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# Similitude in Direct and Thought Experiments in Cave Geology

**By Richard A. Watson**

ABSTRACT

Methodological analysis and illustrations are given of two kinds of geological experiments conducted in speleology. Each kind deals in a different way with problems posed by the great masses of rock and spans of time involved in the evolution of natural features. 1) In *direct* model experiments, Meunier, Lange, Mowat, Ewers and Reams produced features similar to features in caves, speeding solutional processes by using hydrochloric or nitric acid and limestone, or water and salt. They then reasoned by analogy about the genesis of natural features. 2) In *thought* experiments, Pohl imagined sequences of events under given natural conditions, reasoning from these. Meunier's results are valid on his assumptions (and similar to Pohl's), but direct experiments as elementary as his are now seldom performed. Thought experiments seem to provide a closer reproduction of natural conditions and so have been more satisfactory for explaining the development of gross physiographic features. It is hoped that with mathematical techniques of analyzing and comparing materials, direct experiments with scale models will provide important corroborations for thought experiments in cave geology. However, it remains to be established that the assumptions involved in substituting one chemical reaction in a model for a different chemical reaction in nature are valid.

## Introduction

There are two basic kinds of experiment with which one can test hypotheses concerning the genesis of geologic features. *Direct* experimentation with natural materials, processes and rates is most satisfactory, but is not always possible given the sizes, the strengths, and the lengths of time it has taken natural processes to form many of these features. Given the great dimensions in space and time of geologic features and events, direct experimentation involving the genesis of major features is usually impossible. Even when it is possible, the slowness (on the human scale) of the processes involved limits further the obtainable results. In speleology, one could measure directly a stalactite or piece of flowstone, and then measure the growth periodically over a period of years. Here the experimenter would utilize natural conditions, turning the situation into an experiment merely by making measurements. His conclusions can be extrapolated, but still the experiment would have to be conducted over a number of years if he is interested in the effect of climatic fluctuations. Another rudimentary experiment, still using materials in their natural dimensions, would involve manipulation on the part of the experimenter. A number of limestone blocks could be cut to have the same dimensions of size, shape, and weight; these could be placed in various cave water environments, and then checked over a period of years for amount of solution and type of resulting form.

If a geologist wants to test hypotheses about the genesis of major features such as vertical shafts, or about the evolution of entire cave systems, he cannot experiment directly with materials and processes of natural dimensions. In such cases a special type of direct experiment has been attempted. When it is possible through dimensional analysis to scale down the factors of size, strength, and time, usually through the substitution of materials, tests of hypotheses can often be made by direct experimentation upon scale models. The theory of scale models for mechanical systems in geology has been worked out in some detail by M. King Hubbert (1937, corrected reprint 1944), and the principles of this theory are applicable to thermodynamic and electromagnetic systems. It is part of the purpose of this paper to show that the theory has not been developed for systems in which chemical reactions are involved.

Where the actual manipulation of materials is difficult or impossible, geologists often use *thought* experiments which are conducted in the mind of the experimenter who tries to imagine as well as he can what would happen in prescribed natural circumstances. He then looks in the field for features which will bear out (or negate) predictions based on the results of his thought experiments. Even when direct experimentation is undertaken, thought experiments are usually conducted in the planning stage, and the best possible cooperation of a hypothesis is when predictions from it are born out by both direct and thought experiments.

In the following I shall illustrate direct model experimentation with the work of Stanislaus Meunier, and thought experiments with E. R. Pohl's work on vertical shafts. Then I shall compare and constrast the methodology of direct experiments with that of thought experiments. Finally, I shall evaluate direct model experimentation which involves substituting one chemical reaction for another in direct model experimentation, making reference to recent work by Lange, Mowat, Ewers, Reams and others, showing the extent to which such experiments have been theoretically justified.

## Meunier's Direct Model Experiments

Stanislas Meunier has a richly deserved place in the history of the eclectic science of speleology. One of the first experimental geologists, he conducted some of the first direct model experiments concerned with the development of underground phenomena. He experimented on models made of limestone, trying to duplicate natural conditions as well as he could. In *La Géologie Expérimentale* (1899) he devoted a chapter to surficial infiltration water, treating in turn subterranean denudation and sedimentation, Meunier's experiments in sedimentation were elementary, and though they were soon superseded by later work, their results are essentially correct. His experiments with subterranean denudation, or, more specifically, with the formation of cavities by subterranean solutional activity were also elementary, but have not been superseded by later work. Meunier (1904, p. 172) himself was convinced of the finality of his experiments concerning solutional activity:

> "There are certainly few chapters of general geology where the application of the experimental method has been more decisive than in those which comprise the story of surficial infiltration water."

It will be shown later why Meunier's experiments with solution have not been superseded, and in what sense they have significance today, some 90 years after they were performed.

The evolution of natural wells was Meunier's first concern. Bory de Saint-Vincent (1819) had conducted an experiment in which he let a stream of water (a weak concentration of carbonic acid) fall on a prism of sugar. The resulting feature was like a natural well. Meunier (1875), did not know of this experiment when he conducted similar ones. He used calcareous rocks instead of sugar, and substituted a concentration of hydrochloric acid for the carbonic acid of natural ground water. He began with a non-fissured block of limestone. In sequence, a small, more or less hemispheric cavity, then a cone was formed. After the block was perforated, first a cylinder was formed, and then unequal enlargement at several levels. The final stage was bottle-shaped.

The shape depends upon the kind of flow, the acidic concentration, and the quality of the limestone. Meunier attributed the cone shape to the fact that saturated liquid protected the lower parts of the cavity from solution. After the block is perforated, the concentration of acid on the narrower lower portions soon brings the cavity to a cylindrical shape. Then increased solution in the lower portions (presumably because of greater contact with the corrosive liquid) results in the final bottle shape.



From these experiments Meunier thus reasoned to the various stages of development of natural wells. He always cited corroborating examples of natural depressions, sinkholes, and vertical shafts which were similar to the features resulting from his experiments. He believed that one could observe the entire sequence in the field by visiting different natural features.

Meunier also conducted experiments in which the corrosive liquid was directed upward at a block of non-fissured limestone. The resulting cavity was similar in shape to known features in caves.

More important were Meunier's experiments with vertical solution on fractured rocks. He was able to form features similar to all the natural vertical cavities he knew of, varying the shape of his results by varying the fracture pattern in the limestone block. He concluded that most natural wells and other vertical features are controlled by the joint pattern of the limestone in which they are formed.

For the duplication in experiment of horizontal features similar to caves, Meunier used jointed rocks again. A large block of limestone was broken horizontally, the resulting top sheet was broken vertically, and then the three blocks were placed together again. A flow of corrosive liquid was directed horizontally along the line of the vertical fracture. tally along the line of the vertical fracture. Meunier altered the conditions of this experiment to produce replicas of many real caves. Features similar to those of underground rivers were formed by the flow of the corrosive liquid on the unfractured lower block.

Meunier consistently related his experiments to more comprehensive theories than those concerned with the evolution of specific features. He conducted a number of experiments on soils and calcareous rocks containing angular quartz grains. He showed that underground water could remove mechanically or in solution much of the soil and rock, leaving behind quartz sand. If pebbles or larger rocks rested on this sand, they were quite apt to be striated either by sliding on the quartz sand, or by the quartz grains moving along beneath them from the impress of underground water flow. Meunier's conclusions included warnings about using striated rocks as the only criterion for ancient glacial activity. Of course this is obvious if one stops to think about it: Meunier made the experiments.

He also suggested caution in paleo-physiography, that is, in believing that surfaces which seem to be buried (particularly in calcareous terrane) are ancient land surfaces. His experiments showed that the flow of corrosive water can form ravines under layers of sand and pebbles, so the underlying rock surface is not necessarily prior to the deposit upon it. He used this process to explain the evolution of many dry valleys which do not now have nor ever did have surface streams in them.

## Pohl's Thought Experiments

A more common kind of geological experiment begins from observations of nature (as did Meunier's), but is conducted in mind rather than in the laboratory. This is the thought experiment. If one can imagine the passage of time, the processes involved, and has already the notion of evolutionary sequence, then one can observe natural features in the field and imagine the evolutionary sequence in which they were formed. This is how Pohl (1955) argues for his theory of the evolution of vertical shafts by the solutional activity of water seeping down the intersection of joint planes. In Pohl's field investigations he saw that the intersection of joint places in limestone near the line along which ground water flowed over the edge of a truncated impermeable caprock provided a good vertical course for water to seep to the water table. In other observations he saw vertical shafts in all dimensions from a foot wide to a few feet high to over 50 feet wide and over 150 feet high. There are in the region vertical shafts in various degrees of collapse, and finally, thousands of sinkholes on a plain at an elevation some 200 feet lower than the plateau under which the vertical shafts are found. Pohl's experiment consisted of imagining the evolution of vertical shafts under circumstances similar to those he found in the field. Then he argued that the pattern of evolution resulting from his experiment showed the evolutionary sequence of the development of vertical shafts from their beginning in water seeping down the intersection of joints to their ultimate collapse.

## Methodology of the Experiments

The logic of Meunier's experiments is as follows: He argued by analogy from similar results to similar causes. He produced features in direct experimentation on models which resemble features in nature, and then claimed that the natural features were caused by a process and in a sequence similar to the way the experimental features were. He was not satisfied with Bory de Saint-Vincent's experiments. Where Bory de Saint-Vincent used the solution of carbonic acid found in nature (water) but substituted sugar for limestone, Meunier used the limestone found in nature but substituted a solution of hydrochloric acid for water. Both men made their substitutions to save time, assuming that the substituted materials and processes would behave and give the same results as the materials and processes for which they were substituted, only in less time. Thus, Meunier not only assumed that the action of hydrochloric acid is not sufficiently different from that of carbonic acid to alter results, he also assumed that the length of time taken to obtain the results does not essentially affect the results. Finally, Meunier argued from the small cavities found in his model to the large cavities in nature. He did this from similarity in shape.

Meunier concluded that his experiments showed an evolution of underground features, and for vertical cavities in jointed limestone at least, he believed he had provided patterns against which to measure the stage of development of all natural vertical features. He thus argued from his experimental models to explanations of both the active forces in the formation of natural features, and the evolutionary sequence of their development.

Pohl's experiment had as its apparatus the imaginative reconstruction of natural features. The experiment consisted in thinking what changes would be expected over time, and then comparing the series of features resulting in imagination with natural features in the field. Like Meunier's his assumptions consisted of the beliefs that forces active now were active in the past, and that similar features in the same region can be expected to be related in an evolutionary pattern of development. His major assumption was that solutional activity was going on in the past as it is now. If this is true, then it seems reasonable to conclude that the pattern he has given for the genesis of vertical shafts is the correct one.

In the model experiment, a fast solutional process is taken to represent the slow solutional process in nature. In the thought experiment, however, slow evolution over long periods of time (or at least sequential results of this evolution) can be imagined. Though there is ground for philosophical argument on this point, it seems that thought experiments are less open to objection that direct model experiments which substitute in the model some or all materials for natural ones. In thought experimentation at least the natural materials are used (though in imagination). In a model with substituted materials, one cannot always be sure that the comparison is justified between what happens in the model and what happens in nature. The limits of thought experiments seem to be only the limits of man's imagination and his knowledge about natural materials and processes. One possible danger of thought experimentation with respect to time is the tendency to extrapolate linearly. Some processes have little effect up to certain magnitudes, then at a critical point tremendous events take place. For example, water continues to lose heat with drop of temperature, but then it freezes. This might be hard to predict in a thought experiment. Another good example concerns the critical velocities in transport of elastic debris by wind and water (see Wolman and Miller, 1960).

It is important to note that in both direct and thought experiments two similar assumptions must be made. In the direct experiment, a process is *observed* to form a series of stages of development. The experimenter then must find natural features which resemble each stage. He assumes 1) that the process forming the natural features is the same as (or similar to) that forming the artificial, and 2) that the natural features were formed as a series of development stages analogous to those in the model. In the thought experiment, a process and stages of development are *imagined.* Then the experimenter proceeds as above. He finds natural features resembling the stages, assuming 1) that the process forming them is the same as that he imagined, and 2) that the features were formed in a development series of stages as imagined. As always in science, that the natural features *can* be so arranged, and that the proposed process *could* form them, never provides certainty that the features *are* so related and *were* so formed. The best we can do is say that the probability that we are right is greater if the two kinds of experiment corroborate one another. Thus, mutual corroboration by each kind is very desirable.

## Evaluation of Meunier's Direct Model Experiments

Meunier faced problems which face all geologists who would experiment concerning the evolution of massive geologic features. While much special experimentation can be accomplished with natural materials at natural sizes, and in lengths of time similar to those in natural conditions, the evolution of caves (or any such large feature) as a whole must be studied experimentally in models, if at all. This is what Meunier did. He deviated from the natural in his experiments with everything but the limestone, changing the solvent, the time, and the size. His experiments concerning the evolution of gross underground cavities are as adequate as can be devised without dimensional analysis and comparison of materials, and, if one is willing to reason with results from his model experiments to conclusions about natural features, then his conclusions are so far correct. One cannot be certain that natural underground cavities are formed as Meunier concludes, but no argument from analogy is certain.

Meunier is on safest ground with respect to size, for he can point to natural features which are similar in size to those in his models. Minature features like natural wells and caves are found in limestone and in gypsum (for example, in the gypsum beds within Carlsbad Caverns). But even here one must make assumptions concerning the solvent and time. In general, Meunier's approach to experimentation with models is too elementary to be satisfactory today. One cannot just use weaker materials and smaller layouts. One must know exactly the relations between strengths of materials and sizes if one is to compare models meaningfully with natural features. The use of mathematics to provide theoretical justification for models of mechanical systems in geology is discussed at length by Hubbert (1937, corrected reprint 1944).

Satisfaction with thought experiments has as much to do with Meunier's experiments not being specifically challenged as does the fact that his experiments are adequate given his assumptions. Satisfaction in science is an elusive concept, but it just is the case that thought experiments have seemed satisfactory enough to rule out the necessity of further direct model experiments. Of course it is not to be denied that Meunier's experiments could be repeated with more precision than he used, or that different materials could not be used as in the current experiments by Ralph O. Ewers (1964) with salt blocks and water, or by Max W. Reams (1963a, 1963b, 1965) with limestone and hydrochloric acid; however, in the production of gross cavities in rocks which resembled natural underground features, Meunier was a master. The immediate question is whether these experiments are meaningful, or whether they merely result in replicas whose method of genesis is not analogous to that of similar natural features.

