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Speleology in New Zealand

by DAVID V. MAY

ABSTRACT—The New Zealand Speleological Society was founded in 1949. At present there are 5 cave groups which are affiliated in the Society. Karst areas are in the region of Te Kuiti, Port Waikato, Wairo, and Waipu on North Island and at Fox River, Lake Te Anau, Nelson and other areas on South Island. The longest cave in Gardners Gut, 4 miles long. The deepest is Harwood Hole, near Nelson, 1415 feet deep. Scientific work is now developing and covers exploration for fossils remains, primarily moa bones, studies of arthropods and some surveying, hydrological research and work on subterranean radio communication.

ORGANIZATION

The New Zealand Speleological Society (N.Z.S.S.) was formed by two Americans who were inspired by Norbert Casteret's book, *Ten Years Under the Earth.* To quote from Bulletin No. 1, "Impressive letterheads were printed, a receipt book was purchased and the Society came into existence on 1 October 1949, with one member, Henry G. Lambert, who was unanimously elected President, Secretary and Treasurer and who was appointed Editor of the New Zealand Speleological Bulletin."

Shortly after, Judd Davy joined and the two proceeded to raise interest among citizens of Auckland, the largest city, with lectures to clubs and societies, and by articles in local maganzines and the press. The first recorded membership list in 1942 contained 49 names. Since then, membership has increased rapidly until now the Society has about 150 members throughout the country. In 1956 cavers in Hamilton decided to form their own affiliated group called the Hamilton Tomo Group ("tomo" is the Maori word for a vertical shaft or pothole). In 1958 a constitution was adopted by N.Z.S.S. allowing affiliated groups to have representation on the council according to their membership, and in 1959 the Auckland Speleo Group was formed, thus relieving N.Z.S.S. of the administration of the many Auckland members. N.Z.S.S. is now a central body which coordinates the groups, looks after members in centers where there is no group and publishes the Bulletin.

Henry Lambert resigned from the presidency in 1959, having done a wonderful job in creating a full and flourishing Society. L. G. Watson was the newly elected President and found his first assignment the organization of tenth anniversary celebrations to be held at Waitomo. The Society decided to invite local farmers who had extended us hospitality to a social. It was a great success and improved our already good caver-farmer relationships in the area.

At the tenth anniversary, the formation of a new group in Tokoroa, a large pulp and paper mill center, was announced and recently another group was formed in Nelson, in the north of the South Island. There is also a group at Auckland University.

The officers of the N.Z.S.S. and Groups are:

New Zealand Speleological Society—President: Mr. L. G. Watson, 3A Selwyn Street, Hamilton; Secretary: Mr. T. M. Campbell, 289 St. Heliers Bay Road, Auckland; Librarian and Overseas Correspondent: Mrs. B. M. May, 11 Benfield Avenue, Mount Albert, Auckland.

Auckland Speleo Group—President: Mr. L. O. Kermode, 49B Luke Street, Otahuhu; Secretary: Mr. F. E. Walton, 32 Ferndale Road, Mount Wellington, Auckland.

Hamilton Tomo Group—President: Mr. J. Hobson, c/o Auto Tools Ltd., Alexander Street, Hamilton; Secretary: Mrs. B. Tonar, 37 Enderly Avenue, Hamilton.

Others—c/o Secretary, N.Z.S.S.

Karst Areas

The newly created Nelson group is in an almost virgin region of horizontal caves and deep tomos of potential challenge to the world depth record lists. This area contains Harwood Hole which, at a depth of up to 1415 feet (depending on the reference point), is one of the deepest caves in the world. Much of this country is hard marble, but there are also patches of the softer and, to me, more friendly limestones. Other South Island karst areas, not yet investigated by the Society, are at Fox River, Lake Te Anau (where there is a tourist cave) and possibly in Southland (fig. 1).

