.2 \times 10^{-2}$ $°C^{-1}$, $R_N = 5000$ ohms and *a* lies between 0.9 and 1.1. With these values we find the maximum error $\Delta T = 0.0035$° C. This is less by more than one order of magnitude than the required accuracy and thus compensation for conductor resistance variations is essentially perfect.

With the three wire circuit we placed the standard resistances R_N adjacent to the corresponding thermistors in the cave so that they are not exposed to the fluctuation of surface temperature. Temperature changes do not affect the accuracy of the bridge-balancing

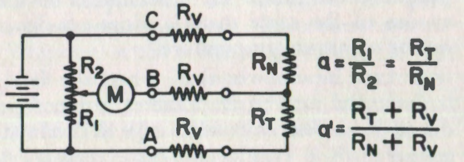

Figure 3.
The bridge and the disturbing conductor resistances.

potentiometer since the quotient of two resistors of the same material does not depend on the common temperature.

It can be shown that, when the bridge is balanced, the galvanometer current produced by an incremental change in thermistor temperature is (neglecting cable resistances):

$$\Delta I = \frac{V \propto \Delta T}{R_1(1+\frac{R_N}{R_T})+R_N(1+\frac{R_1}{R_2})+(1+\frac{R_N}{R_T})\,(1+\frac{R_1}{R_2})R_G}$$

With *a* between 0.9 and 1.1, $R_1 \simeq R_2$ and since $R_N \simeq R_T$,

$$\Delta I \simeq \frac{V \propto \Delta T}{2R_1 + 2R_N + 4R_G}$$

If R_1 is much less than R_T and R_G is much less than R_N, this finally simplifies to

$$\Delta I = \frac{V \propto \Delta T}{2R_N}$$

The light-spot galvanometer we use meets the above requirements, giving a sensitivity of 0.03 °C/mm, which is sufficient.

HYGROMETRY

It is well known that atmospheric humidity (absolute or relative) can be determined using a pair of wet and dry thermometers, or psychrometer (fig. 4). If the thermometers are replaced by thermistors, we obtain an instrument suitable for electrical telemetering. Forced air flow over the wet thermistor is desirable but as a suitable corrosion resistant motor of low power consumption (and dissipation) was not available we have had to dispense with this. Fortunately the effect of air motion is small near saturation so that there is no significant decrease in accuracy and sensitivity.

DISCHARGE MEASUREMENT

The equipment placed in the cave for measuring water flow rates, or discharge, from stalactites or other sources has two parts: a mechanical volumetric flow meter and an electrical unit for counting and transmitting data.

Dripping water is led through a "robot stalactite" – a piece of cotton connected to the stalactite by a plastic tube in such a way that it can be removed if required. Mineral precipitation taking place on the cotton may, from time to time, be weighed with great accuracy in the laboratory.

Figure 4.
Tent for instruments in the cave. Telephone, box protecting the battery, thermistor psychometer and remote control switch in aluminum box (1959).

The water then flows (drips) into a *cistern* of calibrated volume. After a certain volume has accumulated the contents of the cistern automatically siphon into a cup fixed to one end of a double arm lever. The cup has a relatively narrow discharge hole so that water flows out from the cup considerably slower than in from the cistern. When the cistern drains, the cup fills, causing the lever to pivot from its rest position due to the added weight. After the cistern is drained the cup continues to drain so that, after a short while, the lever pivots back to its original postion. When the lever tilts a mercury switch closes the pulse generating circuit of the electrical unit. Thus the quanitity of water in the cistern is registered as a single electrical pulse (fig. 5).

Any uncertainty in the functioning of the siphon affects the accuracy of the discharge measurement. For example, the siphon may start at irregular water levels. This depends, among other things, on the diameter of the siphon tube, on how clean it is and on the constancy and rate of in-flow. At worst this uncertainty may be more than 15%. By careful design of the siphon we have been able to reduce this error to 2 or 3%.

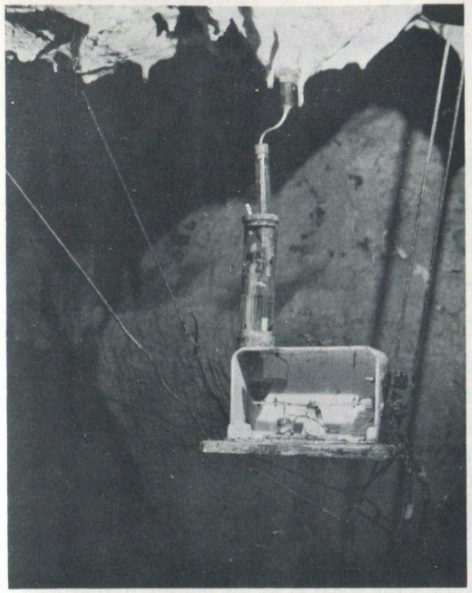

Figure 5.
Flowmeter with 50/5 ml. cistern. Installed in 1962.

When attempting to measure *daily* discharge there is an error resulting from the unknown amount of water remaining in the cistern at the end of each day. Therefore, for daily accuracy, it is necessary to have, say, more than 20 counts for 5% accuracy. This error is reduced by decreasing the cistern volume but the diameter of the cistern, not the height, must be reduced as the latter could increase the uncertainty of the siphon. When choosing the most appropriate volume we had to take into consideration the maximum daily discharge and the fact that, at first, we could not accumulate more than 26 counts. The first cistern was 40mm in diameter and had a discharge volume of 120-130 ml. However in winter this proved to be too large as it sometimes took six or seven days before this quantity accumulated. On the basis of experience we modified this part of our equipment in 1961. In a cistern 30mm in diameter, with a discharge volume of 50 ml, we placed a second siphon set for 5 ml. A valve permits the choice of one or the other. At the same time we constructed a high sensitivity tilting lever with a wedge bearing which would operate consistently with only 5 ml. The capacity of the associated counter was also increased to 52 counts.

The earlier unit used industrial mercury switches encased in glass. These would not have been practicable with the more sensitive unit. Therefore we constructed mercury switches with open cups. On the tilting lever-arm there is only a "U" shaped contact which establishes a connection between two separate mercury pools mounted on the case. In this way no wires need be connected to the lever arm. In spite of all our preliminary fears, the open cup mercury switches work remarkably well.

If the pulses originating from the mechanical unit were to operate a stepping relay or register in the laboratory a fixed connection would be required. Therefore the pulses are counted locally and only temporary sums read at the central unit. This is done by converting "counts" to increments in resistance which may be measured with the central unit bridge. A logarithmic sequence of resistors is wired across the contacts of a stepping relay so that, with each step, we obtain equal changes on the scale of the balancing potentiometer. The minimum resistance is 100 ohms and the steps are each about 10%. With such a large change of resistance at each count the readings are free from error even in the event of variable conductor resistance.

While the accumulated water in the cup is being drained, the circuit is closed for 10 to 30 seconds. The operating current of the stepping relay is about one ampere. This would entail an excessive current consumption. To avoid this, the mercury switch only closes the circuit of an auxiliary relay through a capacitor of 50 microfarad (fig. 6). When the switch closes the auxiliary relay is operated through the capacitor until the latter is charged, which takes only 0.1 to 0.2 seconds. The resulting pulse is sufficient to operate the stepping relay. After

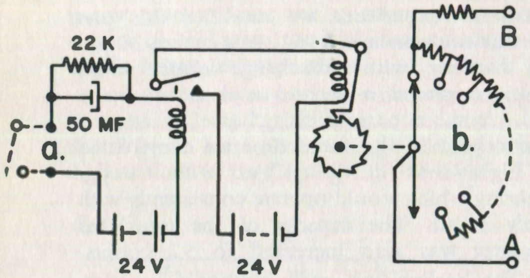

Figure 6.
Circuit of the electrical unit of the flowmeters (discharge measuring instruments).
a: mercury switch.
b: 26 (or 52) resistors on the contacts.
A-B: connection to the remote selecting switch.

the mercury switch opens a resistance of 22K ohms, connected in parallel with the capacitor, discharges the latter.