Consider a simple scale model, one in which all natural materials were used, reducing only the size of the feature. Suppose one took sheets of limestone, broke them up, and fitted them back together in a block 10 meters square and three meters thick to represent 10, 000 square meters of limestone 300 meters thick. Could one do it? Considering the many joints, bedding planes, and fractures it would be difficult. But suppose one could. If the rainfall is one meter per year in the region being modeled, one could them release 10,000 cubic centimeters of water over the model during the course of a year at periodic intervals to represent the regional rainfall pattern. For the sake of the experiment, the water could all be confined and allowed to sink in. Of course in nature there would be runoff from an area as large as 10,000 square meters, but there would also be water running in and ground water flow. Let the experiment run . . . for how many years? Suppose after 20 to 50 years an incipient cave system develops in the model. Could we reason from it to the formation of cave systems in nature? Perhaps. Of course we've left out the influence of a phreatic zone, and not considered temperature variations, pressure changes, and so on. But would the model help us in understanding caves formed in the vadose zone? Probably, though one can question whether solution in small openings forms features similar to those formed by solution in large openings. White and Longyear (1962) have warned about too facile reasoning about ground water flow in limestone.

The point of this is not simply to adumbrate the obvious statement that such an experiment would be too time consuming to be feasible. I give it in detail to illustrate a scale model experiment in which all natural materials are used, and in which time is not scaled down because the process involved operates at natural speed. This is about as close as one can get to the natural. And even if one did run the experiment long enough to get features resembling large cave features, he would have to assume either that the length of time the experiment ran is an adequate replica of the length of time it takes to form large cave systems (which is a doubtful assum-
large cave systems (which is a doubtful assumption), or that a very long continuation of the experiment in an exact (natural size) replica of the cave region would result in large features exactly similar in shape to the small features formed after a few years. This latter assumption is doubtful, too. The relation of laminar to turbulent low in small openings is different than in larger ones, speed is slower, and so on. To get turbulent flow in the small model openings, high velocities would be required. This would have an effect on solutional processes. Finally, there is one thing in the experiment which cannot be scaled down enough (beside the speed of the solutional process), and that is the size of a drop of water. A drop of water falling on limestone as in Meunier's model experiments would be equivalent to a glob of water the size of a barrel falling from a tremendous height in nature, and this doesn't often happen.

It might be mentioned that a simple way to represent longer periods of time in the above model would be to let water flow freely through it as fast as it will go. Roughly, every 10,000 cubic centimeters of water would represent a year. But again it is a question of whether solution from such continuous flow would form features in the same way natural features are formed.

Most scale model experiments in geology have considered only mechanical processes, *e. g.*, Belousov (1961), in which earth movements are represented by relatively rapidly moving pistons. In Meunier's experiments, the element of time is scaled down by the use of a solvent which acts more rapidly on limestone than does water. However, in the study of gross features formed in limestone by the solutional activity of weak carbonic acid (water), it may be theoretically indefensible to reason by analogy from features formed by the solutional activity of much stronger hydrochloric acid (Meunier, 1899) or from features formed by the solutional activity of water on blocks of the much weaker sugar as did Bory de Saint-Vincent (1819). What must be assumed in these cases is that one can see in a short period of time the actual evolution of features analogous to the much longer evolution of morphologically similar features in nature, simply by increasing the rate of solution by using a stronger solvent, or alternatively, by using a more soluble rock. If this is true, the dimensional analysis necessary for comparison between the solvent and chemical reaction in the model, and the solvent and chemical reaction in nature has not been undertaken. One does not know, *e. g.*, how many years of solutional activity on limestone in nature by weak carbonic acid are represented by an hour's solutional activity on limestone in the model by strong hydrochloric acid. The reasons why there is no simple way to make this temporal comparison may be adequate for disqualifying any genetic or morphological comparisons between the models and the gross natural features. For the strength of the solvent, the rate of reaction, and the amount of solute in a given period of time are only three related factors which must be taken into consideration. Diffusion on both a molecular and macro scale, heat generation, and heat transfer must also be considered.

It would seem that any simple reasoning to natural features from models in which one chemical reaction is substituted for another is highly suspect, that the evolutionary stages of development of features formed by a very strong solvent are as likely as not to be different from stages of development resulting from the action of a very weak solvent, no matter how similar the morphological forms of the final products of each might be. I suspect that a careful examination of this problem in scaling may show that such experimentation has no sound basis in theory. Certainly if it does it remains for someone to present the defensibility of scale model experimentation in which one chemical reaction is substituted for another.





## Dimensional Analysis

Meunier's experiments were satisfactory and adequate given his assumptions. Similar experimentation is neither satisfactory nor adequate given our present knowledge of physics and chemistry. Today, model experimentation must be justified theoretically by dimensional analysis. In simplest terms, dimensional analysis leads to the mathematical description of materials and processes, and results in certain dimensionless numbers (*e. g.*, the Reynolds number for flow velocities) so that different systems can be compared in explicit terms. With such analysis, one might be able to describe, *e. g.*, both a model of a bridge and the actual bridge with similar equations, or at least be able to state definitely how the model deviates from the actual bridge. The basic theory for mechanical systems has been developed by Bridgman (1949), Langhaar (1951), Duncan (1953), Sedov (1959), and many others. I have already mentioned its development by Hubbert (1937, 1944) with explicit reference to geology. Much mathematical description in geology has been done by Scheidegger (1961). An introduction to work in hydrodynamics and fluid mechanics, of importance to geologists interested in caves, can be found in Milne-Thompson (1955), Birkhoff (1960), and Bradshaw (1964). A review of dimensionless numbers is given by Boucher and Alves (1959).

It must be noted that all the above work has to do with mechanics. The theory is well developed, but there are many problems in practice even with mechanical systems. If, in building a model of a river, one finds that coal dust should be substituted for sand grains, problems of increased cohesion, chemical activity, and buoyancy in water arise, simply from the reduction in size. For some of the problems in building models of rivers, see Friedkin (1945) and Lewis (1944). For discussions concerning mathematical interpretations, see also Leopold (1953), Leopold and Maddock (1953), Leopold and Miller (1956), and Leopold and Langbein (1962, 1963). A challenge to the work Leopold has been involved with is presented by Mackin (1963). As a matter of fact, it is common knowledge that in building scale models of big buildings, bridges, dams, and the like, one can describe the materials of which the model should be made, but such materials often just aren't available. Thus, such models are made empirically of materials which "seem to behave as they should" with less than a slavish eye to theory. So the theoretical justification is there for model experimentation with mechanical systems, but the actual model experiments aren't explicitly justified by theory. On this subject again one finds an immense literature. Those interested should look at the work of Buckingham (1914), Murphy (1950), Charlton (1954), Beaujoint (1960), Oberti (1960), Rocha, Serafim, and Terreira (1960), Pahl (1962, 1963), and Pahl and Soosaar (1964). Besides the difficulties of finding materials with which to make the models, there are certain mathematical problems with dimensionless numbers. In many cases there are relations between factors such that scaling for one precludes scaling for the other. There is some pessimism as to whether this can be overcome, and some workers conclude that complicated mechanical systems simply cannot be studied with models. An introduction to this issue with reference to specific cases is found in Soper (1963) and Ezra (1963). Such problems are also evident in attempts to experiment on mechanical models in zoology, and discussions of them in Brown (1960) and Beament (1960) are good introductions to the whole field of model experimentation. Beament's (p. 92) caution is worth quoting:

> Even dimensionless parameters can change with a change of scale, as anyone who has worked on aerodynamics will certainly know, and one cannot but repeat the warning that this device, which may appear to facilitate experimentation with a model, can lead one to draw false conclusions, or to spend a great deal of time investigating the secondary problem of the properties of the model system one has erroneously created.

Thus, it seems clear that even in the theoretically justifiable work with mechanical systems, experimentation upon models has many pitfalls. The least ingratiating conclusion is that the experimenter at least builds a museum model. Let us hope that the nicest thing we can say about his work is not just that he finds out how the *model* works. It is interesting to note that Scheidegger (1964) with explicit reference to mechanical processes is quite pessimistic about model experiments in geology. He suggests that the systems are too complex to be reproduced adequately in models.

### Similitude of Chemical Reactions

So far as I can discover, no explicit theoretical justification has been developed for experiments upon models in which one chemical reaction is substituted in the model for another in nature. Krumbein (1955), *e. g.*, doesn't mention it in his paper on experimental design in the earth sciences. Chemical engineers work continuously with problems of scaling up and scaling down, and an elementary text such as Levenspiel (1962) will introduce one to these problems. The issue, however, is always how to produce, *e. g.*, something at a thousand pounds an hour of which half a gram has been produced in a test tube. There is no substitution of one chemical reaction for another. Nevertheless, the problems of increased heat, transfer, and so on are so great that even though the chemical reaction remains basically the same in the test tube and in the large production reactor, the characteristics of the reaction in the test tube are but the bare beginnings for reactor design. Some chemical engineers say that from an engineering standpoint it would be incredible that anyone would ever think it possible to build a large production reactor (think of a cave system) from the examination of a small scale system (think of a model using limestone and hydrochloric acid) in which the chemical reaction (solution by hydrochloric acid) is *actually different from* the chemical reaction (solution by carbonic acid) in the large system. Of course, the chemical engineer is not concerned to reproduce everything in the production reactor just as it was in the test tube; indeed, the whole business of reactor design rests on the fact that such simple duplication cannot be accomplished. The bearing this has on the model experiments under consideration will be apparent, it is a more complicated matter than it might first appear.

Straightforward experimental work has contributed to knowledge of the solubility of calcium carbonate and limestone. Garrels and Dreyer (1952) show the variables applicable and their relations one to another. Kaye (1957), working with hydrochloric acid on calcite crystals and small blocks of limestone, has shown how motion of the solvent affects solution. (It is interesting that Kaye's eventual theory of cave genesis as a plumbing system rather than a flow net in a porous media is based more on theory than on his experimental results. His hypothetical conclusion as to how cave systems develop is the result of a thought experiment.) Weyl (1958) relates the solution of limestone to the saturation of the solvent and rate of transportation of the solute. In the work of all three of these men, it is not *necessarily* to be inferred that what they have discovered experimentally about the action of one solvent is to be generalized for the action of all solvents. Kaye, for example, has shown the effect of hydrochloric acid. For this his results are as good as can be expected with present techniques. The question is whether his results, generalized, hold for solution by carbonic acid on limestone, as he evidently believes they do.

Most experimentation by geologists where chemical reactions might be involved are of the above type which a physical chemist might do, or simply involve determining free water absorbing capacity, etc., as does Verstappen (1964). The work of Lange (1959, 1960, 1962, 1963, 1964a, 1964b) and Mowat (1962a, 1962b) is more explicit about the use of an experimental model. Lange (1959) experimented with salt blocks and a water bath to determine only the subsequent forms taken by initial forms during solution. Mowat did the same with limestone and nitric acid. The experiments demonstrated the usefulness of Lange's prior theoretical development of the general hypothesis of surface retreat by uniform crescence, and are noteworthy for having borne out the predicted preservation of sharp exterior angles and rounding of interior sharp angles during retreat. The technique and experimental design are excellent. The only question would again be whether the experiments show that the theory holds for more than salt blocks dissolved in water and limestone dissolved in nitric acid. Can one use these experiments to claim that the theory holds also for limestone dissolved in carbonic acid? Though this need not necessarily be inferred from the work, such generalization is certainly suggested. What must be stressed is that there is a break in the analogy which leads to the generalization, for the chemical reaction in each experiment is different from that in nature. The question here is whether the gross process of solution is similar enough in each case to support reasoning to similarity of forms and sequential development produced by uniform crescence, despite the different chemical reactions involved.

More ambitious claims are made for experimentation upon models by Ewers (1964) and Reams (1963a, 1963b, 1965). Ewers experimented on salt blocks, using water as the solvent. Reams used limestone blocks and hydrochloric acid. The control and measurements in these experiments are far superior to Meunier's, but the theory behind the experimentation is basically the same. Ewers and Reams argue from the sequence of forms observed in their model experiments to the sequential development of much larger features with similar forms in caves.

The implied principle upon which these experiments are based is that solution is solution. A gross analogy is made from solution by one chemical reaction in the model to solution by another chemical reaction in nature. But as a generic term, "solution" is very indefinite. Solution of limestone by carbonic acid is quite a different chemical reaction from solution of limestone by hydrochloric acid. The solutional processes are analogous in a gross way. But it is not clear that they are similar enough in action and effect to warrant inferences from the sequence observed in a model under one process to the (unobserved) sequence in nature under the other process. The question is: Does the fast action of hydrochloric acid dissolve limestone in a model in a way which results in a sequence of forms which are similar to the sequence of forms produced by the slow action of carbonic acid on limestone in nature? If it does, then the next question to be answered is: A specific amount of time in the model represents what amount and regime of water for what length of time? Thus, it is clear that the problem is twofold: First, the chemical reactions must be shown to be theoretically comparable in terms of actual process, rate, mass transfer, heat distribution, and so on. Second, supposing the first can be done, the exact water amounts and relations in nature represented by the model must be determined. Even if the chemical reactions are comparable, the scaling up from the model to nature might result in implausible water regimes. That is, the strict interpretation of the experiments *might* be that caves are formed in a few hundred years by immense quantities of water at high temperature and pressure moving at very great velocity. Though such experiments might show that caves *could* be so formed, one might want to deny that they show that caves actually have been so formed. My point in bringing up negative possibilities is not to create a pessimistic attitude in the reader and experimenter. Rather, it is to stress that the experiments prove little until theoretical justification is given for them. Gross comparisons based on the simple principle that solution is solution are neither adequate nor satisfactory given the present state of physical and chemical knowledge.

### Conclusion

Meunier, Lange, Mowat, Ewers, and Reams have gone from the natural features to the actual production in direct model experiments of similar features. Pohl went from the natural features to the imaginary production in thought experiments of similar features. All checked their experimental results against existing natural features. Meunier's results stand if one is satisfied with the assumption that solution by a strong solvent is in a general way like solution by a weak solvent. His results are similar to Pohl's, whose experiments are satisfactorily based on present knowledge of the actual processes involved. However, experiments as elementary as Meunier's are not often made now. Problems of scaling in the use of weaker and stronger materials than the natural are more complicated than Meunier assumed. There is theoretical justification for model experimentation in mechanical systems, but still many problems. Theoretical justification has not been developed for model experiments involving the substitution of one chemical reaction for another.