The North Island contains two main grades of limestone: the Te Kuiti group, which is found around the Waitomo tourist caves, and a softer, more sandy type found in the region of Port Waikata, at Waipu and Whangarei in Northland, and also in the Hawkes Bay and Dannevirke karst districts. Many of the caves in the Te Kuiti limestone are outstandingly beautiful. It is thought that this is due to the covering of rain forest bush which acts as a "smoothing agent" for the flow of water. The prevention of sudden surges of flood water greatly decreases the silting of caves and stops mud seeping onto formations such as occurs in some caves under cleared land. The caves in other North Island areas tend to be smaller and muddy, with comparatively little formation. Some encouraging finds, however, have been made by a small, active group in Wairoa, Hawkes Bay

In addition to the limestone caves, New Zealand has the usual small sea caves round its coasts and in Auckland are many lava caves. These were formed by large bubbles or streams of gas forcing their way through the molten lava flows that came from Auckland's numerous, now extinct, volcanoes. They are quite short, the longest being 100 yards long, and they vary in size from small squeezes to passages 15 feet in diameter. The walls are very rough with sharp projections. Sometimes small stalactites are found where drops of molten rock have solidified on the room. The lava caves are of little but academic interest but being right

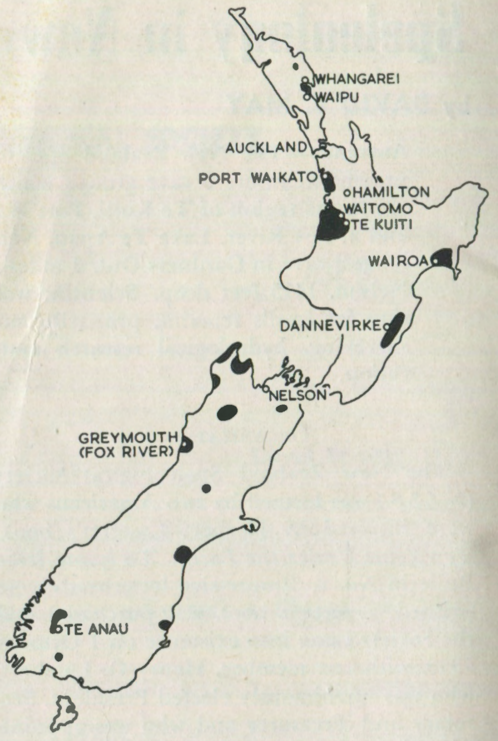

Figure 1
New Zealand showing karst areas.

on the doorstep for Auckland cavers, they have been used for such purposes as first aid and stretcher practices and, on one occasion, an annual general meeting.

Prominent Caves

The majority of the well known caves in New Zealand are in the Waitomo district. I shall briefly describe these, as well as a few in other areas.

The first major project of the Society was the exploration of Karamu Cave, 13 miles southwest of Hamilton. Part of the cave had been known for a long time by locals, and this was how the Society came to hear about it. In the initial stages of exploration, wonderful tales of massive formations and terrific lengths of passages were told. Indeed, the official length of passages once rose to 8 miles and it used to be common practice to pitch camp half way when "doing" the cave.

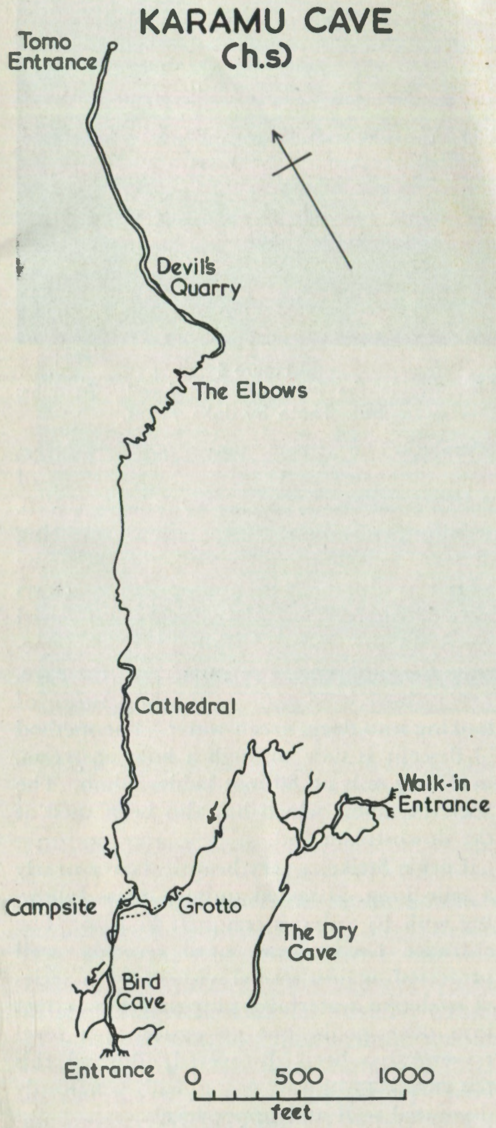

Figure 2
Map of Karamu Cave

Now, with the discovery of new entrances and, no doubt, added confidence in one's capabilities, it is traversed from end to end in three or four hours. The latest survey gives an end to end length of 1½ miles and a total of about 2½ miles. However, I would say that it is still one of our more interesting caves.