CONDUCTIVITY MEASUREMENT

In addition to variations in water discharge rates it is very desirable to know the composition of the dripping water and its variations. At present we content ourselves with a remote measurement of electrical conductivity, which is only characteristic of total hardness.

In the cistern of each discharge measuring station there is a bell-shaped conductivity cell containing a pair of blacked platinum electrodes. The cells are installed with their opening upward, the opening in the neck being closed. The dripping water goes first into the overturned "bell" from where it brims over into the cistern. The upper rim of the "bell" is somewhat higher than the maximum water level of the cistern which insures that the measuring electrodes are always covered by fresh water. Consequently it is always the conductivity of the dripping water we measure, unaffected by the quantity of water in the cistern and possible precipitation going on therein. We use, of course, alternating current for conductivity measurements.

A signal of about one kilocycle is produced by a transistor oscillator with inductive coupling. The coupling from the emitter circuit was made at first with a capacitor but the new tapped coil oscillator with grounded emitter has a separate coupling coil (fig. 7). This is located in the central unit.

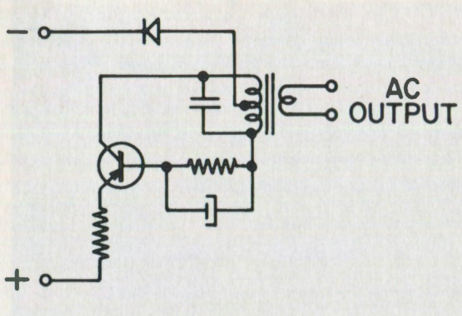

Figure 7.
Oscillator circuit.

The main switch in "start" position reverses the polarity of the supply voltage which could destroy the transistor. To avoid this the circuit is protected by a Tungsram GD 1 germanium diode.

Originally we used headphones for null detection. To obtain the required sensitivity, the signal from the bridge was amplified by a transistor operating in a grounded emitter circuit. In 1962 we replaced this simple detector by one using a two stage amplifier and a phase sensitive ring rectifier working into the built-in meter (fig. 8).

When we dial the conductivity measuring station, the oscillator and the AC indicator are automatically switched on. The direct voltage supplying the bridge is turned off to prevent polarization of the electrodes.

Balancing an AC bridge requires phase compensation. Therefore there are usually two variable components in such a bridge. In our remote measurements important wire capacitances are in parallel with the unknown resistance to be measured. We encountered more difficulties than in usual impedance bridges since there is only a slight difference between the absolute values of ohmic and reactive impedances. On the other hand, the value of disturbing wire capacitance is nearly constant. Since daily measurements are made by the warden of the Research Station, who has no special knowledge in this field, we had to find a solution where compensation can be effected simply. Therefore the bridge is coupled in a different way from usual (fig. 9). To compensate for the capacitances C_N and C_W we make:

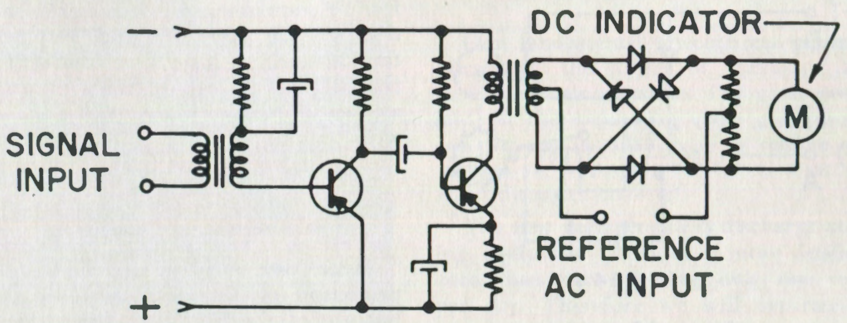

Figure 8.
AC null-detection indicator.

$$C_1 = C_W \frac{R_N}{R_2}$$

and

$$C_2 = C_N \frac{R_N}{R_2}$$

Consequently, if R_2 and R_N do not change while C_N and C_W are practically constant, C_1 and C_2 can be built in as fixed capacitors.

Changes in conductor resistance lead to errors in these measurements also. The error caused by small changes in conductor resistance can be shown to be (similar to temperature measurement error):

$$\frac{\Delta R}{R} = \left(1 - \frac{R_N}{R}\right) \frac{\Delta R_V}{R_V + R_N}$$

With the electrodes we use $R_N = 700$ ohms. Taking ΔR_V to be 5 ohms then for a maximum error of 1%, R must be greater than 280 ohms. For a maximum error of 0.5%, R must lie between 400 and 2600 ohms. Observation has shown that fluctuation in conductivity of dripping water of one stalactite remains within the range of values permissible for an error less than 0.5%.

Because of differences in electrode constants and the variable hardness of dripping water at different places in the cave it is advisable to determine the values of the resistances R_N individually. Good matching of electrode constants and standard resistors not only improves the accuracy but also facilitates the evaluation of measurements. The extra work it requires is worth the trouble.

REMOTE CONTROL

The remote control switches are assembled from telephone type components. In the cave there is a stepping switch (originally one for 11 stations) which moves in synchronism with one in the central unit. The latter operates the lamps showing the position of the switch, connects the compensating capacitors for conductivity measurements and operates the relay which activates the oscillator and AC indicator.

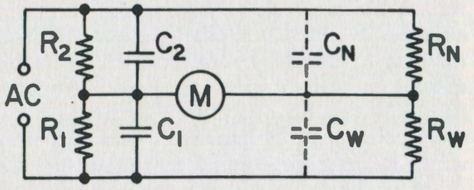

Figure 9.
Circuit of the AC Bridge.
C_N, C_W: compensating capacitances.
C_1, C_2: disturbing capacitances.

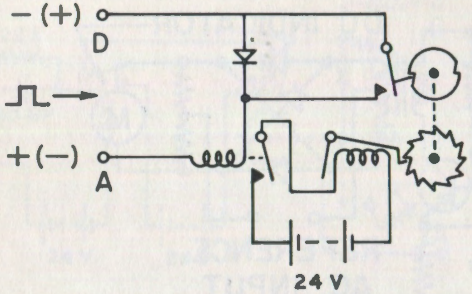

Figure 10:
Circuit of the remotely controlled switch (stepping relay).

The pulses from the telephone dial on the central unit operate the two stepping switches through local pulse-repeater relays (fig. 10). This is necessary because of the large current consumption of the stepping relays.

The stepping relays are synchronized from their "zero" position by means of a pair of contacts on them which are open in the "zero" position and closed in any other. The circuit of a pulse-repeater relay passes through this pair of contacts, which are bridged over by a germanium diode. When the central unit switch is in "working" position, the polarity of the pulses is opposed by the diode. Thus when a stepping switch is in "zero" position the control relay cannot operate. The stepping relays in a position other than "zero" will return to "zero" with a sufficient number of pulses and will not reply to further pulses. On setting the main switch to "starting" position, the polarity of the pulses is reversed and the auxiliary contact is effectively shunted by the diode, allowing the stepping relay to respond to signal pulses. With this method only two wires are needed for control and synchronization. The main (key) switch remains in "starting" position only while being depressed. With this system the number corresponding to the difference between the actual position of the stepping relay and the required position is dialed.

In 1959 our network had only one remotely controlled switch (300 meters from the cave entrance) operating 11 stations. In 1961 we put into operation three switches (each for 28 stations) moving in synchronism (at distances of 100, 300 and 500 meters in the 600 meter main cave passage). When the first 28 places for taking measurements are all in service the capacity of our network can be increased to 81 places with the use of only one new pair of control wires.