*Direct* experiments are always more satisfactory when possible, but in geology where time and size play such great roles, the *thought* experiment where these factors are handled in natural dimensions (even though only in imagination) seems to be more versatile, requires fewer deviations from the natural, and has proved more fruitful. It is to be expected that the refinements of scale model experimentation due to dimensional analysis will be applied to problems in cave geology soon, and in particular that the problem of chemical scaling will be investigated. Such work will indeed supersede, though it will be historically rooted in, the pioneer work of Stanislas Meunier.

ACKNOWLEDGMENTS

I should like to thank Richard J. Reardon, William B. White, and Rane Curl for criticizing earlier versions of this paper. They will neither agree nor disagree with all I say here. The reader should note that I am neither a chemist nor a mathematician. It is hoped that more specific treatment of some of the general issues raised here will be presented in later issues of this journal.

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# Short-Faced Bear (Arctodus) Fossils From Ozark Caves

**By Oscar Hawksley**

ABSTRACT

Specimens representing no less than four individuals of *Arctodus pristinus* Leidy are reported from three cave sites in the Ozarks of Missouri. These specimens provide one nearly complete set of teeth, a dentary with all significant teeth, limb bones, and fore and hind foot elements for study. Comparisons are made with short-faced bear specimens from other localities in North America, but especially with the abundant material from Potter Creek Cave and Rancho La Brea in California.

## INTRODUCTION

Recent speleological investigations in Missouri's Ozarks have brought attention to the numerous deposits of Pleistocene vertebrates in caves and have emphasized the importance of these cave deposits in enlarging our knowledge of Pleistocene faunas.

Previous to the three finds of *Arctodus pristinus* treated in this paper, short-faced bears in central North America have been known mainly from a partial cranium from the Jinglebob of Kansas (Rinker, 1949), a large humerus from the Hay Springs fauna of Nebraska (Barbour, 1916), a few teeth from Friesenhahn Cave, Texas (Kurtén, 1963), and a maxilla and premaxilla from the Hill-Shuler fauna of Texas (Slaughter et al., 1962).

Kurtén (1963) reviewed the North American arctotheres and came to the conclusion that although Leidy's type (1854) is but a single $M_2$, it is clearly recognizable as being conspecific with specimens described later as various species of *Arctotherium, Ursus* and *Dinarctotherium.* The name *Arctodus pristinus* Leidy is therefore used here.

Due to the range in size of individuals, sexual dimorphism, and the often limited and fragmentary material, taxonomic studies of extinct bears are difficult. There is still some question as to whether two groups, which differ strongly in size, are actually conspecific. Some recent authors have wisely refrained from describing new forms of short-faced bears from fragmentary speciments and await the discovery of additional material. A principal objective of this paper is to make data available from hitherto unknown or little known specimens from the Midwest.

The Missouri specimens of short-faced bears have been collected at three localities: Carroll Cave and Perkins Cave in Camden County and Bat Cave in Pulaski County. The two Camden County sites are about three miles apart, on the west side of Mill Creek Valley.

The following abbreviations are used throughout this paper:

| | |
|---|---|
| CM | Central Missouri State College |
| LAM | Los Angeles County Museum |
| UC | University of California |
| UMVP | University of Missouri Vertebrate Paleontology |

## ACKNOWLEDGMENTS

I especially wish to acknowledge the alertness of Tom Tucker who recognized the importance of the Perkins Cave material when he found it and recovered at once those parts which might have been damaged by continued traffic over the site. Mr. Tucker also made a second trip to the cave to recover more bones, carried out preliminary processing, and then contributed his find to the Central Missouri State College collection.

Jack Reynolds has, by his prolonged and continued efforts in collecting and studying

Pleistocene vertebrates from Ozark caves, not only secured many of the specimens which made this study possible, but has stimulated a general interest in Pleistocene vertebrates among speleo-zoologists in Missouri.

Dr. M. G. Mehl, Department of Geology, University of Missouri at Columbia, and Dr. William A. Clemens, Museum of Natural History, University of Kansas, have cooperated through loans of material and other courtesies. Ruben M. Frank kindly sent me casts of *Arctodus* teeth in the collection of the Texas Memorial Museum, University of Texas.

Art work (figs. 7, 9) was by Pamala Petre. Photography was by Everett Bake (figs. 4, 6) and Martin Andresen (figs. 1, 2, 3, 8).

Assistance with excavation, use of field notes and other field and laboratory assistance from Gary Schevers, Kenneth Ornes, Edward Pembleton, Everett Bake, Forrest McCarty, Jerry D. Vineyard, and Gregory Yokum are also gratefully acknowledged.

## Carroll Cave

The first Missouri specimen, a complete left humerus (fig. 1), was discovered in Carroll Cave in the spring of 1959 by Gary Schevers, a student at the Missouri School of Mines and Metallurgy. The bone was found lying on a clay terrace at a point no less than 15,000 feet from the cave entrance. Since the bone was on top of well compacted clay and there was no impression of it in the clay, Schevers was certain that the bone had been carried from its original location by some caver, then set down and forgotten. This is unfortunate because it is likely that more of this important specimen exists, perhaps in some side passage, but there is presently no clue as to the location of that site.

Carroll is an exhausting cave and Gary Schevers only carried the bone part way out when he found it. The following winter he returned to the place where he had left it and brought it out. In spite of jests from companions who said it probably was a cow bone, he took it to Dr. M. G. Mehl at the Department of Geology, University of Missouri at Columbia.

Dr. Mehl recognized the significance of the entepicondylar foramen in this large humerus and identified it to genus (Mehl, 1962). Later, Jack Reynolds, then a graduate student at Central Missouri State College, made a trip into the cave to recover the fragile proximal end which had not been removed by Schevers, and Dr. Mehl was able to restore the bone. It is recorded as VP 682 in the University of Missouri collection.

It is unlikely that the bear entered the cave by way of the present entrance. The passage in which the bone was found ends in collapse about 4,500 feet beyond the bone site. There are numerous side passages in this great cave, most of them still unexplored.

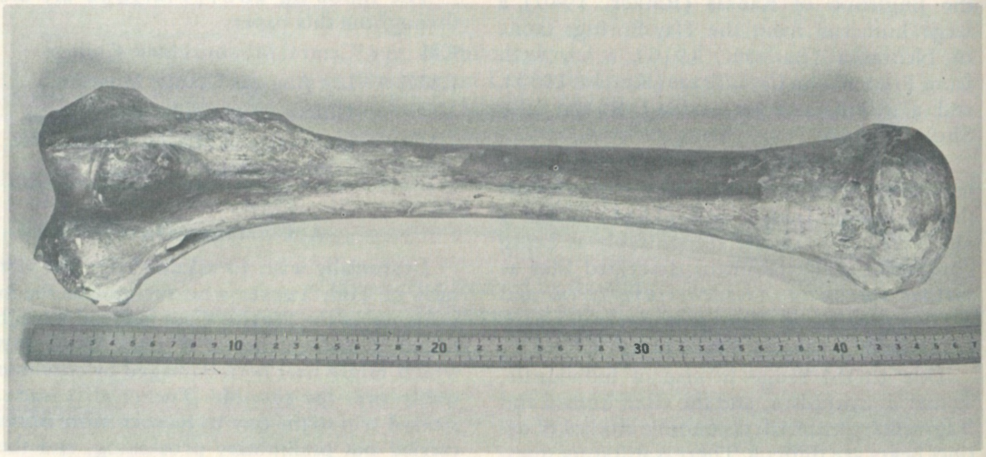

**Figure 1.**
Left humerus of short-faced bear (**Arctodus pristinus** Leidy), UMVP 682, Carroll Cave, Missouri. Measurements in mm.



**Table 1. Comparative measurements (in mm) of Arctodus humeri.**

| | Carroll Cave, Mo. | Potter Creek Cave, Cal. | | Rancho La Brea, California | | | Frankstown Cave, Pa. | Cass Co., Nebr. |
|---|---|---|---|---|---|---|---|---|
| | UMVP 682 | UC 3001 | UC 3039 | LAM Z 30 | LAM Z 77 | UC 20085 | | |
| Greatest length | 465 | 447.8 | 445.7 | 497 | — | 446.3 | — | 633 |
| Greatest anteroposterior diameter of proximal end measured from anterior end of greater tuberosity | 114.9 | 110 | — | 118.5 | — | 107.6 | — | 158 |
| Greatest width of proximal end. | a 91 | 91.9 | 90 | 97.3 | — | 95.2 | — | — |
| Transverse diameter of shaft at middle. | 39.6 | 41.2 | 40.9 | 43.5 | 46.4 | 42.4 | — | a 64 |
| Anteroposterior diameter of shaft at middle. | 43.7 | 46.2 | 48.7 | 53 | 60 | 48.8 | — | — |
| Greatest width at distal end | a 113.5 | 123.2 | — | 126.8 | 156 | 126.7 | 155 | 178 |
| Greatest width of distal articulation. | 87.8 | 90.2 | 91.6 | 97 | 116.4 | 92.8 | 107 | 130 |

a. approximate

Other vertebrate remains have been found in the cave but at such widely separated points and levels that they can hardly be considered to have been "associated" with the short-faced bear. These include *Canis dirus* (Hawksley, et al., 1963), *Castor canadensis, Odocoileus virginianus, Ursus americanus,* and a human ulna. The beaver, deer, and bear are probably post-glacial. The human bone, found in a clay bank with a few other unidentifiable bone fragments is indeed puzzling. Some details of the stratigraphy of detrital fills in the cave and the location of bones in relationship to these fills are given by Helwig (1964).

As may be noted from Table 1, *Arctodus* specimens fall into two general size categories. For convenience of discussion, these two size groups are designated in this papaer as the smaller *"Arctotherium simum"* from Potter Creek Cave in California and the larger *"A. californicum"* from Rancho La Brea (Merriam and Stock, 1925). The specimen from Nebraska described by Barbour (1916) is extremely large but is represented by only a single humerus. If Kurten (1963) is correct in assigning them all to one species, and if the size differences are due to sexual dimorphism, then the Carroll Cave humerus, which represents an adult animal, is probably from a female. However, some of the California specimens which most nearly approach its proportions are shorter and broader.

## Bat Cave

While making a study of the Pleistocene fauna of Bat Cave in Pulaski County, Reynolds (1962) recovered a right dentary fragment (fig. 2) with all teeth except P (right $M_2$ and $M_3$ were isolated); isolated teeth including left $M_1$, right and left $I^2$, left upper C, right and left $P^2$, left $P^3$; metatarsals I, II, IV; five basal phalanges, eight terminal phalanges, and a fragment of the parietal. This represents a single individual collected within a three foot area and is recorded as CM 21 in the Central Missouri State College collection.

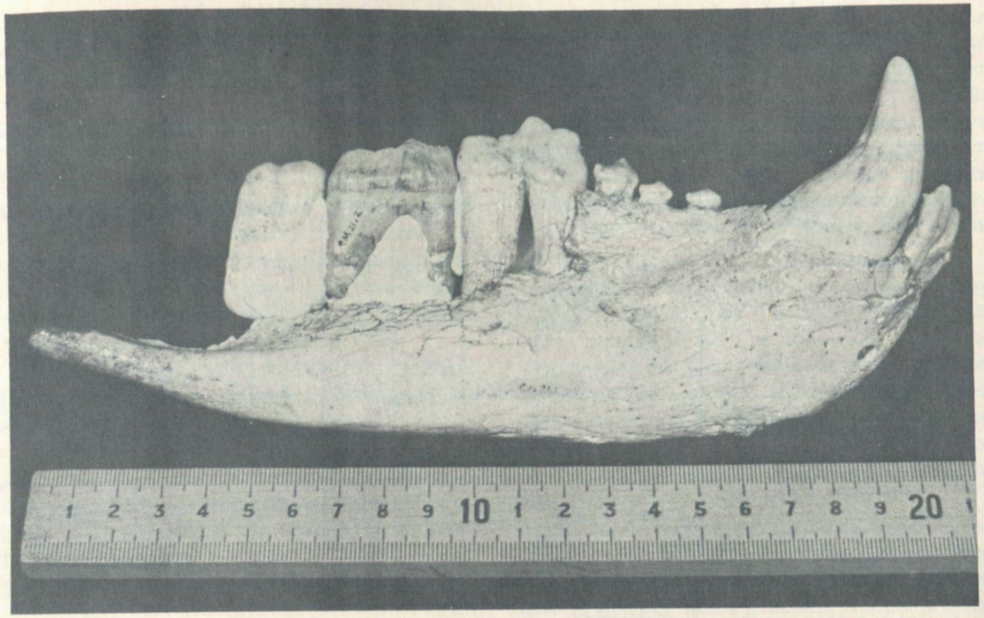


Figure 2.

Dentary fragment of **Arctodus pristinus** Leidy with teeth, CM 21, Bat Cave, Missouri. Note turned $P_4$ and lack of diastema between $P_3$ and $P_4$. Measurements in mm.

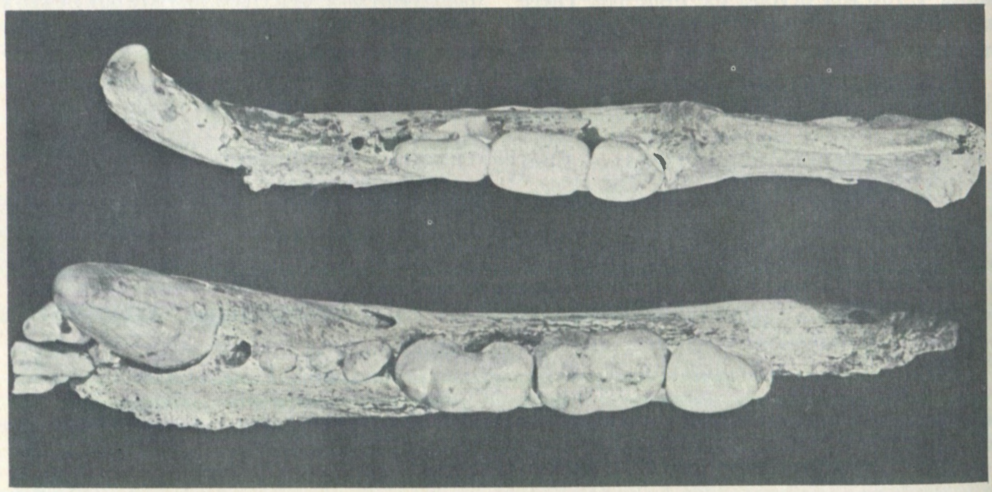

Figure 3.