The "walk-in" entrance was the first known and the passage from this carries a stream into the cave (fig. 2). A short way in, there is a roughly circular domed cavern and it is here that most inexperienced or unguided parties turn back after failing to find the small concealed exit. From here, one continues along the stream until just before it siphons where an upper level runs above the stream course. This level includes The Grotto, a higher level chamber whose walls are very beautifully decorated with flowstone, stalactite and straw formations. It then widens into the Campsite, a part of the passage 10 feet wide by 15 feet high, whose floor is covered with dry gypsum sand, making an excellent camping spot for those wishing to stay the night in the cave. In 1952 the Annual General Meeting of the Society was held here.

At this point, the cave forks. To the right, one can go upstream past the Cathedral, a mighty pillar 10 feet through, reaching to the roof 20 feet above, through the Devils Quarry of huge, fallen blocks and flakes, and so to the Tomo entrance, a sheer 40 foot pothole unclimbable unless ladders have previously been lowered. The distance along this branch is 1 mile. The left hand passage takes both the streams, which meet below the Campsite, down to an impassable rockfall. About half way, however, an upper level passage leads to an entrance which is quite remarkable. In a side chamber with a dry, sandy floor, an exploring party noticed many rat footprints coming from under one wall. They noticed a slight draft and on further investigation could see daylight. Sand was frantically scraped from the base of the wall and soon a hole large enough to take the smallest member was excavated. He pushed his way through about 30 feet of squeeze and emerged from a crack half way up a cliff at the side of the valley holding Karamu Stream. Since then, more sand has been moved and the squeeze is now regularly used as an entrance and exit.

Karamu has been described fairly fully as it is typical of the plan of most New Zealand caves. The well known caves near Waitomo have a good deal more formation but

Figure 3
Vivienne's Needle in the Peter Lambert Levels of Gardners Gut. Photo by John Pybus

still follow the general pattern of a main stream with tributaries and upper levels.

The next cave to occupy the full attention of the Society was the Lost World. This imagination-stirring name was given to a hole west of Te Kuiti, 400 feet by 100 feet at the top and enclosing about half an acre of bush 300 feet below. It is one of a series of holes leading to the Mangapu Stream in its underground course. The system is not yet surveyed but the surface distance from end to end is 2 miles.

The first descent in 1954 was made through a small hole, adjacent to the large one, in two stages totaling 200 feet. A reporter accompanied the party and the descent brought much publicity to the Society. The cavern takes the form of a long cleft, 300 feet deep at the downstream end, continuing in each direction as a lofty stream

Figure 4
Helictites in the Peter Lambert Levels, Gardners Gut. Photo by John Pybus.

passage. The stream, which is fairly large, flows along one wall from which a slope of debris from above reaches to the other wall. It is on this slope that vegetation, consisting of fern and succulent growth, occurs, some as tall as a man. The atmosphere is always humid, causing wreaths of vapor to swirl gently in the shafts of sunlight which penetrate the otherwise dim interior of the cave. From above, one receives the impression of looking into deep, green water. The method of descent is now through a hole upstream, involving only an 80 foot ladder climb. The Society's motor winch has also been used at the downstream end.

Luckie Strike, a very beautiful cave nearly a mile long, attracted quite a press following with its arduous conquest in 1956. The entrance passage was, until recently, well protected against casual visitors by a series of undercut waterfalls, plunging 4 to 6 feet into deep pools, but an easier high level traverse has been discovered. Beyond this the cave is quite easy going, with generously decorated wall and upper levels.