Corrosion Protection

Much care must be taken for corrosion protection of the instruments in the cave because of the high humidity of the atmosphere. Therefore we put all the underground switches (control switches and counters) in boxes as hermetically sealed as possible. Each box contains hygroscopic material (silica gel) as well.

At first we used for this purpose aluminum first-aid boxes. In addition to their original rubber gasket, a paraffin layer on insulating tape was put around the gaps to insure good sealing. The wires passed into the boxes via screw connectors insulated with synthetic rubber discs. Paraffin was molded about both the internal and external sides of the screws. By taking such precaution we succeeded in avoiding instrumental errors caused by electrical leakage. However it soon turned out that, even with the most careful insulation, a surface conductance developed between the aluminum box and the copper screws because of condensing water which was sufficient to cause a noticeable disturbing voltage in the system. At the same time it was found desirable to observe the units without opening the boxes.

Therefore we put the remote control switch in a plastic box. Later the electrical units of the flow discharge meters were also placed in plastic boxes (fig. 11 and 12). For these remote control switches there are polyethylene insulated wire terminations – the wires being soldered to the terminals. For the counters the original screwed connectors have been retained. Unfortunately the strength of the available plastic boxes is much inferior to that of the aluminum and it is more difficult to close them hermetically. In spite of these disadvantages, the plastic box has proved to be superior even if they require more care.

Figure 11.
Eleven point remotely controlled switch in plastic box (open) and two electrical (counting) units in aluminum boxes (one open) - 1960.

The greatest problem of all, which makes it difficult to obtain regular measurements, is the lack of a suitable interconnecting cable in the cave. Water repellent insulation is indispensable for the cables. Impregnated textile or paper insulation gets wet through sooner or later in spite of the most perfect impermeable cover and end-seals. We learned this to our cost with our first cable.

Heavy cables (lead sheathed, etc.) are out of the question in our difficult cave. We tried to use polyethylene television ribbon-cables but their insulation proved not to be thick enough. We have recently installed (1963) a silicone rubber insulated cable. We do not have enough experience, as yet, to know if this will be more satisfactory.

Power Supply

In the beginning power supplies consisted of 45 volt anode batteries. Although made for low load they were of high quality and could supply one ampere for the switches for quite a long time. Nevertheless dry cells turned out to be rather expensive. In 1961 we converted to accumulators, constructing 24 volt packs from small button accumulators (Type G1 0.45; 1.2 volt, 0.45 ampere-hours). The short circuit current of these packs is about 5 amperes when charged and about 1.5 amperes when discharged. These accumulators seem, so far, to stand well the great pulse current loads.

Experience and Further Plans

Our fundamental conceptions proved applicable in the course of operating the remote measuring system. The great demands laid on the measuring cable give good reason for the installation of a remote switch instead of a multi-wire cable, even in the short distances involved.

The new high sensitivity discharge measuring equipment provides a more detailed record than that allowing only one reading per day. Therefore we will separate these instruments from the measuring network and install an independent automatic register network with a multi-wire cable transmitting the pulses of the mercury switches of the various measuring stations, directly to registers on the surface. For this purpose a cable of inferior quality will be adequate.

Next we are aiming at increasing the accuracy of temperature measurements to 0.01° C. We intend to test thermistors using vanadium pentoxide. This type is a Hun-

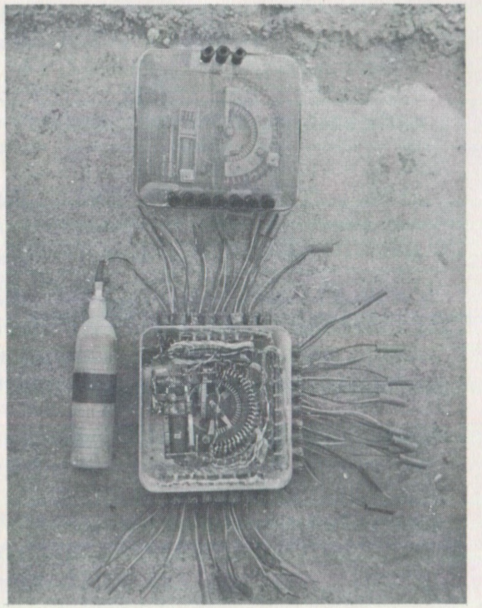

Figure 12.
Electrical counting unit in plastic box (left). 28 point remotely controlled switch in plastic box (open) and small button-type accumulator pack for 24 volts (1962).

garian invention and excells with its great stability, although its temperature sensitivity is somewhat lower.

Valuable hydrological and microclimatological conclusions can be drawn, of course, when we are in possession of a continuous series of data obtained over several years.

SUMMARY

The Department of Minerals and Geology of the Technical University of Building and Transport (Budapest, Hungary) had a Research Station built near the Vass Imre Cave in the vicinity of Jósvafő in the Aggtelek Karst (North Hungary). The collaborators of the Research Station established an electrical remote measuring network in order to measure the temperature, humidity, discharge and conductivity of dripping water, at several locations in the cave, from the laboratory of the research station.

The connection between the underground measuring instruments and the equipment of the central unit can be established by dialing, in a manner similar to a telephone exchange. Between the central unit in the laboratory and the underground remotely controlled switch is a four wire connection, aerial wires on the surface and a silicone rubber insulated cable in the cave. Hermetically closed miniature "button" accumulators assembled in packs of 24 volts supply the necessary power for the underground instruments. The accumulators may be recharged from the surface through the measuring cable when measuring is suspended.

In the construction László Maucha, geologist (Chief of the Research Group), István Czájlik, Ferenc Cser and István Fejérdy, chemical engineers, undertook the major part, under the technical direction of the author. While constructing this equipment they were all students. Head of the Department of Minerals and Geology, Dr. Ferenc Papp, Professor of Geology, encouraged them in their work and they all owe their professor thanks for his generous assistance and support.

Department of Minerals and Geology, Technical University of Building and Transport,
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Proceedings of the Society

MEETING IN BLOOMINGTON, INDIANA, JUNE 1965

GEOLOGY SESSION

THE MODEL OF CAVE DEVELOPMENT IN THE CENTRAL MENDIP HILLS OF ENGLAND

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In the central Mendip Hills Mississippian limestones dip to the south at 15° – 40°. Local relief is 800 feet. Five large engulfment caves are known, spaced over five miles. They head at similar elevations and have been penetrated to comparable depths. Two are type examples of the vadose cave theories, one is a water table cave, and two had a deep phreatic origin.

Development is reconciled in a single model: in the vertical plane, early cave passages made deep loops below, and returning toward, a linear water table created by the cave genesis. Each loop consisted of a descending bedding plane segment and a return up a joint or fault. The amplitude of phreatic loop penetration became reduced with a growth in quantity of minute groundwater conduits which could be utilized to guide principal passages.

The deep phreatic caves in the Mendip sample are the oldest. They are the remains of single phreatic loops with, in detail, a mile or more of complex passage developed in each. The water table cave is younger: its loops are shallower and have been largely eliminated by filling and by-passing, a gradational process which must occur in all of the caves, given sufficient time. The vadose caves are youngest, having developed in an uppermost zone which became air-filled as a consequence of cavern expansion in loops below. The characteristic form of each cave was determined by the time of integration to a major spring, related to a falling eustatic base level in allogenic rocks.