Occlusal view of inferior dentition of **Arctodus pristinus** Leidy, CM 21, Bat Cave, Missouri compared with **Ursus americanus**, cf. **U. a. amplidens** Leidy, CM 175, Perkins Cave, Missouri. Note turned $P_4$ and lack of diastema between $P_3$ and $P_4$ in **Arctodus** specimen.



Other specimens which are probably from the same individual are recorded as follows: CM 41 and CM 43, rib fragments; CM 71, a basal phalanx and five medial phalanges.

The Bat Cave material was within one foot of the surface in an unstratified matrix of clay and residual material from the Gasconade dolomite in which the cave is located. The matrix is damp but firm and can usually be broken easily with the hands.

The cave has three entrances, all nearly equi-distant (about 1300 feet) from the site from which *Arctodus* material has been taken. The "site" is the floor of a passage which shows evidence of having established its present connection with the main cave by means of a stream piracy. A survey of the cave indicates that this Devil's Kitchen passage probably had an entrance in the bluff only a short distance from the site where the bones were found.

In considering several possible ways in which bones could have been deposited in this passage, Reynolds (1962) concluded that the most logical theory is that they were moved from an original location in the main passage of the cave to their eventual position in the lower Devil's Kitchen passage by the downcutting of the main cave stream as it took the new route through the lower passage. The alluvial nature of the bone matrix, ripple marks and channel ridges on the floor, and the random distribution of much of the other fossil material in the matrix supports this idea.

On the other hand, a dentary, isolated teeth, metatarsals and phalanges probably did not come to rest in an area three feet square by this means. It seems more likely that the animal died on or near the spot, possibly in a "bear bed" which has since been obliterated, and that other bear bones have been removed by stream action, decay, spelunkers, or a combination of these factors. The cave, including this passage, has been popular with local spelunkers for many years. At least one group of large bone fragments is known to have been removed and lost since 1958.

If we accept the idea that at least the bear bones were not moved far by a stream, we still have no answer as to whether the bear entered the passage via one of the present entrances or via the nearby "entrance" (now filled) at the end of the Devil's Kitchen passage.

Later excavation, "upstream" from the bear site, by the author and Gary Powell failed to produce more bear bones, though numerous bones of peccary (*Platygonus compressus*), dire wolf (*Canis dirus*) and smaller mammals were found (Hawksley, et al., 1963). A more detailed report on the Pleistocene fauna from this passage of Bat Cave is being prepared by Reynolds.

Both dentition and metatarsal measurements indicate that the Bat Cave bear was a slightly smaller individual than those from Perkins Cave.

The anterior end of $P_4$ is turned inward with the anteroposterior axis about 35 degrees out of line with the tooth row and it is crowded by $P_3$ (fig. 3). In contrast, a specimen of "*A. simum*" illustrated by Merriam and Stock (1925) show $P_4$ in line, with a diastema equal to the diameter of the alveolus of $P_3$ between $P_3$ and $P_4$. Peterson's (1925) figure also shows a diastema and only slight turning of $P_4$. The *Arctodus* maxilla and pre-maxilla reported from Texas by Slaughter, et al. (1962) showed a reduction of the upper premolars to two, accompanied by crowding of the anterior premolar out of line, and Slaughter suggests the possibility of an undescribed form. The relationship of the Bat Cave dentary to this Texas specimen or the possibility of a new form cannot be decided without additional material. However, shortening of the muzzle is certainly suggested in both the Dallas and Missouri specimens.

There seems to be considerable variation in the number and position of mental foramina in *Arctodus*. In the Bat Cave dentary there are two: the larger anterior one situated below the center of $P_4$ and the small posterior one below center of the talonid region of $M_1$ (see fig. 2).

## PERKINS CAVE

In the spring of 1963, Tom Tucker found bones in a passage leading into a domepit in Perkins Cave. Some fragments, which had accumulated a "flowstone" deposit, were found on the floor of the domepit proper. Examination of these bones revealed that they were principally a mixture of *Arctodus* sp. and *Ursus americanus*, but a few teeth

Figure 4.
**View of Perkins Cave bone site from domepit. Workers at left are at point B (fig. 5) where several limb bones of *Arctodus* were recovered. Worker at right is excavating skull of large Pleistocene black bear.**

of a wolf (*Canis* cf. *dirus*) and beaver (*Castor canadensis*) were included.

Encouraged by this find, Tucker, the author and assistants made systematic excavations of the bone-bearing passage as time permitted during the next two years. It soon became apparent that the deposit came from a collapsed "bear bed" and that bears of three distinct sizes were represented.

The Perkins site is located about 1100 feet from the present entrance of the cave. However, at a point about 750 feet from the bear deposit there is a small room which contains bone and shell fragments typical of those found in midden heaps in caves which have been occupied. The organic type of soil at this point indicates that there is an old entrance there which has become closed. It is also evident that the passages of the cave are close to the surface in many places throughout its 1700 foot length. Thus, the bear "hibernaculum" may have been closer to an entrance in the Pleistocene and in more recent times as well.

Perkins Cave is developed in the upper part of the Gasconade Formation, of Canadian (Lower Ordovician) age. The Gasconade is a medium grained dolomite with several prominent chert beds. Above it is the Roubidoux Formation. Perkins Cave lies in the interval between Lower Gasconade and the Gasconade-Roubidoux contact. Domepits in the Gasconade seem best developed immediately beneath the sandstone beds of the lower Roubidoux. (J. Vineyard, pers. comm.). The point at which the bear bones have been found is near the end of a side passage which terminates in such a domepit which is 33 feet high by about 20 feet in diameter.

Two passages lead into this pit. The upper one opens into the pit at a point about 10 feet from the floor of the pit. The lower passage is entered via a hole in the floor of the upper passage just big enough to admit a man.



From the bottom of this hole, the floor of the lower passage widens and slopes downward to the floor of the domepit.

Bones have been found on the upper level around the hole and along the entire lower passage, which is about 10 feet long. However, the largest concentrations of bones were within 10 inches of the surface at the outer end of this short passage, where it is about eight feet wide, and in a crevice along one edge of the passage (see figs. 4 and 5).

The matrix is a combination of sand, chert, and other sedimentary material derived from the Roubidoux (some ceiling breakdown) and of dolomite sand, some chert and residual clay and silt from solution weathering of the Gasconade. There is a layer of fine textured "red cave clay" several inches thick between the bone matrix and the Gasconade dolomite which forms the floor of the passage. The bones of bears of three distinct sizes are mixed through the bone bearing layer.

It is apparent that the "bear bed" in which the bones originally accumulated was on the upper level, on or near the place where the present entrance to the lower passage is now located. The upper passage floor caved in, probably during a time when it was thoroughly saturated with water, and the mixture of mud and bones flowed down the lower passage, slowing and settling as the passage widened. Some of the material apparently reached the floor of the domepit where it was subjected to erosive action until only fragments remained.

Whatever stratification of the bones there may have been was lost as the mixture of mud and bones flowed down the passage, but some related bones remained together. Near the center of the outer face of the mud flow (fig. 6) the shank of a femur and a nearly complete tibia of a short-faced bear were found with the fibula lying midway between them. A crevice on one side of the passage, which had been filled with mud, contained most of the well preserved bones of a large Pleistocene black bear (*Ursus americanus* cf. *U. a. amplidens Leidy*). The skull and jaws, which were still close together, had travelled the greatest distance and reached the lowest level. No such relationship was noticed in the location of bones of the smaller *U. a. americanus*. These post-glacial black

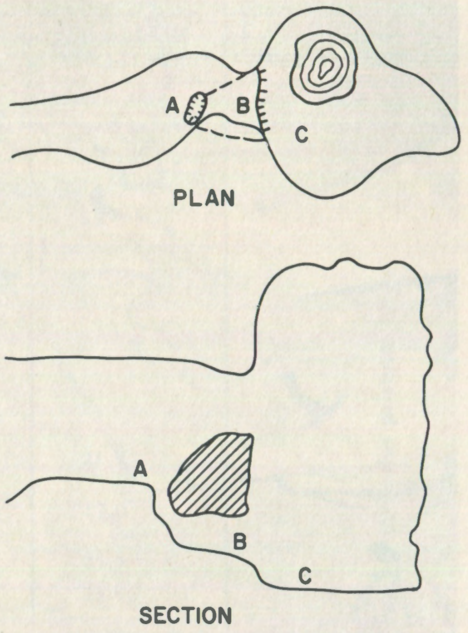


Figure 5.
**Diagram of Perkins Cave bone site: A, location of "bear bed"; B, location of largest concentration of *Arctodus* bones; C, bone fragments from floor of domepit.**

bears were more common and seemed to be thoroughly mixed through the matrix.

The short-faced bear specimens from Perkins Cave represent at least two individuals since three ulnae have been found. Although the teeth recovered in various digs are listed under two catalog numbers, they probably come from a single individual since there is no duplication. The more important specimens from this cave are listed below. The number of specimens of each part are indicated in parentheses.

CM 123: $I^1$, $I^3$(2), $P^4$, $I_1$(2), $I_2$(2), $I_3$(2), lower right C, $M_1$, $M_2$, $M_3$,
proximal end of ulna, proximal end of radius, matacarpals I, II, III, IV, fibula fragments, calcaneum, astragalus, cuboid, navicular (2), ectocuneiform (2), mesocuneiform, entocuneiform, metatarsals I, II, III (2), V, sesamoids (14), basal phalanges (7), medial phalanges (6), terminal phalanges (7), miscellaneous fragments.

**Figure 6.**

**Shank of femur (left), fibula (center) and tibia (right) of Arctodus exposed in matrix, Perkins Cave, Missouri.**

CM 171: squamosal and occipital fragments of cranium, upper right C, $M^1$, $M^2$(2), $P_4$, $M_3$, lumbar vertebra, right ulna, distal end of radius, scapho-lunar (2), unciform (2), magnum (2), pisiform (2), cuneimetacarpals I, III, IV, V, shaft of femur, left tibia (proximal end incomplete), patella, left astragalus, mesocuneiform, sesamoids (5), basal phalanges (6), medial phalanx, terminal phalanges (3), miscellaneous fragments.

CM 172: left ulna.

CM 173: shaft of femur.

CM 174: axis.

The Perkins Cave material is extensive enough to make some discussion and comparison of it with other North American specimens worth while. It is apparent that most of the bones, like the teeth, are from a single individual, although the teeth may be from one animal and the majority of the bones from a second. However, indications of size and proportions of an individual can be given more accurately than with disassociated parts such as many of those from Rancho La Brea. Tables of measurements are included only if they contribute to the discussion. Less significant measurements are omitted.

*Dentition.* With the exception of $P_4$, which is slightly smaller, tooth measurements fall within the extremes which numerous authors have given for *Arctodus.* Teeth from the Missouri specimens show no strong trend toward the size of either the smaller or larger *Arctodus* from the California collections. For example, $M^2$ approaches the "californicum" end of the scale in length while $M_2$ and $M_3$ from Friesenhahn Cave in Texas are smaller than those two teeth from the Missouri specimens but in other details they are nearly identical. Dental dimensions of the Missouri specimens are presented in Table 2.



**Table 2. Dental dimensions (in mm) of Missouri specimens of Arctodus pristinus Leidy.**

| | Bat Cave, Missouri CM 21 | Perkins Cave, Missouri CM 123, 171 |
|---|---|---|
| $I^1$, greatest transverse diameter | | 7.1 (w) |
| $I^2$, greatest transverse diameter | 9.2, 9 | |
| $I^3$, greatest transverse diameter | | 12.2, 12.8 |
| $\underline{C}$, anteroposterior diameter at base of enamel | 30.5 | 28.6 |
| $P^2$, greatest anteroposterior diameter | 9.0, 9.2 | |
| $P^2$, greatest transverse diameter | 6.1, 6.2 | |
| $P^3$, greatest anteroposterior diameter | 9.2 | |
| $P^3$, greatest transverse diameter | 6.6 | |
| $P^4$, greatest anteroposterior diameter | | 21.7 |
| $P^4$, transverse diameter across protocone | | 17.0 |
| $M^1$, greatest anteroposterior diameter | | 25.5 |
| $M^1$, greatest transverse diameter | | 25.0 |
| $M^2$, greatest anteroposterior diameter | | 35.8, 35.9 |
| $M^2$, greatest transverse diameter | | 23.5, 24.2 |
| Length from anterior side $\bar{C}$ to posterior side of $M_3$ | a 151.0 | |
| Length from posterior side $\bar{C}$ to anterior side of $M_1$ | a 42.2 | |
| Length from anterior side $M_1$ to posterior side of $M_3$ | a 78.2 | |
| $I^1$, greatest transverse diameter | 5.0 | 5.4 (w), 5.6 (w) |
| $I^2$, greatest transverse diameter | 7.7 | 8.2 (w), 9.1 |
| $I^3$, greatest transverse diameter | a 12.0 | 9.9 (w), 10.2 (w) |
| Width, right half of incisor row | 26.0 | |
| $\bar{C}$, anteroposterior diameter at base of enamel | 29.4 | 28.0 |
| $P_4$, anteroposterior diameter | 12.2 | 12.2 |
| $P_4$, transverse diameter | 8.0 | 8.0 |
| $M_1$, anteroposterior diameter | 31.4 | 32.1 |
| $M_1$, transverse diameter across protoconid | 14.8 | 15.9 |
| $M_1$, width of heel | 16.3 | 17.8 |
| $M_2$, anteroposterior diameter | 30.2 | 30.5 |
| $M_2$, transverse diameter across protoconid | 19.7 | 21.1 |
| $M_3$, anteroposterior diameter | 20.7 | 21.6, 20.9 |
| $M_3$, transverse diameter across protoconid | 16.5 | 17.2, 17.2 |