SEMIDIURNAL MOVEMENT ALONG A BEDROCK JOINT IN WOOL HOLLOW CAVE, CALIFORNIA – PRELIMINARY REPORT

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A 22-hour record of strain has been obtained from three mutually perpendicular transducing cells across a joint in the wall of Wool Hollow Cave, Calaveras

County, California, in the hope of determining the causes of strain. The rock cover at the instrument station is 25 meters thick, and the air temperature at the instruments ranged from 11.25-11.42°C during the observations. The joint, which strikes N. 50 E. and dips 27° NW, cuts recent travertine as well as the bedrock. The slippage showed two maxima and two minima roughly coincident in time with the theoretical earth tides. At high tide the hanging wall of the joint moved southeastward up the dip 0.4 micron with respect to the footwall, and just before high tide, 0.6 micron northeastward along the strike of the joint. A seismic disturbance with an amplitude of 0.01 micron from the Moluccan earthquake of March 21, 1965, was superimposed on the slower tidal fluctuation during a 5-hour period, and it appears to have caused abrupt deflections as large as 0.03 micron, indicated by steps on the strain record.

BEDDING PLANE ANASTOMOSES AND THEIR RELATION TO CAVERN PASSAGES

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Bedding plane anastomoses (branching, freely interconnecting, braided tubular cavities) occur in many sizes and appear to form a continuum beginning with those of millimeter size and terminating with the largest form which consists of the spaces between the largest roof pendants. Bedding plane anastomoses are common in areas of poorly jointed limestone appearing on the underside of the stratum. These features extend over large areas of a bedding surface and are strongly influenced by minor fractures.

Bedding plane anastomoses are unquestionably phreatic in their origin and often certainly predate adjacent or confluent cavern passages. In many cases it appears that the cavern passage is an extension of the anastomoses along a route predetermined by the presence of a minute fracture and/or the breaching of a stratum by growth of anastomoses from below where they exist superposed on adjacent bedding planes.

CORRELATION OF CAVES AND EROSION SURFACES IN THE SOUTHERN CUMBERLAND VALLEY OF PENNSYLVANIA

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In spite of the general acceptance of the theory of a shallow phreatic origin for caves in low to medium relief terrains, there have been very few experimental tests. The recent completion of the Southern Cumberland Valley portion of the Pennsylvania Cave Survey has provided a more complete sample of cave development in a geologically homogeneous area than has previously been available. The Southern Cumberland Valley is a rolling topography with a relief of about 300 feet. It is floored with complexly folded and faulted limestones and dolomites of Ordovician and Cambrian age, and effects due to lithological control would be expected to be cancelled out. Data on 83 caves totaling 20,400 feet of passage have been examined for possible relationships to present and past regional base levels. Plots of cave length versus elevation and number of entrances versus elevation both give curves with very pronounced maxima at 500 feet and 700 feet elevation. There is a somewhat more subdued maximum at 600 feet and a weak maximum at 900 feet. It is proposed that these maxima correspond to pauses in the base level lowering of Yellow Breeches, Conodoguinet, and Conococheaque Creeks.

THE SEDIMENTARY RECORD AT THE CHEDDAR CAVES, SOMERSET, ENGLAND

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Recent study of cave sediments, particularly in Europe, suggests that, rather than being a part of a general mode of cavern development, they reflect the vicissitudes of Pleistocene climate in the environs of the given cave. This is upheld by a study at Cheddar, England. In the lowest abandoned level of a complex springhead cave system there, barren deposits have been correlated with an inhabited site at the entrance to yield the following later Würm (Wisconsin) chronology:

1. At the base, a nearly complete fill of laminated clays deposited in a phreatic environment. A very cold climate, with most groundwater blocked by a permafrost, is postulated. Above the water, a breccia and stalagmite is probably correlative.

2. The above fill was largely cleared by vigorous floods which laid coarse, laminated sands. Wet interstadial conditions are implied.

3. Finer laminated sands and silts were laid upon the Phase 2 deposits, signifying a weakening of flood discharge.

4. The cave was drained to a lower level. Stream gravels from a nearby gorge and frost breccia from the cave roof are intermingled with remains of Younger Dryas hearths. A partial reversion of permafrost conditions must be postulated.

5. 3 – 12" of stalagmite was laid on the earlier fill. Archaeologists date this to the Atlantic-Boreal phases of the post-Glacial, a little warmer and wetter than the present. This poses a grave dynamic problem.
6. Modern times are marked by some block fall, accumulations of weathering earth and the re-solution of much stalagmite by waters from the formative sources.

AN ALPINE KARST IN THE UNITED STATES

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University Park, Pennsylvania

The Teton Mountain Range, located in the northwestern section of the state of Wyoming, is an isolated range in the Rocky Mountains. Structurally, the range is a westward tilting, up-thrust block fault with Precambrian crystalline peaks reaching near 14,000 (4,250 meters) feet on the eastern flanks and sloping Paleozoic sediments on the west. Both sides ofthe range are deeply incised by canyons.

South Darby Canyon (No. 1), at an elevation averaging 9,000 feet (2,750 meters) is floored by dolomites and walled with limestones. Karst features and caves are present.Little speleological investigation has been done in this remote area but it is assumed that the caves (in the canyon walls) are pre-glacial and the canyon floor karst is post-glacial. Rainfall data indicates that current surface solutional activity occurs under snow cover. Exposed karst is physically different from most European examples and is highly joint controlled.

SESIMIC INVESTIGATION OF NEAR-SURFACE CAVITIES – A PRELIMINARY REPORT

Joel S. Watkins, R. H. Godson
and
Kenneth Watson

U.S. Geological Survey
Flagstaff, Arizona

Recent field investigations have successfully delineated two lava tunnels located a few feet below the surface of the ground, and a cavity formed as a result of an underground nuclear explosion and subsequent collapse of the overlying rock at the Nevada Test Site. The top of the cavity at the Test Site was 25 m below the surface.

Three seismic phenomena, cavity oscillations anomalous amplitude attenuations, and delays in arrival times, have been observed in the vicinity of the cavities. Of these three phenomena, cavity oscillations are the most significant diagnostic criteria for location and delineation of cavities because the waves cannot be amgiguously caused by any other geological phenomenon. Anomalous attenuations of amplitudes and delays in arrival times, however, can be caused by local geological conditions other than cavities, and hence require careful design of the seismic experiment to eliminate other possible causes.

DEVELOPMENT OF A KARST VALLEY IN MONROE COUNTY, INDIANA

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Indiana Geological Survey
Bloomington, Indiana

A karst valley in western Monroe County has developed where the surface stream of a former southward-flowing tributary of Indian Creek was diverted westward underground into valleys that are minor tributaries to Richland Creek. The diversion of water from the karst valley was caused by a lower base level along Richland Creek. This subterranean diversion was channeled through three multilevel cavern systems, each with mapped passages in excess of one mile, that lie beneath the ridge of clastic rocks which separated the surface drainage of Indian Creek and Richland Creek. These caverns were dissolved within the westward-dipping limestone strata which are exposed in the floor of the valley and along Richland Creek. Segments of the karst valley presently drain into these three known cavern systems. Abandoned levels in the caverns and depositional and erosional terraces in the karst valley and in Richland Creek indicate that there were several distinct stages during the diversion of surface drainage of the karst valley to subterranean drainage. These erosion levels developed during the late part of the Tertiary Period and during the Pleistocene Epoch.

THE SOLUBILITY OF GALENA DOLOMITE IN CAVE WATERS

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Iowa City, Iowa

Data on the concentration of carbonate ($CO_3^{=}$) ions in the waters of Level Crevice Cave, Dubuque, Iowa were used to calculate the solubility product of Galena dolomite in the water, based on the assumption that all of the carbonate present was due to solution of the bedrock by the water alone. The result indicates that the solubility product is $1.15 \times 10^{-21} \pm 2.70 \times 10^{-21}$, in cave water at 10° C. This indicates that the solubility of the dolomite is much lower (by a factor of 10^{-15}ς) than that of the individual components of the dolomite taken in a pure state. It may be concluded that such solution of the dolomite, under present conditions, did not figure significantly in the formation of the cave.

BIOLOGY SESSION

BACTERIAL DEPOSITION OF METALLIC OXIDES IN THE CAVES OF DUBUQUE, IOWA

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Northwestern University

Microscopic examination of iron and manganese oxide deposits from caves of Dubuque, Iowa, shows the deposits to be composed of curved rod-like structures. The curved rods are similar to those found in the iron precipitate of epigean springs containing sheath bacteria. Sheath bacteria have been recovered from caves and mines near Dubuque. It is consequently suggested that the iron and manganese deposits in the caves are the result of bacterial activity.

PLEISTOCENE BONE REMAINS FROM CAVES IN PERRY COUNTY, MISSOURI

Ronald D. Oesch

Kirkwood, Missouri

Four years ago detailed studies on a karst region in Perry County, Missouri were initiated. As mapping investigation of the caves proceeded, mineralized bones of

Pleistocene animals were found. Sometimes the bones were found in gravel and sometimes they were cemented by calcite to the cave walls. It was observed that most of the bones occurred approximately one and one-half feet above the present cave floor. It is possible that the bones were deposited on or near the floor of the cave when they first entered the passages. If so, erosion and abrasion have lowered the cave floors quite rapidly since the bones were introduced into the caves. Remains of Peistocene horses, camels, peccaries, deer, rabbits, and turtles have been found in Perry County caves to date.

PLEISTOCENE BEAR FOSSILS FROM A "BEAR BED" IN PERKINS CAVE, MISSOURI

Oscar Hawksley

Central Missouri State College,
Warrensburg, Missouri

A deposit of bear bones from Perkins Cave, Camden County, Missouri has yielded valuable information of Pleistocene bears in the Ozarks. The bones were apparently deposited in a "bear bed" or winter den over a considerable period of time, then moved to their recent location by collapse of the floor which contained the "bed." The bones represent at least two specimens of *Arctodus pristinus,* the short-faced bear; two specimens of *Ursus americanus amplidens,* a large, extinct subspecies of the black bear; and several specimens of *Ursus americanus americanus,* the recent black bear. Also associated with the bears are teeth of beaver, *Castor canadensis,* and of the dire wolf, *Canis dirus.*

Nearly complete dentition and an excellent representation of foot elements from a single specimen of the short-faced bear will be valuable in determining the exact taxonomic status of these large bears in North America.

Ursus americanus amplidens had teeth which approached the size of those of some modern grizzlies (*Ursus horribilis*), but although their limb bones were more robust than those of the recent black bears, they were not as heavy as those of the grizzlies.

It is interesting to note that a particular winter den was used over such a long period of time by three distinct kinds of bears, and to know that short-faced bears had much the same habits in this respect as the present black bears. All three bears might be considered to be late Pleistocene. However, the short-faced bear may be Sangamon in age while the specimens of the recent form of the black bear are undoubtedly post-glacial.

PRELIMINARY OBSERVATION ON THE BIOLOGY OF SHELTA CAVE, ALABAMA

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Science Dept.
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Shelta Cave, Huntsville, Madison County, Alabama, displays one of the most interesting and unusual underground ecosystems in North America. It is one of only two caves in the United States definitely known to contain three distinct species of troglobitic crayfish, *Cambarus jonesi, Orconectes pellucidus* and *Orconectes sp. O. pellucidus* is the largest (carapace lengths to 42 mm.) and by far the most numerous macroscopic organism in the aquatic community. The other *Orconectes* is a rare, undescribed form of which only eight specimens have been captured after much exhaustive collecting. When described it will be the second really distinct troglobitic *Orconectes* discovered in over 120 years. Possible character displacement among the members of this community is indicated by the fact that there is little if any overlap in adult size among Shelta's aquatic troglobites. The *pellucidus* are dramatically larger than those found in other caves, and the *jonesi* smaller than those from the type population in Cave Spring Cave. Shelta harbors one of the two known species of troglobitic atyid shrimp in the United States, *Palaemonias alabamae,* described in 1963 by Smalley. Two aquatic vertebrates are found in the cave, the troglobitic fish *Typhlichthys subterraneus,* and a large, apparently neotenic salamander of the genus *Gyrinophilus* (cf. *palleucus*). The cave is also the home of many terrestrial organisms, including the troglobitic beetles *Pseudanophthalmus l. lodingi, Ptomaphagus* (*Adelops*) *henroti ellipticus,* and *P.* (*A.*) *lodingi,* and the rare endemic dipluran *Plusiocampa henroti.* The terrestrial invertebrate fauna also contains forms which are as yet unidentified and perhaps undescribed, including collembola (*Troglosinella?*), troglobitic and eipgean millipedes of several distinct species, troglobitic and eipgean spiders, apparently-troglobitic opilionids, and epigean terrestrial isopods and snails. The terrestrial salamanders *Plethodon g. glutinosus* and *Eurycea lucifuga* are recorded from the cave. Two mammals have been seen there, the bat *Myotis grisescens* in a population of about 500 individuals, and a single rodent which appeared to be *Mus musculus.* Water levels in the cave fluctuate tremendously from season to season, and apparent population density follows suit. The water is rich in plankton. The systematic and ecological study of the fauna of this cave, initiated in the summer of 1963 by M.S. Riser and the author, is continuing.

A PROGRESS REPORT ON STUDY OF THE CAVE BEETLES OF TEXAS AND MEXICO

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The beetles of caves of Texas and Mexico include representatives of the families Carabidae, Catopidae, Pselaphidae, Staphylinidae, and Tenebrionidae. Trogidae and Dermestidae occur in guano caves, and representatives of a few other families occur sporadically. Most of the troglobitic species are trechine and anchomenine carabids, notably species of the genera *Mexaphaenops, Rhadine,* and *Mexisphodrus.* Recent discoveries of note include (1) the intense speciation among troglobitic *Rhadine* of the *subterranea* group in central Texas; (2) the new genus of pselaphids, *Texamaurops,* from central Texas; and (3) the new hemispheric records of sphodrine carabids from Vera Cruz, San Luis Potosi, and extreme southern Texas.

CIRCADIAN RHYTHMS AND SEASONAL CYCLES IN CAVE FISHES AND CRAYFISH

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Date for a number of aquatic troglobites show that reproduction is apparently keyed to the time of spring flooding or rising base level. In particular, data collected over a three-year period on *Orconectes pellucidus* in Shiloh Cave, Indiana suggest that time of egg laying and subsequent fall molting differ in time and extent with differences in time and sharpness of spring flooding. These data can be interpreted as indicating some mechanism of assessing elapsed time, since molting in crayfish and preparation for reproduction in both crayfish and fish occur during fall when there are no discrete environmental cues. Our present hypothesis is that of spring floods synchronize biological clocks of the animals and trigger reproduction. The clock allows the organisms to measure time elapsed and thus prepare for reproduction more or less synchronously. We have evidence that circadian rhythms of activity are lost only in the most specialized cave amblyopsid fish and that circadian rhythms of oxygen consumption are still present in a specialized troglobitic crayfish, *Orconectes pellucidus*.

BIOLOGY OF THE CAVES OF THE GOMEZ FARIAS REGION, TAMAULIPAS, MEXICO

James R. Reddell

Association for Mexican
Cave Studies

Fifteen caves have been investigated in the Sierra de Guatemala in the vicinity of Gomez Farias, Tamaulipas, Mexico. The area is of unusual interest in that there is a complete change of climate and vegetation types within a distancs of 30 km. Drainage on the eastern slopes is entirely subterranean with a typical karst topography present. The caves investigated range from elevations of 100m to 2000m. A rich cave fauna was found at all elevations and included obligative cavernicoles in several groups. Of special interest are the millipeds, beetles, crickets, and spiders. Included is the first recorded troglobite for the New World in the cricket family Gryllidae. Several groups are present in the caves which are not known from the area. Despite complete changes in the climate, vegetation, and surface fauna the same group of cavernicoles, even in most instances the same species, occur at all elevations.