a. approximate (w) tooth worn down

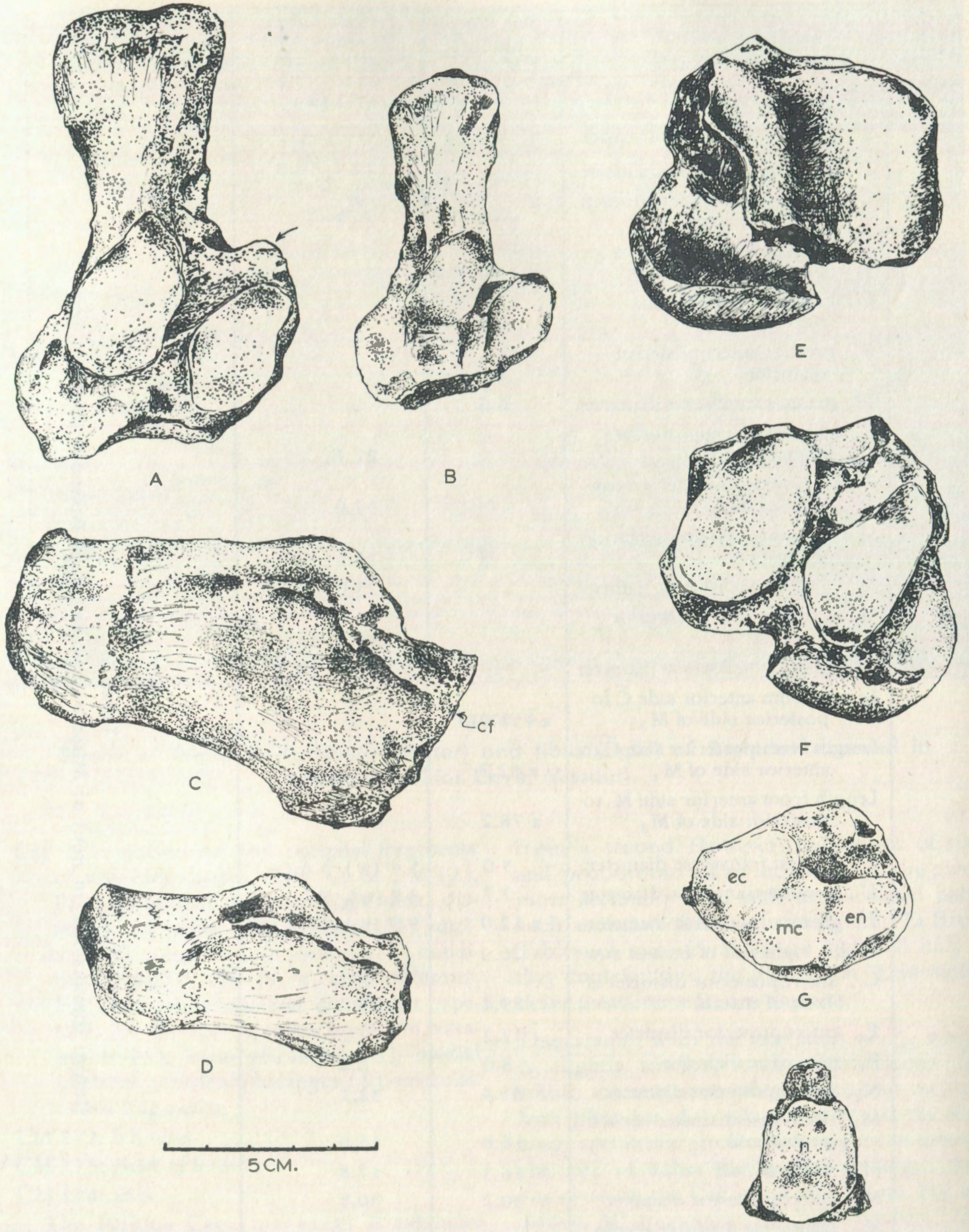


Figure 7.

Axis of **Arctodus**: A, ventral view; C, lateral view; B, axis of **Ursus americanus** cf. **U. a. amplidens**, ventral view. Cuneiform of **Arctodus**: D, inferior surface; E, superior surface. F, pisiform of **Arctodus** showing ulnar surface (u). Perkins Cave, Missouri.



Table 3. Measurements (in mm) of the axis, **Arctodus pristinus** Leidy.

| | Rancho La Brea | Perkins Cave |
|---|---|---|
| | LAM No. Z 39 | CM 174 |
| Transverse diameter across articulating surface for atlas | 84.6 | |
| Greatest transverse width across postzygapophyses | 64 | a 61 |
| Greatest length of neural spine. | a 80.7 | a 92 |
| Least anteroposterior diameter of pedicle of neural arch | 22 | 22.6 |
| Greatest length of vertebra from anterior end of odontoid process to posterior face of centrum. | a 82 | a 79 |

a. approximate

*Axis.* The rather well preserved axis from Perkins Cave exhibits certain differences from the one figured and described by Merriam and Stock (1925) for *"A. californicum."* In the Missouri specimen, the lesser depth of the neural spine in front of the pedicle of the arch, supposedly a difference from *Ursus*, is not so pronounced. However this differs even within *Ursus* and I would ascribe it to an age difference. The neural spine is relatively longer (see Table 3 and fig. 7) and the postero-lateral edge of the articulating surface for the atlas is more nearly vertical.

The ventral edge of the articular surface is broadly bowed at an angle of approximately 28 degrees from the anteroposterior axis while in *Ursus* the articulating surface appears quite angulated (at about 37 degrees) from the ventral view. The body is also relatively shorter than in *Ursus*.

Since the California specimen compared in Table 2 is from the larger *"A. californicum"* group, the smaller size of the Perkins Cave specimen is consistent (except for the greater length of the neural spine) with the size relationship noted for the humerus from Carroll Cave.

*Radius and ulna.* Two ulnae (right and left but not a pair) lack only the styloid processes so that the total length can be estimated. They fall into the same range as the Potter Creek specimens but, except for the width of the olecranon process, they are generally less robust. The only measurements possible on the radius are of the diameters of the proximal and distal extremities. These also agree well with Potter Creek material.

*Carpus.* The scapho-lumar, unciform and magnum are similar in general form to those figured in Merriam and Stock (1925) for *"A. californicum"*, but the cuneiform differs considerably from their figure for that "species". From the inferior view, the Perkins example has an articulating surface much less broadly triangular (fig. 7D). From the superior view, the articulating surface is nearly rhomboidal while that of LAM No. Z 107 is ovoid (fig. 7E).

The pisiforms from Perkins also differ from the figure of Merriam and Stock for *"A. californicum"*. This is most apparent from the ulnar side. The surface for the ulna in *"A. californicum"* is broadly triangular and extends to the internal edge. In the Perkins specimens this surface is more acutely angled or rounded and extends only two-thirds of the way to the internal edge (fig. 7F).

*Metacarpus.* The series of metacarpals from Perkins Cave, which are probably from a single individual, was compared with metacarpal measurements from single individuals from Potter Creek Cave (UC No. 3040) and from Rancho La Brea (UC No. 17754). They were intermediate in size as to length and antero-posterior diameter of the proximal end, but nearly identical to the Potter Creek material in least width of the shaft and in width at the distal end. A partially reconstructed manus appears in figure 8.

*Femur.* Not all the Rancho La Brea "*A. californicum*" specimens fall into the large size category. Femur measurements provided by Merriam and Stock (1925) for UC No. 20082 indicate a shorter femur, with diameters in proportion, compared to UC No. 10211 from Potter Creek Cave.

The two femur shafts available from Perkins Cave provide transverse and antero-posterior diameter measurements intermediate between these two California specimens but the single patella available is even smaller than that from a small "*A. californicum*".

*Tibia.* Except in its narrower transverse diameter at the distal end (79mm. vs. 87mm.), the single tibia from Perkins Cave most closely approaches measurements from a Potter Creek Cave specimen. It would also appear to be relatively longer but the proximal end is incomplete and an accurate measurement cannot be obtained.

*Tarsus.* Only one calcaneum is available but it is perfect in every detail. It measures smaller than one of "*A. simum*" and in several respects it does not agree with those from the California sites: the posterior process is *not* relatively narrower in transverse diameter than in *Ursus* and the inner facet for the astragalus is *not* supported by a pointed process but by a rather rectangular process which extends 10 millimeters or more beyond the posterior edge of the facet and parallel to it (fig. 9A). The medial surface appears very rough because of deep grooves and ridges for muscle attachment.

More obvious differences from *Ursus*, than those described by Merriam and Stock, are those which may be noted from the lateral aspect. As seen from the outer side, the calcaneum is like a truncated triangle, the superior side of the posterior process diverging from the inferior side at an angle of about 25 degrees. In *Ursus*, superior and inferior surfaces of the posterior process are nearly parallel. From this same view it may be noted that the anterior edge of the cuboid facet is inclined forward while in *Ursus* it is nearly vertical or inclined slightly back (see fig. 9C,D).

The astragli compare favorably in size with figures given for "*A. simum*" and a small "*A. californicum*" except that California specimens have a width noticeably greater than the length, whereas the two from Missouri have width and length essentially the same (fig. 9E, F). The cuboid also falls in with the "*simum*" group and although good series of measurements are not available, the same seems to be true of the navicular and ectocuneiform.

*Metatarsus.* Since no sets of metatarsals from single individuals from the California sites were available, it is difficult to compare those from Missouri. They are generally smaller than those from the "*californicum*" group.

*Phalanges.* Although numerous phalanges have been collected in both Perkins and Bat Caves, there is so much variation in size from one digit to another that size comparisons would seem to have little value. There is little chance for confusion of the phalanges, with those of bears of other species occurring at the same sites, because of their large size and the shortened claw core of the terminal phalanx (fig. 8).

### Discussion

The arctotheres from Missouri fall generally into the smaller or "*simum*" group rather than into the "*californicum*" group. However, if we were to accept these two groups as distinct species there would be a few characteristics of the Missouri specimens which would not check well with either group. These include the indication of longer, yet more slender limb bones, proportionally more slender metacarpals, and smaller tarsal elements than in "*A. simum*". Differences noted in cuneiform and calcaneum may be species differences. The tendency toward a shortened



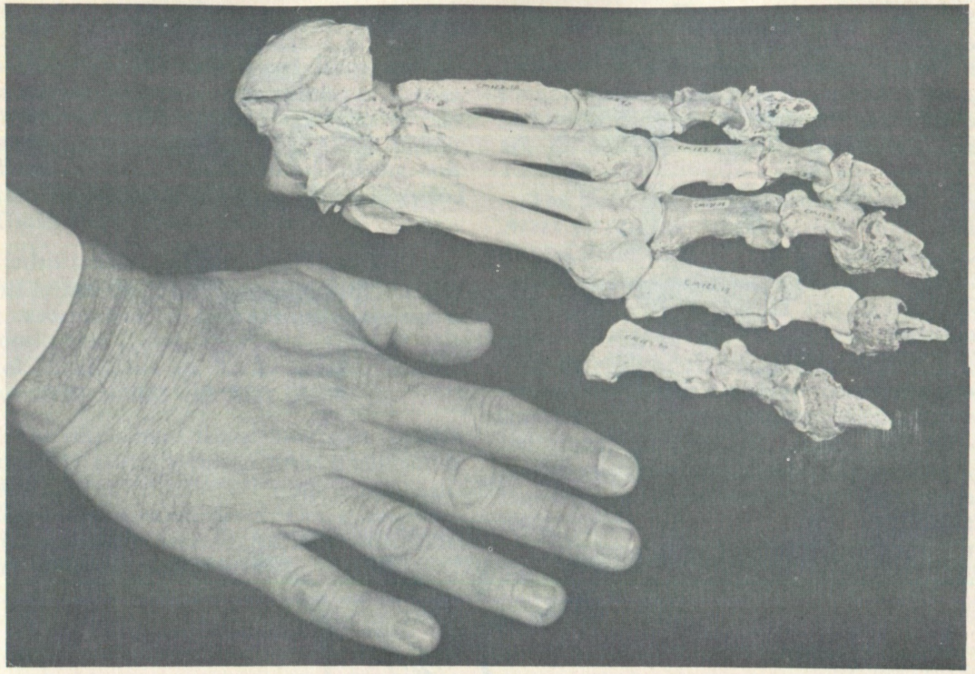

Figure 8.

Partially reconstructed manus of **Arctodus pristinus,** including scapho-lunar, unciform, magum and metacarpals I-IV. CM 123, 171, Perkins Cave, Missouri.

muzzle may indicate a close relationship to the Dallas specimen and possibly to the cranium from Kansas.

If we assume that differences in *Arctodus* are due mainly to sex dimorphism, then the specimens from Potter Creek Cave in California and those from Missouri must all be females, a risky assumption unless there was a greater tendency for females to seek winter dens in caves. Cahalane (1947) says of black bears that a "pregnant female takes more pains with her winter dwelling" but does not cite any authority for this. The bear fossils from Perkins Cave indicate that at least some male bears favor caves as dens because there is a perfect baculum for the large Pleistocene black bear from that site.

There are a number of pit type caves in the Ozarks in which bears became trapped and died, but it is evident that the bears from Bat Cave and Perkins Cave walked in and were not trapped or lost. It is my opinion that the short-faced bears in both these caves died during their winter sleep. The "bear bed" in Perkins Cave was certainly used as a winter den by innumerable bears of more than one species. "Bear beds" are familiar cave features to Ozark spelunkers and are easily recognized as shallow, rounded depressions in clay floored passages. They may be considered as potential sources of fossil bear material.