MICROCLIMATE SELECTION WITHIN THE CAVE BY BATS

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Many species of bats use caves for over-wintering hibernation; within these caves each species selects a specific location. Because fat stores are limited, the bat must select a microclimate which is not stressful. In this study observations of microhabitat selection in the hibernaculum were correlated with laboratory observations of physiological responses to controlled climates. Interpretations were made of discrimination of, and physiological suitability, of microclimates. Two species were studied; the little brown bat, *Myotis lucifugus*, and the Indiana bat, *Myotis sodalis*. Most observations were made in one cave in northern Kentucky over three years. Temperature: in the cave the little brown bat selected a warmer area where minimal temperature in late winter was 3° to 5°C.; the Indiana bat selected areas with lower temperatures averaging 1° to 2°C. by late winter with frequent drops below 0°C. In the laboratory, the little brown bat was found to be incapable of regulation of body temperature at air temperatures below 0°C., while the Indiana bat thermoregulated well at air temperatures down to -5°C.

Relative humidity and wind: the little brown bat selected a clustering site in which the air was always nearly saturated with water vapor, while the relative humidity of the sites selected by the Indiana bat was variably lower than 100%. Air movement would tend to enhance evaporation in unsaturated air. Air circulation was always minimal where the little brown bat clustered, but the sites selected by the Indiana bat frequently had strong winds. The little brown bat lost water at slightly faster rates, and consumed more water than the Indiana bat. (Supported in part by a grant from the Cave Research Foundation)

MEETING IN BERKELEY, CALIFORNIA, DECEMBER 29, 1965

Complete texts and abstracts of papers presented at the Symposium on Limestone Hydrology, jointly sponsored by the National Speleological Society, the American Association for the Advancement of Science, and the Geological Society of America, will appear in the July issue of this publication.

SHORTER CONTRIBUTIONS

Free Living Mites (Acarina) In Australian Caves

By Elery Hamilton-Smith

ABSTRACT

An examination of the free-living mites (Acarina) from Australian caves indicates taxonomic parallels with other recorded cave faunas. The majority of species are associated with bat guano, and although a large number are apparently confined to the cave habitat, none appear to be truly troglobitic.

INTRODUCTION

In discussing the free-living mites of American caves, Holsinger (1965) draws attention to the parallels between this fauna and that of European caves. It may therefore be of interest to list the recorded Acarina of Australian caves as this listing also demonstrates further parallels, at least taxonomically, with cave faunas of other continents.

Although the study of Australian cavernicoles is in its infancy, the Acarina is probably one of the best-known groups, largely through the taxonomic work of Robert Domrow and the late Herbert Womersley. Many species parasitic upon or commensal with bats have been described, but these will not be dealt with here except to briefly mention certain species which are occasionally found separated from their hosts.

In the list below, where the familial classification now generally in use differs from that of Baker and Wharton (1952), the classification used by Baker and Wharton is added in brackets to facilitate comparison with other papers. Most of the species recorded below are in the collections of the Australian Cave Fauna Survey, conducted by the author in conjunction with the South Australian Museum, and forming the biospeleological collection of that institution. Where locality records from caves or other relevant data is included in the species description, this reference is listed in the bibliography.

ANNOTATED LIST

Suborder MESOSTIGMATA

Family CILLIBIDAE Trägårdh, 1944

Cilliba coprophila Womersley, 1960

This species occurs throughout Eastern Australia in caves with large deposits of bat guano, particularly in those caves used by bats as maternity colonies. The specific localities are too numerous to list here. This mite occurs in immense numbers and at the Bat Cave, Naracoorte, South Australia (the type locality), the author found that counting a number of samples revealed an average population of 1,000 living specimens per square inch of surface area.

Family ICHTHYOSTOMATOGASTERIDAE Sellnick, 1953 (PHYTOSEIIDAE Berlese, 1916)

Asternolaelaps australis Womersly & Domrow, 1959

Described from a single male taken from a bat, *Miniopterus schreibersi,* at the Bat Cave, Naracoorte, South Australia. A unique female of the same genus and possibly referable to this species has been collected from the floor of Cave B12, Buchan, Victoria.

Family SPINTURNICIDAE Oudemans, 1901

Several species of this family, the most common of which is *Spinturnix psi* (Kolenati), occur as parasites on Australian bats. However, in maternity colonies, the larval form falls from clusters of young bats in immense numbers and may consequently be collected from the floor below. However, these specimens will not survive once removed from their host.

Family LAELAPTIDAE Berlese, 1892

Most species of this family recorded from Australian caves are parasitic upon bats but a free-living species of *Cosmolaelaps* has been collected from guano in Church Cave, Wee Jasper, New South Wales by the author. It is also recorded from the same habitat in an unused railway tunnel at Samford, Queensland (Domrow, pers. comm.).

Family MACROCHELIDAE Vitzthum, 1930

Macrocheles tenuirostris Krantz & Filipponi, 1964

Orginally described from the nesting burrows of the Mutton-bird, *Puffinus tenuirostris,* but since collected by the author from guano along with *Cilliba coprophila* at Panmure Cave, near Warrnambool, Victoria.

Suborder IXODIDES

Family IXODIDAE Murray, 1877

Ixodes simplex simplex Neumann, 1906

A common parasite of bats in eastern Australia (and elsewhere), this species is often collected from the walls of caves frequented by bats.

It may also be of interest to record a specimen of *Ixodes ornithorhynchi,* a parasite of the Platypus, collected from a mud-bank in Cave M35, Murrindal, Victoria. The river flowing through this cave is inhabited by the host animal, and this is clearly a fortuitous occurrence.

Suborder TROMBIDIFORMES

In addition those forms listed below, a number of currently undetermined trombidiform mites have been collected from other caves, and can be tentatively assigned to the superfamily *Erythraeoidea* Grandjean, 1947.

Family LEEUWENHOEKIIDAE Womersley, 1948 (TROMBIDIIDAE Leach, 1815)

Neotrombidium neptunium Southcott, 1961 (*N. tridentifer* Southcott, 1957 preocc.)

Clogg's Cave, East Buchan, Victoria.

N. gracilare Womersley, 1963

Fig Tree Cave, Wombeyan, New South Wales; Murder Cave, Cliefden, New South Wales; Puchbowl Cave, Wee Jasper, New South Wales.

N. gracilipes Womersley, 1963

Fig Tree Cave, Wombeyan, New South Wales. (Womersley points out that this is probably the larval form of N. *gracilare,* but this cannot be definitely established without breeding experiments.)

Members of this family are generally parasitic upon arthropods in their larval stages but free-living as adults. At present the larval hosts of the Australian species are unknown.

Family LABIDOSTOMIDAE Oudemans, 1904

A single specimen of *Labidostoma* sp. has been taken from Cliefden Caves, New South Wales.

Suborder SARCOPTIFORMES

Family TYROGLYPHIDAE Donnadieu, 1868 (ACARIDAE Ewing & Nesbitt, 1942)

Coproglyphus dewae Womersly, 1963

In bat guano from the following sites: Fig Tree Cave, Wombeyan, New South Wales; Basin Cave, Wombeyan, New South Wales; unused railway tunnel, North Sydney, New South Wales; Bat Cave, Naracoorte, South Australia

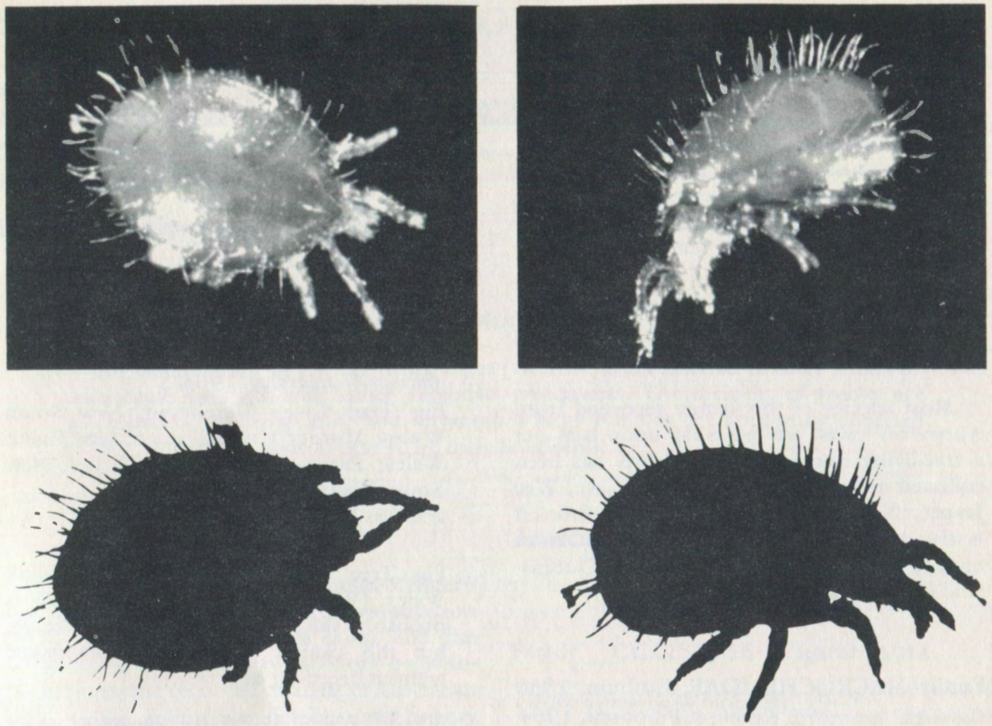

Figure 1.

Dorsal and lateral views of *Cilliba coprophila* Womersley. Microphotographs are compared with silhouettes of the same specimen. Overall length of the animal is approximately 1 mm.

DISCUSSIONS AND CONCLUSIONS

Of the families listed, only the Cillibidae and Ichthyostomatogsteridae do not appear to have been previously recorded from caves. Both the Spinturnicidae and Ixodidae have a virtually world-wide distribution as bat parasites and could well be found in similar circumstances to those described above. The Laelaptidae, Macrochelidae, Trombidiidae, and Labidostomidae are all recorded by Holsinger (1965) as occurring in caves in both North America and Europe.

Other records which provide interesting parallels with the above are the occurrence of *Macrocheles* sp. in Malaysia (Frantz, pers. comm.); of the Trombidiidae in Japan, Madagascar, and the Congo (Vandel, 1964) and in Central America (Nicholas, 1962); and of the Tyroglyphidae in Europe (Vandel, 1964).

By way of contrast, the Rhagidiidae and Parasitidae, both significant families in the caves of the Northern Hemisphere, have not yet been recorded from Australian caves. It seems reasonable to suggest that this fact may bear some relation to the absence of troglobitic forms and the probable recent development of the Australian cavernicolous fauna.

Moore (1964) and the present author (in press) have already drawn attention to the comparative paucity of troglobites in Australia, even though a large number of species are known only from cave habitats. This has been postulated as being due to hot, arid conditions at some time in the post-glacial period which has resulted in a secondary extinction of cave-dwelling fauna.

This summary of the Acarina supports this general hypothesis and suggests that the species concerned are comparatively recent immigrants to the cave habitat. It is of particular interest that two of the species concerned have established themselves in unused railway tunnels, both of very recent origin.

ACKNOWLEDGMENTS

The author wishes to record his appreciation of the support provided by the South Australian Museum for the Cave Fauna Survey, of which the above study forms a small part. In particular, the late H. Womersley, Dr. G.W. Krantz, and R. Domrow have assisted with data and the determination of material. Mr. W.A. Jackson has assisted greatly by accomplishing the very difficult task of providing excellent photographs.

REFERENCES

Baker, E.W., and G.W. Wharton
1952 An introduction to acarology: The Macmillan Co., New York, 465 p.

Holsinger, John R.
1965 Free living mites (Acarina) in caves of the eastern United States: Bull. Natl. Speleological Soc., v. 27, pp. 47-54.

Moore, B.P.
1964 Present day cave beetle fauna in Australia – a pointer to past climatic change: Helictite, v. 3, pp. 3-9.

Nicholas, Brother G.
1962 Checklist of troglobitic organisms of Middle America: American Midl. Nat., v. 68, pp. 165-188.

Vandel, A.
1964 Biospeleologie, la biologie des animaux cavernicoles: Gauthier-Villars Editeur, Paris, 619 p.

Womersley, H.
1960 A new coprophilous uropodid mite, *Cilliba coprophila* sp. nov. from a bat cave in South Australia (Acarina-Cillibidae): Rec. South Australia Mus., v. 13, pp. 471-479.

1963 Two new species of Acarina from bat guano from Australian caves: Trans. Royal Soc. South Australia, v. 86, pp. 147-154.

1963 A new larval Neotrombidium (Acarina, Leeuwenhoekiidae) from bat guano: Rec. South Australia Mus., v. 14, pp. 473-476.

Womersley, H. and R. Domrow
1959 A new Asternolaelaps from Australia (Acarina, Ichthyostomatogasteridae): Rec. South Australia Mus., v. 13, pp. 355-358.

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Naturally Polished Pebbles From Black Hills Caves

By Dwight E. Deal

ABSTRACT

"Cave pearls" that may have been naturally tumble polished are found in Bethlehem Cave and Jewel Cave, South Dakota. They are formed from fragments of limestone, calcite, other speleothems, and chert (?). Due to the questionable identification of the chert fragments a solutional origin cannot completely be ruled out.

INTRODUCTION

A few small pockets in the floors of Bethlehem Cave and Jewel Cave, in the Black Hills of South Dakota, have been found partially filled with small, loose, highly polished rock fragments. These are not cave pearls as such as they are not semispherical, layered, mineral growths. The occurrences in Bethlehem Cave are called "Duck Nests" and have been known for many years. The one Jewel Cave occurrence was discovered in 1961.

I would like to thank Father Gilbert Stack for permission to work in Bethlehem Cave and the National Park Service for permission to work and collect in Jewel Cave.

DESCRIPTION

The "Duck Nests" in Bethlehem Cave are restricted to one locality and occur as pockets in both flowstone and limestone, some on top of breakdown blocks. The pockets rarely larger than six inches in diameter and most have polished floors.

The fragments in the pockets are irregular in shape but have smoothed and rounded outlines (fig. 1). They range in color from dark reddish-brown to white to almost colorless. The majority are opaque but some nearly colorless fragments are translucent. Some of the latter clearly show rhombohedral and scalenohedral outlines (fig. 2).

The one occurrence in Jewel Cave is essentially identical to those in Bethlehem Cave. It contains an almost perfect, colorless, calcite cleavage rhomb with slightly rounded edges. Two fragments from Jewel Cave were removed and sectioned. One was a calcite cleavage fragment and the other a piece of Pahasapa Limestone, the formation in which the caves are developed. Neither had any secondary coating or outer layer.

The ceiling height over the pockets ranges between six and 10 feet. The pocket shown in figure 1 is the only one noted that has a stalactite located above it. This stalactite is very small and not active. No evidence of seepage, past or present, could be noticed above the other pockets. None of the pockets contained water.