It is to be expected that certain animals typical of the Rancholabrean "faunal zone" (Flint, 1957) would frequently be associated with *Arctodus* fossils, but one such animal stands out above all others in the frequency with which it occurs at the same sites or in the same local faunas. This is the dire wolf, *Canis* (*Aenocyon*) *dirus,* or a closely related form. It occurs at the following *Arctodus* localities: the three Missouri sites; Potter Creek Cave, Rancho La Brea and McKittrick in California (Merriam and Stock, 1925; Frankstown Cave (Peterson, 1925) and Port Kennedy Cave (Gidley and Gazin, 1938) in

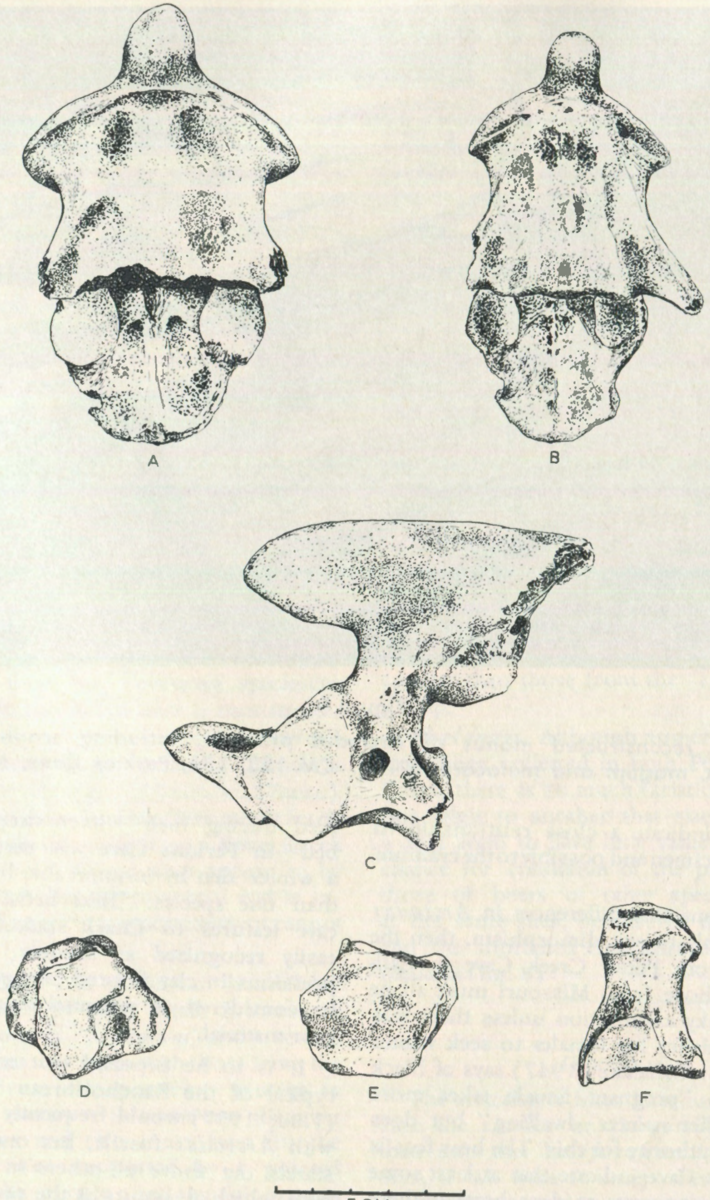


Figure 9

**Arctodus:** A, calcaneum, superior view showing rectangular process (arrow); lateral view showing triangular shape and angle of cuboid facet (cf); E, astragalus, superior view; F, inferior view; G, naviculum showing facets for ectocuneiform (ec), mesocuneiform (mc) and entocuneiform (en). H, ectocuneiform, navicular surface (n). **Ursus americanus cf. U. a. amplidens:** B, calcaneum, superior view; D, lateral view. Perkins Cave, Missouri.



Pennsylvania; Friesenhahn Cave (Milstead, 1956) and Hill-Shuler (Slaughter, et al, 1962) faunas of Texas; Cragin Quarry fauna (approximately same horizon as Jinglebob) of Kansas (Hibbard, 1963); Hay Springs fauna of Nebraska and its counterpart in the Alaska-Yukon (Frick, 1930). It seems to be missing only from the Cumberland Cave site in Maryland (Gidley and Gazin, 1938).

Also frequently associated with *Arctodus* fossils are those of *Platygonus* sp., usually *P. compressus,* though peccaries are not as consistently found as is some form of dire wolf. *Mylohyus* sp. has been much less frequently associated with *Arctodus.*

The very limited faunal lists from the Missouri *Arctodus* locations make it impossible to comment extensively on age and climate. Clay samples taken from Ozark caves for pollen analysis have so far all proven to be sterile but sampling is being continued.

Bat guano samples have been equally disappointing for pollen analysis. Since only the first few inches of guano, which represents probably no more than a 500 year span of time, yield pollen (R. F. Myers, pers. comm.), carbon-14 dates available for the guano piles are of no help in giving a picture of the Pleistocene.

The best clue, at present, to age of the *Arctodus* fossils is their association with *Canis dirus* and *Platygonus compressus,* both late Pleistocene forms. Slaughter, et al. (1962) suggest Sangamon age for the Hill-Shuler fauna due to its general correlation with the Jinglebob in Kansas. There are similarities in the *Arctodus* from these two faunas and definite similarities (dentition size and muzzle shortening) between the Hill-Shuler specimen and those from Missouri. However, the Friesenhahn Cave fauna, also including *Arctodus* and *C. dirus,* is thought by Slaughter, et al. (1962) to be "early last glaciation," the earlier half of a period 25,000 to 10,000 B.P.

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# Observations of a New Troglobitic Crayfish (With Notes on the Distribution of Troglobitic Crayfishes in the Ozark Region[1])

By M. S. Bedinger[2] and Horton H. Hobbs, Jr.[3]

## ABSTRACT

The recently described *Cambarus zophonastes,* together with the previously described *C. setosus* and *C. hubrichti,* brings to three the number of albinistic species of crayfishes recorded from the Ozark region. *C. zophonastes* is known from only one locality in Arkansas, and its discovery adds information to the known distribution of albinistic crayfishes in the Ozark region. The individual species are confined to distinctly separated areas. Two are found only in the White River basin, and one species, *C. setosus,* is found in both the White and Arkansas River basins. Though *C. setosus* and *C. zophonastes* are closely related, the ostracod commensals on *C. zophonastes* are more closely related to those on *C. hubrichti* than to those on *C. setosus.* It seems likely that the parent stock of the three species migrated to the Ozark region by way of the White River basin, but data do not permit a hypothesis as to which stock was the earlier migrant.

## INTRODUCTION

A survey of albinistic crayfish of the Genus *Cambarus* by Hobbs and Barr (1960, p. 14) indicated that two species of albinistic cave crayfishes, *C. hubrichti* (Hobbs) and *C. setosus* (Faxon), occur in the Ozark region. A new species from that region, *C. zophonastes* , has recently been described (Hobbs and Bedinger, 1964). This species, known from a single locality, is the third species of troglobitic crayfish described from the Ozark region and the first from Arkansas.

This paper includes an account of the occurence of *Cambarus zophonastes* and the significance of this species in relation to the geographic distribution of cave-dwelling crayfishes in the Ozark region.

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1. Publication authorized by Director, U. S. Geological Survey and the Secretary, Smithsonian Institution
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## *Cambarus zophonastes* HOBBS AND BEDINGER (1964, p. 11)

*Cambarus zophonastes* is known only from Hell Creek Cave, Stone County, Arkansas. Hell Creek Cave is at the headwaters of Hell Creek about 1 mile from the creek's debouchment into the White River. The cave is developed in the Plattin Limestone of Ordovician age. The length of the cave, measured along the stream that flows through it, is about 1,500 feet. The cave stream issues as a spring from the east side at the bottom of the V-shaped valley of Hell Creek. This spring and another which issues from the west side of the valley make up the perennial flow of Hell Creek.

The crayfish were observed in the cave stream within a distance of 30 feet from where the cave stream is first encountered. This portion of the cave, 150 feet from the entrance, is in perpetual darkness.

An epigean species of crayfish, *Orconectes neglectus* subsp., was collected at the same location as the troglobitic form. Also an epigean species of fish was observed at this location. These observations indicate that the cave is accessible to small aquatic organisms from the outside by way of the spring opening.

*Cambarus zophonastes* is an albinistic cave-dwelling crayfish. Its eyes are reduced in size and without pigment. Experimental data obtained by Wells (1959, p. 11-12) show that in *C. setosus,* the species most closely related to *C. zophonastes,* the eyes, eyestalks, anennae, and antennules do not act as receptors of light. However, Wells reports that *C. setosus* is sensitive to light only when the head of the animal is illuminated and suggests that possible the cerebral ganglion functions directly as a photoreceptor.

It may be expected that *C. zophonastes* is somewhat similar in its sensitivity to light. The crayfish showed no obvious response to light of lanterns' however, they crawled slowly while being observed. Williams (1954, p. 903) observed that *C. setosus* in dark regions of caves did not seem to be affected by the light of lanterns.

*Cambarus zophonastes* is sensitive to turbid water and to unnatural disturbances in the water. When the water was roiled and became turbid, some specimens crawled up the sides of the stream to clear water near the surface. *C. zophonastes* is sensitive to touch and swims away quickly if not captured on first contact.

The interested reader is referred to Hobbs and Bedinger (1964) for a systematic desciption of *C. zophonastes.*

## Distribution of Albinistic Crayfish in the Ozark Region

The distribution of the three species of albinistic crayfish of the Ozark region is shown in figure 1. The following discussion will present information on the geographic distribution and genetic affinities of the crayfishes and their ostracod commensals which has a bearing on the distribution of the crayfish.

As shown in figure 1, all three species of albinistic crayfish, *Cambarus setosus, C. zophonastes,* and *C. hubrichti,* are found in the White River drainage basin. In addition, *C. setosus* is found in the Arkansas River drainage basin. Members of the genus *Cambarus* have been found in northeastern Oklahoma, but their disignation to *C. setosus* is questionable (Hobbs and Barr, 1960, p. 27). These species are found only in the Ozark region and each is confined to an area distinctly separated from the others.

Troglobitic members of the genus *Cambarus* fall into three distinct groups (Hobbs and Barr, 1960, p. 14) that are closely related anatomically and genetically. Two of these groups are represented both in the Ozark region and in cave areas east of the Mississippi River. *Cambarus setosus* and *C. zophonastes* are members of the Asperimanus Group and presumably are derived from a common parent stock. *C. hubrichti* has been placed in the Tenebrosus Group and is thus believed to have been derived from a different parent stock from that of *C. setosus* and *C. zophonastes.*

The parent stocks of both groups probably migrated to the Ozark region by way of the White River, but data do not permit a hypothesis as to which stock was the earlier migrant. The occurrence of *C. setosus* in both the Arkansas and White river drainage basins poses the significant problem of migration of this species. Because the crayfish are largely confined to subterranean aquatic habitats, it is difficult to account for the accurrence of this species in two different, though adjacent, drainage basins. The possibility exists that by changes in drainage patterns, either surface or subsurface, the basins themselves have "migrated" rather than a basin-to-basin migration of the crayfish *per se.*

Of interest to the distribution problem of the three species is the relationship of their ostracod commensals. Insofar as is known, the ostracods, like their hosts, are largely confined to aquatic habitats, and it seems probable that they are transmitted from one host to another by contact. The ostracod commensals of *Cambarus hubrichti* and *C. setosus* were described by Hart and Hobbs (1961). The ostracods on *C. zophonastes* are different from both of these but are more closely related to the ostracod on *C. hubrichti* (Hobbs and Belinger, 1964). This is somewhat unexpected in that *C. zophonastes* has its closest affinities with *C. setosus.* It is concluded that these two species have been separated for a long period of time. The affinities of the ostracod commensals on *C. hubrichti* and *zophonastes* may have been



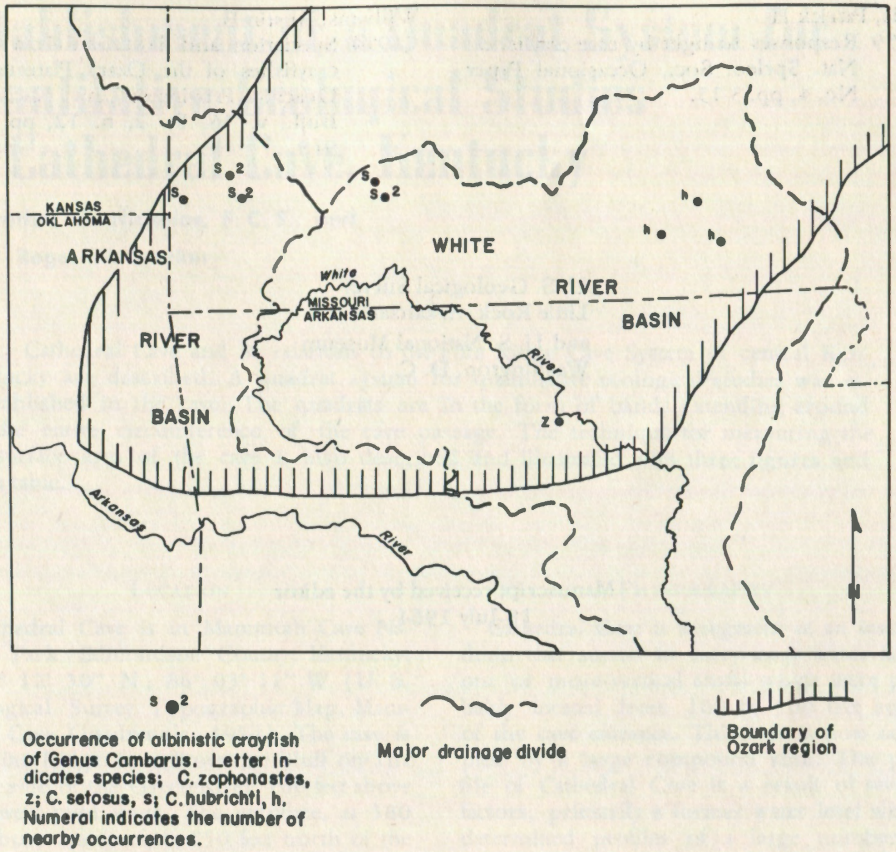


Figure 1
Distribution of albinistic cambarids in the Ozark region.

brought about by contact of ancestors of the two species or by way of their common contact with other crayfish.

From the foregoing it is obvious that additional data on the troglobitic crayfish fauna of the Ozarks are needed for a definitive explanation of the distribution of these organisms. Cavers are urged to report their findings of troglobitic crayfish. Cave life is sparse and indications are that populations of cave crayfish have decreased. Collections should be made under supervision of qualified biologists.

## Acknowledgments

The authors are grateful for the assistance of Mr. George Distler and Dr. Orville A. Wise in making observations on the crayfish and their habitat and Mr. John W. Stephens in collecting specimens.

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# Establishment of a Quadrat System for Quantitative Ecological Studies In Cathedral Cave, Kentucky

By Brother G. Nicholas, F. C. S., and
Roger W. Brucker

Cathedral Cave and its relations to the Flint Ridge Cave System of central Kentucky are described. A quadrat system for quantitative ecological studies was established in the cave. The quadrats are in the form of bands extending around the entire circumference of the cave passage. The technique for measuring the surface area of the cave is also described and illustrated with three figures and a table.