Several of the pockets that contained loose fragments were surrounded by a knobby surface (fig. 1) that looked as if it was formed of similar rounded fragments cemented together by and coated with calcite.

ORIGIN

The fragments all appear to be locally derived material. The cave floors in the vicinity of the pockets are littered with fragments of limestone and white to colorless calcite crystals. The dark reddish-brown fragments in Bethlehem Cave appear to be pieces of chert from the Pahasapa Limestone. This could not definitely be established, however, as no similar fragments were noted in Jewel Cave and permission to examine the pockets in Bethlehem Cave was granted only with the stipulation that they not be touched or disturbed in any way. The owners feared that such disturbance would cause the "pearls" to stop forming and become cemented to the side or walls of the pockets.

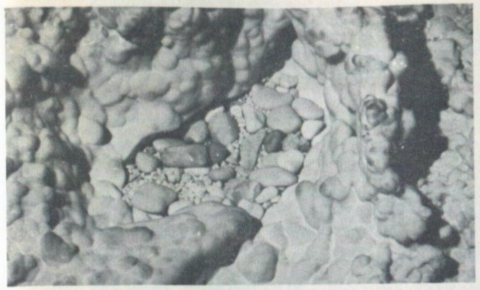

Figure 1.
A typical "duck nest" in Bethlehem Cave. The long diameter of the "nest" is six inches. The dark fragments just left of center are thought to be pieces of chert.

Figure 2.
Two "nests" filled with translucent fragments. The width of the picture is six inches. The fragment in the center of the photograph has a scalenohedral shape.

Water probably entered the cave through the ceiling above the pockets and dripped or flowed into them. Although there is considerable amount of calcite deposited around the pockets, none of the fragments appear to have any secondary coating related to their rounding and polishing. A few fragments were obviously rather complex, perhaps coated, pieces of limestone and calcite before the rounding and polishing was initiated. This rules out an accretionary origin.

Two other possible mechanisms or origin remain: solution or abrasion. If the reddish-brown fragments in Bethlehem Cave are truely chert fragments, it is highly unlikely that they have been rounded by solution. If water entered the pockets with sufficient force it could have agitated the fragments and caused them to be rounded and polished in much the same fashion as gem-stones are tumbled and polished.

Figure 1 might suggest that the water welled up into the pocket from below. This is not the case as some pockets can be seen to have solid limestone floors and some are formed on the upper sides of breakdown blocks.

Highly polished pebbles are fairly common in Missouri caves, springs, and solution channels (Beveridge, 1960) where violent water and large quantities of very fine clays occur. Vineyard (1960) describes an occurrence in Devil's Well, a partially spring-filled cave, where fine silt and mud serve as abrasive and polishing agents and a waterfall splashing into a rock basin keeps the pebbles in almost constant agitation.

The Black Hills deposits lack the fine muds which serve as jewler's rouge and, as a result, are much more difficult to account for. I feel that it is unlikely that water entered the "Duck Nests" and the pocket in Jewel Cave with sufficient force to polish the pebbles without the presence of other polishing agents. If it were not for the questionable presence of polished chert fragments in Bethlehem Cave, I would definitely think the deposits were solutional rather than abrasional in origin.

REFERENCES

Beveridge, T.R.
1960 Guidebook to the geology of the Rolla area emphasizing solution phenomena: Missouri Geol. Survey, Misc. publication (multilithed), p. 29.

Vineyard, Jerry D.
1960 Natural gemstones in a Missouri cave: Missouri Speleology, v. 2, n. 4, p. 126.

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Mud Stalagmites In Jewel Cave, South Dakota

By Dwight E. Deal

ABSTRACT

Mud stalagmites five to eight millimeters in diameter and 40 to 50 millimeters high occur in Jewel Cave, South Dakota. They are composed of rounded quartz grains in a clay matrix. A semi-liquid flow of mud and sand dripped from calcite crystals overhead to form the stalagmites.

There is an unusual occurrence of mud stalagmites in Jewel Cave, South Dakota (fig. 1). The stalagmites are five to eight millimeters in diameter, 40 to 50 millimeters high and cover an area of about 0.5 meter. Microscopic examination of the two samples collected reveals that they are composed of 0.05 to 0.1 millimeter rounded quartz grains in a clay matrix. As a check an x-ray diffraction pattern was made of one sample and only the peaks for quartz and a clay mineral were present.

One sample was concentrically layered, each layer 0.3 to 0.5 millimeter thick, with four distinct layers around a thicker central core. The other sample was not layered.

The cave wall above the deposit is very knobby due to a thick coating of calcite crystals and the wall overhangs slightly. There is a small side passage above the stalagmites and it appears that a semi-liquid flow of moist mud and sand issued from it, some of which dripped off the ends of individual calcite crystals to form the stalagmites.

Considerably larger and more complex mud stalagmites in Indiana have been described along the underground course of Lost River by Malott and Shrock (1933). These partially clay-filled passages subjected to periodic flooding by quiet, silt-laden waters. Water dripping intermittently from the passage ceiling redistributes the clay and silt after each flooding to slowly build the stalagmites, some of which reach 18 inches in height (Malott and Shrock, p. 55). Malott and Shrock (p. 58) describe the process as follows:

> "The successively falling drops make a pit in the mud banks one-half of an inch or more in diameter and usually about two inches in depth. The material displaced from the pit makes a little welt or ridge about the pit. A flood follows and the silt accumulates in the pit. On the withdrawal of the flood waters the falling drops from the roof splash out from the pits most of the silt-sludge which accumulates about the pit. Other floods follow and the silt of each succeeding flood is thrown out of the pit and the welt about the pit grows into a mud stalagmite."

The Jewel Cave deposits, in contrast, were formed quickly by one mud flow.

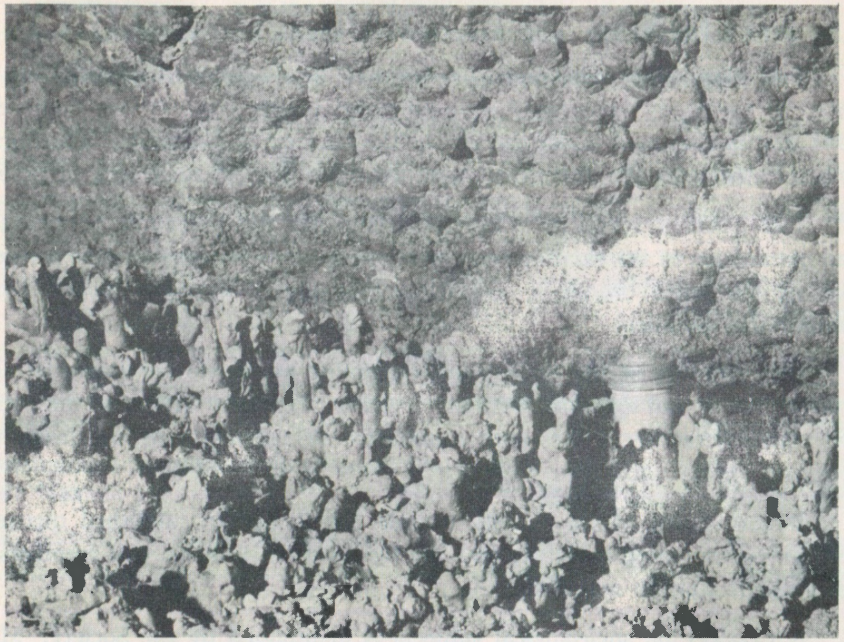

Figure 1.
Mud stalagmites in Jewel Cave, South Dakota. Note the irregular, mud-spattered wall of large calcite crystals. A 35 mm. film can indicate scale.

REFERENCE CITED

Malott, C.A., and R.R. Shrock
1933 Mud stalagmites: Am. Jour. Science, 5th ser., v. 25, n. 145, pp. 55-60.

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