## LOCATION

Cathedral Cave is in Mammoth Cave National Park, Edmondson County, Kentucky, at 37° 12' 50" N., 86° 03' 11" W. (U. S. Geological Survey Topographic Map, Mammoth Cave Quadrangle, 1954). The cave is on Flint Ridge in a limestone bluff on the south side of the Green River, 160 feet above the river pool stage. The entrance, at 580 feet above sea level, is 750 feet north of the Floyd Collins Crystal Cave entrance.

## STRATIGRAPHY

The rocks of Flint Ridge are Mississippian in age. The Golconda Formation consists of 30 feet of soluble limestone underlain by 10 feet of thin-bedded conglomerate and shale. Below this lies 60 feet of firmly cemented Big Clifty (Cypress) sandstone. Underlying the Big Clifty is 120 feet of the Girken (Renault-Paint Creek or Gaspar) Limestone. (fig. 3). The basal member, extending below the water table, is 180 feet of Ste. Genevieve Limestone. This is a thick, massive, crystalline limestone, jointed and readily subject to solution and cave development. The largest and best known of Kentucky's many caves are developed partially or entirely in this stratum (McGrain, 1961). Flint Ridge caves are developed in both the Girken and Ste. Genevieve strata (Weller, 1927).

## PHYSIOGRAPHY

Cathedral Cave is a segment of an inactive drain that served to carry away water from one or more vertical shafts which were probably located from 100 to 500 feet south of the cave entrance. This area is now occupied by a large compound sink. The profile of Cathedral Cave is a result of several factors, primarily a former water level which determined profiles of a large number of cave passages throughout Flint Ridge. This control horizon is stratigraphically located from 580 to 600 feet above sea level. It is characterized by relatively small passage cross-sections, generally from four to 40 square feet in area. Base level control of this horizon must have been relatively short because no major passages have been found at this level, and because nearby passages have been deepened into canyons, presumably as a result of rapid change of base level. Cathedral Cave was abandoned as an active drain passage before the lowering of the base level. Water from deepened shafts to the south drained through lower passages.

Since its abandonment as a drain, several vertical shafts have intersected Cathedral Cave. Because of their small surface drainage area, about 1000 square feet, these small shafts are probably much older than nearby shafts many times their size which drain watersheds of 100 or more acres.

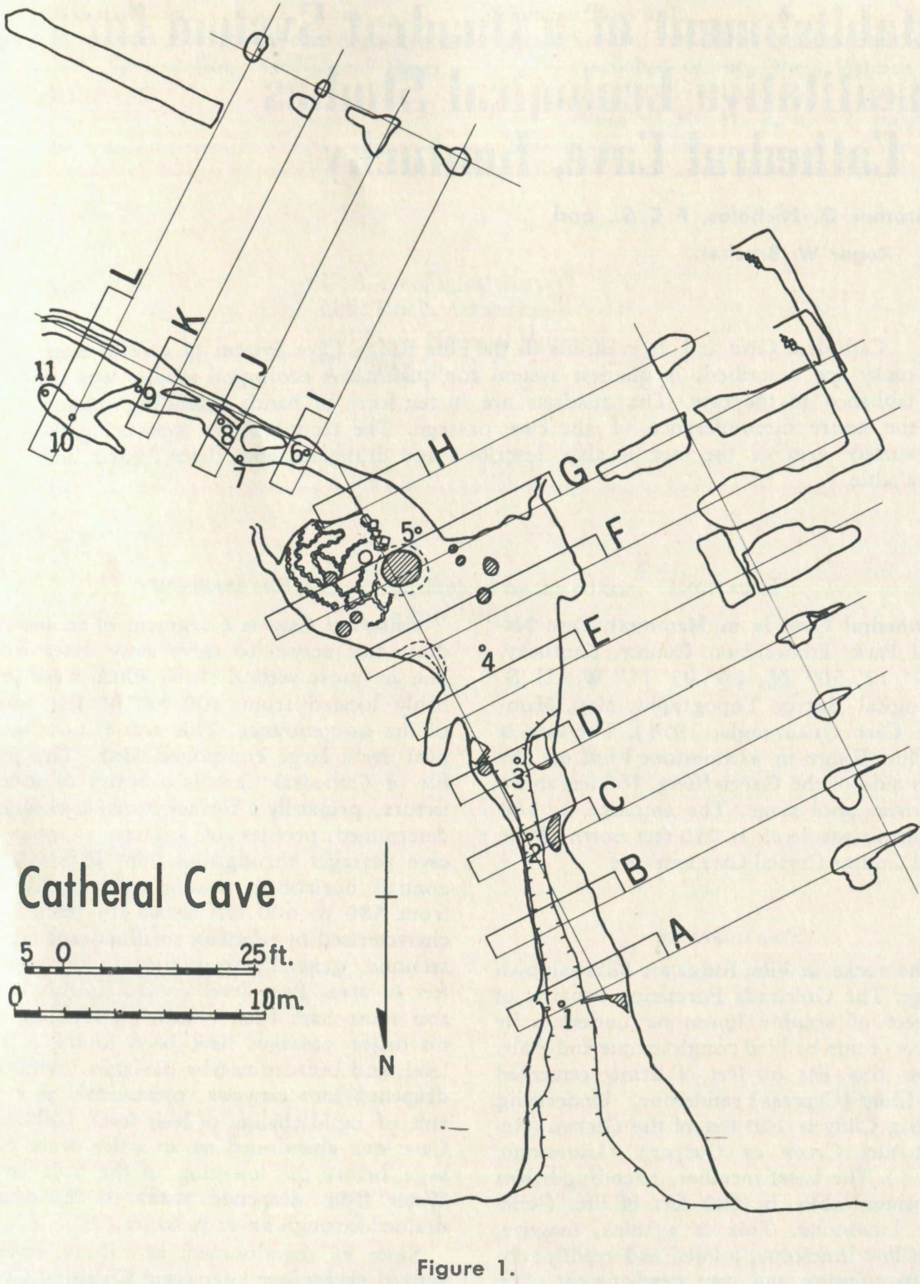


Figure 1.

**Map of Cathedral Cave. Quadrats indicated by capital letters. Cross section at northern boundary of each quadrat indicated on left side of figure. Stations for measurements of environmental factors indicated by numerals. Cross hatched areas signify columns between ceiling and floor. Wavy line at quadrat G signify rimstone dams.**

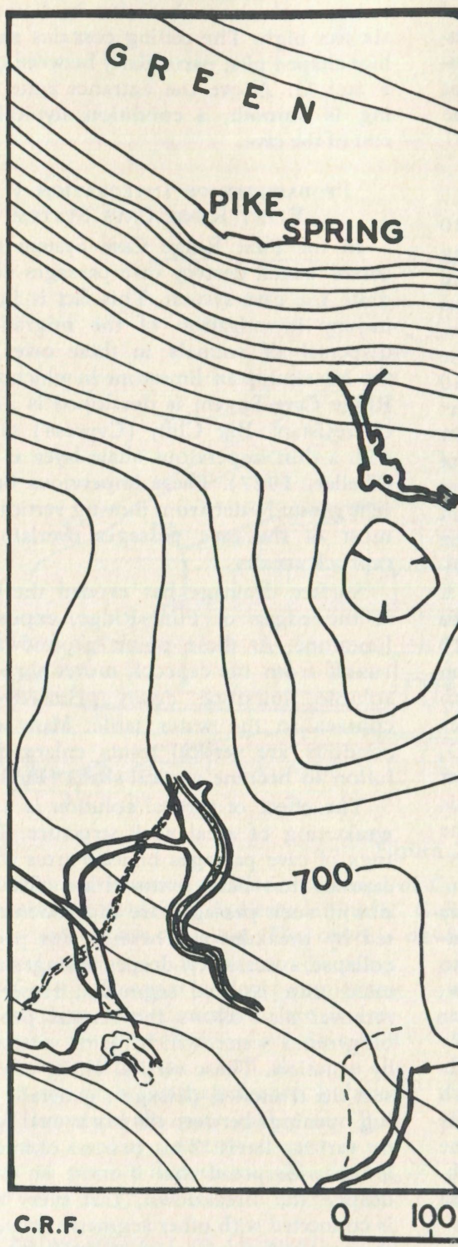


Figure 2.

**Topography at surface at Cathedral Cave. Outline of cave is imposed on topography.**

Cathedral Cave passages are a segment of the Flint Ridge Cave System drainage pattern. Bedrock joints and other openings control passage direction; consequently, the joint set for the region is roughly mirrored in the total cave passage plan.

### Description of Cathedral Cave

The entrance to Cathedral is set back 20 feet beneath the edge of a wide, overhanging ledge (fig. 3). Due to this obstruction, and the growth of trees around and below the entrance, no direct sunlight enters the cave. The entrance passage is six feet square. The main passage tapers over a distance of 30 feet at quadrat C to a crawlway three feet high and two feet wide. Beyond this point the passage opens to the widest portion of the cave, beyond quadrat F, where the cave is 40 feet wide and varies in height from four to 15 feet. Flowstone layers coat the walls and remnants of stalagmites and stalactites litter the floor. A small opening at the southwest edge of quadrat F leads into a vertical shaft four feet in diameter and 20 feet high. A crawlway (fig. 1, cross-section beside quadrat F) leads toward the northeast from the top of this shaft, but pinches out after 10 feet. Between quadrats F and G, two rimstone dams form pools near the east wall of the cave. Stalactites overhead at this point drip water, maintaining levels of the pools with seepage occurring through crevices around the rimstone.

Beyond quadrat G is a narrow crawlway 16 inches wide, extending 20 feet to quadrat J. The ceiling height varies from two to six feet. The next 10 feet remain narrow, but it is possible to squeeze through in an upright position. At quadrat K the cave splits into two passages. The southwest fork leads into a muddy crawlway two feet high which becomes impassible to humans 15 feet farther on. The southeastern fork leads into the room with the highest ceiling, 30 feet high. The passage ends 15 feet beyond this room under another vertical shaft 20 feet high.

The floor is generally rock with a coating of mud in the entrance zone and in quadrats H through J. Three feet above the floor in the west wall of the entrance zone is a one foot high crevice which extends for 10 feet into the west wall. Along the east wall between quadrats G and I are three small rooms each about three feet in diameter and six feet high. The ceiling contains many beehive shaped pits, particularly between quadrats F and G. Above the entrance zone the ceiling is smooth, a condition atypical of the rest of the cave.

### Probability of Integration With Flint Ridge Cave System

In the Flint Ridge Cave System the processes which destroy cave passages also integrate the cave system. This fact is important in any investigation of the migration and dispersal of animals in these caves. Above the Mississippian limestone in which the Flint Ridge Cave System is developed is a caprock of resistant Big Clifty (Cypress) sandstone with a thin impervious shale layer at its base (Weller, 1927). These impervious beds prevent groundwater from moving vertically, thus most of the cave passages overlain by the caprock are dry.

Surface drainage has eroded the caprock at the edges of Flint Ridge, exposing the limestone. At these points groundwater and runoff from the caprock moves through the soluble limestone down primarily vertical courses to the water table. Many of these conduits are vertical joints enlarged by solution to become vertical shafts (Pohl, 1955).

The effect of vertical solution is a general weakening of areal rock structure. The ceilings of cave passages beneath areas where the caprock has been removed are often broken down; such passages are thus often terminated by breakdown. Through this process of collapse, successively deeper passages are truncated into isolated segments. However, the removal also allows the vertical penetration of ground water which forms vertical shafts by solution. These vertical shafts often intersect the truncated passages, generally providing openings between the horizontal segments on various levels. This process of integration is so widespread that it must be assumed, despite the breakdown, that every segment is connected with other segments (even though the connecting passages or shafts may be very small) unless positive evidence is found to the contrary.

The passage at the southwest end of Cathedral Cave, for example, is too small to permit human inspection, although it is sufficiently large to permit the entry of all troglobitic



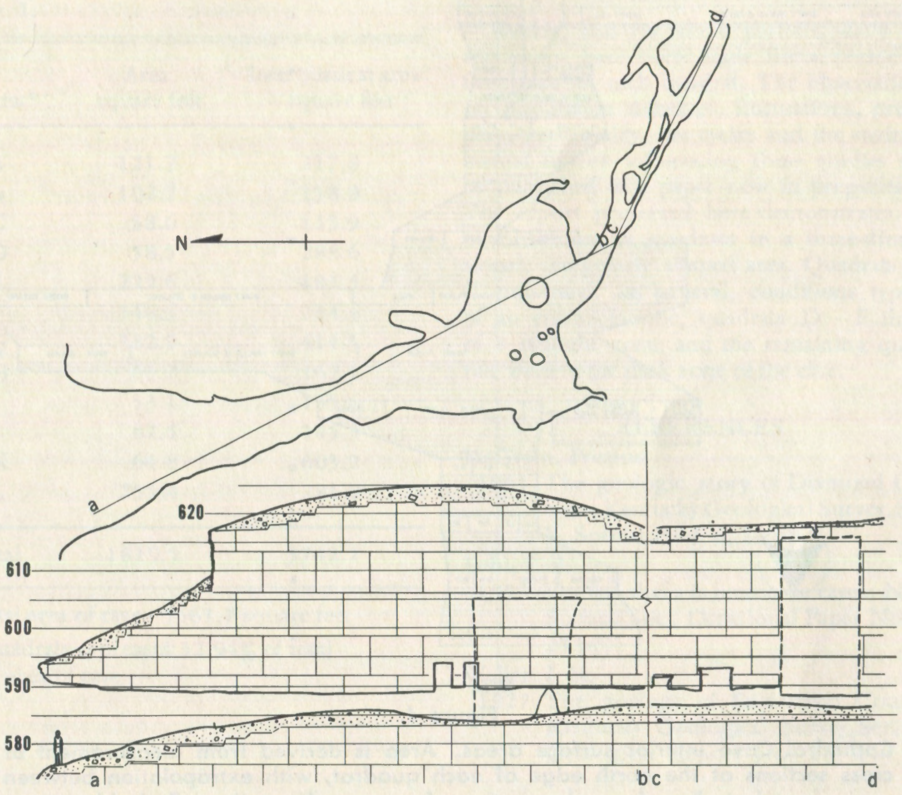


**Figure 3.**

**Stratigraphic cross section of Cathedral Cave. Outline of cave at top of figure. Figures in bold face indicate altitude. Golconda Limestone and Big Clifty Sandstone are missing. The cave is developed in the Girken Formation.**

forms (fig. 1). Stronger evidence supporting the assumption that Cathedral Cave is integrated with the Flint Ridge Cave System is that the water from the small shafts in the cave does not drain out the entrance. It drains through lower levels, presumably out Pike Spring (fig. 2). The quantity of water is not sufficient to permit fluorescene dye tracing, however.

### Establishment of Quadrats

Cathedral Cave was surveyed in November, 1960. A total of 12 quadrats were established. Pegs were set every 10 feet through the cave, starting at the entrance. These pegs were set in the center of the cave passages, each site having been determined by Brunton compass and level. An interval of 3.4 feet in width was then measured from the peg, along the center line of the transit, toward the rear of the cave. Thus, an interval of 6.6 feet exists between each quadrat. Each quadrat is a band 3.4 feet in width encompassing the ceiling, walls, and floor. Band diameter thus varies according to the width and height of the cave passage (fig. 1, cross-sections). All observations were made in these quadrats, which constitute approximately 33 per cent of the total area of the cave (table 1). In the absence of any similar study of cavernicolous ecosystems, and in particular the application of quadrat techniques, no data were available from which we could judge the minimal sample area necessary to describe the size of the popula-

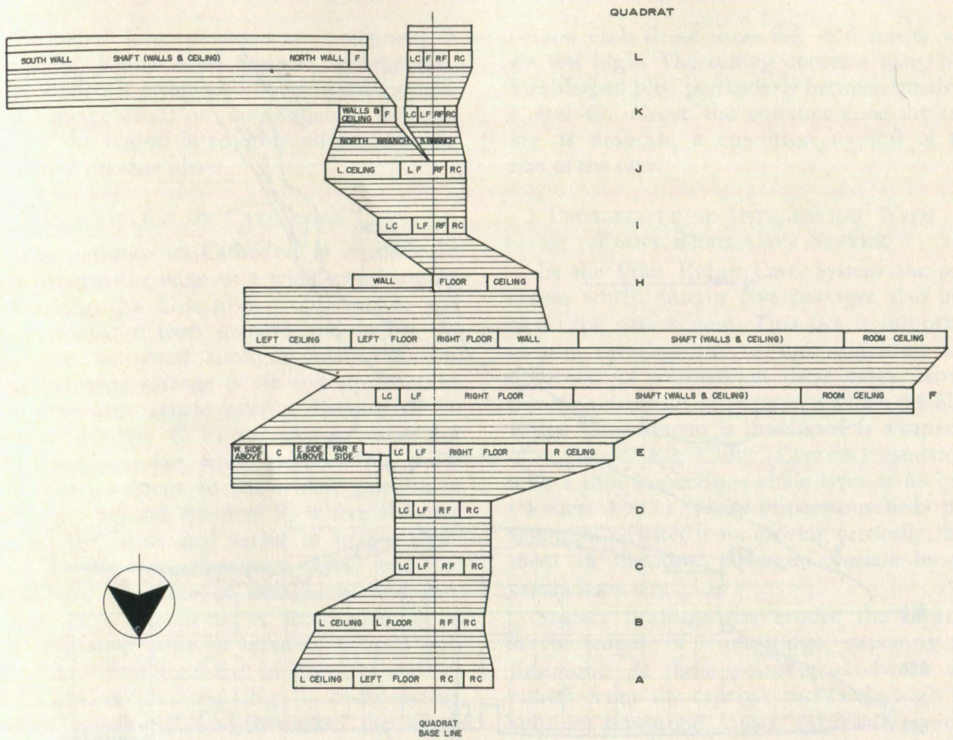


**Figure 4.**

**Cathedral Cave interior surface areas. Area is derived from measurement of cross sections at the north edge of each quadrat, with extrapolation between quadrats based on observation of cave configuration. Probable limits of error: ± 2%.**

tion and its movements. Thus, we sampled a large percentage of the total area.

### Calculation of Cave Surface Area

After laying out the quadrat system, it was necessary to determine the number of square feet of cave surface exposed in each quadrat and in the areas between the quadrats. Cross-sections of the passages were constructed for each quadrat at its northern boundary. The circumference of each cross-section was then measured with a map measurer. Compensation for mechanical lag was made by using the average value of three measurements. Circumference distance for each quadrat was then multiplied by 3.4 feet to calculate square feet. Assuming the walls to be smooth, the resulting values are one to two per cent too high. However, since the walls are rough and contain irregularities which increase the surface area, the values are probably not excessive. For the calculation of inter-quadrat areas, each was divided into seven bands, six of them one foot wide and one 0.6 feet wide.

The maps and cross-sections used for these calculations were made with great care. However, their accuracy is in direct proportion to the difficulty of making the initial observations. The values obtained for the upper areas of the vertical shafts, therefore, are less accurate than the areas which could be measured directly. However, the final values are probably within two per cent of the true value in all cases except the areas at the tops of the shafts, where the area may be as much as 10 per cent. The total area is thus 5,562 (plus or minus 11) square feet. The area of each quadrat and interquadrat is given in table 1. Figure 4 shows the plan of the total surface area of the cave.



**Table 1.**

| Quadrat* | Area square feet | Interquadrat area -- square feet |
|---|---|---|
| A | 121.7 | 217.8 |
| B | 102.7 | 158.9 |
| C | 58.6 | 113.9 |
| D | 58.5 | 288.6 |
| E | 222.6 | 481.5 |
| F | 348.5 | 734.4 |
| G | 382.9 | 414.3 |
| H | 63.2 | 167.1 |
| I | 53.1 | 135.6 |
| J | 87.5 | 145.3 |
| K | 64.8 | 603.2 |
| L | 255.4 | 281.2 |
| Total | 1819.5 | 3742.2 |

Total area of cave 5561.7 square feet

*Quadrats represent 32.94% of total area of cave

### Quadrat Analysis

Weekly, and for some periods, daily observations have been made for a period of five years in each quadrat. The observations on population densities, fluctuations, predation, territoriality, life cycles and the environmental factors influencing these studies will be published in a paper now in preparation. The report presented here demonstrates the establishment of quadrats in a three-dimensional, irregularly shaped area. Quadrats A - C presented, in general, conditions typical of an entrance zone; quadrats D - F those of a twilight zone; and the remaining quadrats were in the dark zone of the cave.

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# SHORTER CONTRIBUTIONS

Short papers reporting new techniques, procedures and methods, papers of timely importance and discussions of previous papers are presented in the Shorter Contributions Section.

# Artesian Origin of Fissure Caves in Missouri: Discussion

**By James Hedges**

## Introduction

The recent paper by Langford Brod, Jr., "Artesian Origin of Fissure Caves in Missouri" (NSS BULLETIN 26:83-114), is an ingenious and generally convincing piece of work. There are, however, several points among his geomorphic contentions which I should like to dispute.

## Critique

Landforms developed on the Paleozoic rocks of the Ozark province, on the edge of which the fissure caves occur, have most frequently been interpreted with reference to similar features in the Central Lowlands and Interior Low Plateaux provinces rather than with reference to the Mississippi Embayment region (Fenneman, 1938). If, however, the latter, novel, procedure is to be followed, then it must be recognized that there is a profound disagreement by middle and upper Mississippi valley geologists (cf. Leighton and Willman, 1950; Trowbridge, 1954) with the "loessification" ideas of Russell (1957), whom Brod cites, and of Fisk (1951). Failure to appreciate the bases of these differences of opinion can lead to erroneous conclusions regarding terrace-like topographic forms in the lower Mississippi valley, their ages and origins.

Although there is a definite lack of agreement among students of middle and upper Mississippi valley geomorphic history as to the number and precise ages of base-level surfaces in these regions, and even as to the preglacial location of Mississippi river itself and the age of its "deep-stage" bedrock valley, Illinois geologists have developed a coherent and among themselves non-controversial interpretation of the Cenozoic history of these areas which was reviewed and elaborated by Horberg (1950). Results obtained by workers in neighboring states have tended to agree with those of the Illinois geologists despite the above-mentioned uncertainties.

## New Correlations

Correlation of the base-level surfaces in the fissure cave region, as described by Brod, with surfaces developed on the Paleozoic rocks of Illinois yields somewhat different ages for them and for the Rockwoods fold and the fissure caves than the ages derived by their attempted correlation with terrace-like topographic forms in the Embayment region.

*Yarmouthian Terraces.* "Yarmouth terraces" occur at the same elevation as Horberg's Central Illinois peneplain east of Mississippi River and should be correlated with that surface. Leighton and Willman suggested a correlation of the Central Illinois peneplain with Russell and Fisk's Bentley terrace, which the latter believe to be of Yarmouthian age. Horberg, however, assigned to the Central Illinois peneplain a preglacial, late Tertiary age, rather than a Yarmouthian age.

Hedges and Darland (1963) have described in Maquoketa River valley, Iowa, a strath equal in elevation to and at Savanna, Illinois, merging with the Central Illinois peneplain but which, on the bases of relationships with preglacial and modern drainage, stratigraphic relationships, and sediments in associated caves, appears to have been developed during Aftonian time. At the time of writing, no other means of correlation with the Central Illinois peneplain besides equivalence in elevation was possible. However, it has since been found that Bretz (1923, pp. 232-234) discovered an iron-cemented gravel closely resembling the Rockville conglomerate (Tuttle and Northup, (1955) in the preglacial valley of Rock River near Rockford, Illinois. The upper surface of this gravel lies at the level of the Central Illinois peneplain, just as the upper surfaces of the Rockville and Pine Creek (Udden, 1898, pp. 316-319) conglomerates lie at the levels of the Scotch Grove strath and of the Central Illinois peneplain in their respective areas. There is thus some stratigraphic evidence that the Scotch Grove strath is an extension of the Central Illinois peneplain and that the latter, also, may have been developed along preglacial valleys during Aftonian time at the level of the Nebraskan outwash train filling the deeper portions of these valleys.

*Pre-Nebraskan Strath.* The "pre-Nebraskan strath" is equivalent in elevation to the Calhoun peneplain remnant between Mississippi and Illinois rivers north of St. Louis. Horberg has correlated this plateau with the Lancaster-Ozark-Highland Rim peneplain, which is of late Tertiary age, although Leighton and Willman have suggested a correlation of it with the Williana terrace of Russell and Fisk. The Williana terrace is held to be of Aftonian age by Russell and Fisk.

*Pliocene Surface.* Brod's "Pliocene surface" bearing Lafayette-type gravels is a remnant of the Dodgeville (summit) peneplain. The Dodgeville transects Eocene strata, as Brod states, but probably was dissected long before the Pliocene. Consequently, the age of the Rockwoods fold and of the fissure caves is probably not Pliocene; rather, it is middle Tertiary.

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# Artesian Origin of Fissure Caves in Missouri: Reply

By Langford G. Brod, Jr.

The interpretations in my paper were based on references which assigned ages to landforms in the Mississippi Embayment region. However, an important publication which permits me to re-evaluate my earlier conclusions has recently become available: *Geomorphic History of the Ozarks of Missouri* by J Harlen Bretz (1965). Bretz has concluded that most of the numerous erosion surface remnants in the central Missouri Ozarks are remnants of a single erosion surface, the Ozark peneplain. He considers the gravel bearing plain of western St. Louis County to be a remnant of this same surface, a conclusion which I also stated. Bretz also considers the Ozark peneplain to be correlative with the Lancaster and Calhoun peneplains. An older, pre-Ozark stage, the Springfield peneplain, is correlated with the Dodgeville of Wisconsin. My attempted correlation with the Dodgeville is thus erroneous, consequently Hedges comments on the Dodgeville are not relevant. A late Tertiary age of the Ozark peneplain does not appear to be inappropriate, and a Pliocene age for the highest Rockwoods surface (800 ft.) appears to be in order.

Bretz also identifies two post-Ozark surfaces, the older of which is termed the Osage strath and considered to be equivalent to the Central Illinois peneplain of Horberg. It appears that the surfaces which I have termed pre-Nebraskan strath are correlatives of this Osage strath, rather than the Calhoun peneplain as Hedges states. My attempted correlation with the Lancaster is also in error, inasmuch as the Lancaster and Calhoun are equivalent.

A younger post-Ozark surface, termed simply the post-Ozark strath, has been identified by Bretz and correlated with the Havana strath of Illinois; the age is considered to be pre-Pleistocene or very early Pleistocene (Bretz, p. 125). Hedges and Darland (1963) however, have tentatively assigned an Aftonian age to the older Central Illinois peneplain. Consequently, the Osage strath surfaces of the Rockwoods-fissure cave area would be Aftonian, on the basis of this reference. Thus, the post-Osage strath could be no older than Yarmouth age; post-Osage terraces lying at an altitude of 560 feet in the Rockwoods area would then also be of Yarmouth age, as I originally concluded in my paper. Personally, however, I would be inclined to consider the Osage strath-Central Illinois peneplain as pre-glacial, as it seems unlikely that a strath of that extent could be developed during the relatively transitory interglacial period.

After a careful re-evaluation of my original conclusions on the basis of the new information, I have concluded that the ages assigned to the various surfaces in the Rockwoods-fissure cave area are essentially correct. The attempted correlation with surfaces in Illinois was completely in error, and for this reason a new correlation table is included here. For reference purposes the names of local terraces have been included. I wish to thank Mr. Hedges for bringing to my attention the discrepancies in my paper and trust that this revision will provide an adequate correction.

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**Revised Correlation table**

| nominal altitude | local surface | age, from Brod, (1964) | revised age | from Bretz (1965) | equivalent surfaces |
|---|---|---|---|---|---|
| 900 | High Ridge plain | mid-Tertiary | mid-Tertiary | Springfield peneplain | Dodgeville peneplain |
| 800 | Grover plain | Pliocene | late Tertiary | Ozark peneplain | Lancaster peneplain |
| 650 | Kirkwood strath | pre-Nebraskan | pre-Nebraskan | Osage strath | Central Ill. peneplain |
| 570 | Bouef terrace | Yarmouth | Kansas or Yarmouth | post-Osage strath | Havana strath |
| 470 | Gumbo terrace | Sangamon | | | |
| 440 | Bonfils terrace | Peorian | | | |
| 400 | flood plain | recent | | | |

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