Together with Waipuna, Hollow Hill, Rumbling Gut, Warrens Self Respect, Virginia and Garners Gut (figs. 3, 4), Luckie Strike is one of the popular caves of the Waitomo district for photography and guided parties. All these caves, with the exception of Gardners Gut, were found between 1956 and 1959, and contain much outstanding calcite formation. A few notable features are the Giants Cavern in Hollow

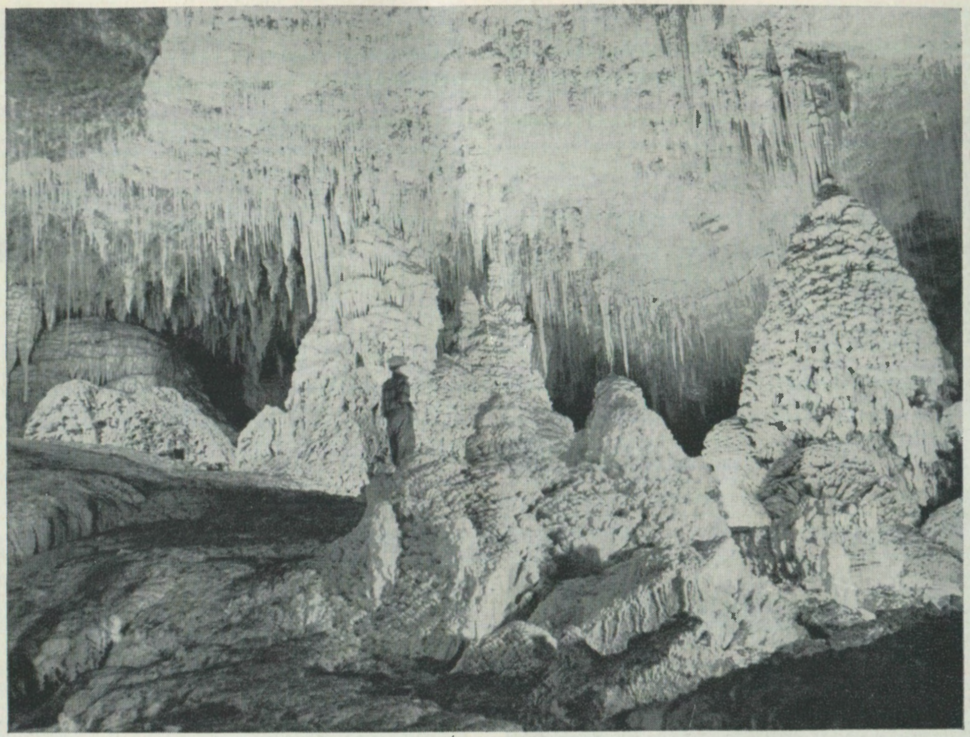

Figure 5
Hollow Hill. The "castles" in Castle Grotto. The calcite "leaves" at the base of the stalagmite on the extreme right emit a high pitched ring when tapped. Photo by S. A. Rumsey.

Hill, the largest known cavern room in this country; it would be capable of containing a large passenger liner (fig. 5); the Studio, a beautifully decorated chamber in Waipuna (figs. 6, 7); the Last Minute Crawl, the only connection between the dry and wet systems of Rumbling Gut; and the Birthday Candle in Gardners Gut, so called because the discovery of this magnificent formation highlighted the weekend of the Society's tenth anniversary celebrations. It stands 25 feet high and is New Zealand's largest stalagmite in her longest cave (4 miles).

Possibly the most outstanding cave discovered yet is Harwood Hole in Nelson province. This huge chasms was first brought to the notice of the Society during a prospecting trip to the area in December 1957. The party at that time had neither the manpower nor the equipment to tackle it. An assault was planned for Christmas the following year, using a motor winch built by one of the members. This party made the initial 610 foot descent and explored the stream system below to a depth of 1210 feet, where the stream appeared to sump (fig. 8). Last Christmas, a larger exploration party found a way around the sump and reached the cave outlet 1415 feet below the entrance. It was on this expedition that the tragic death of the leader, Peter Lambert, occurred when a fall of rock came from the top of the hole.

Equipment and Techniques

For a long time, caves were found merely by asking farmers or locals the whereabouts of disappearing or emerging streams, or of holes down which stock were lost. However, it soon became evident that this system had its limitations. A more systematic approach was adopted and every tomo or likely looking depression on a given property or

Figure 6
The Miniature Pine Forest, a corner of the Studio in Waipuna. Photo by S. A. Rumsey.

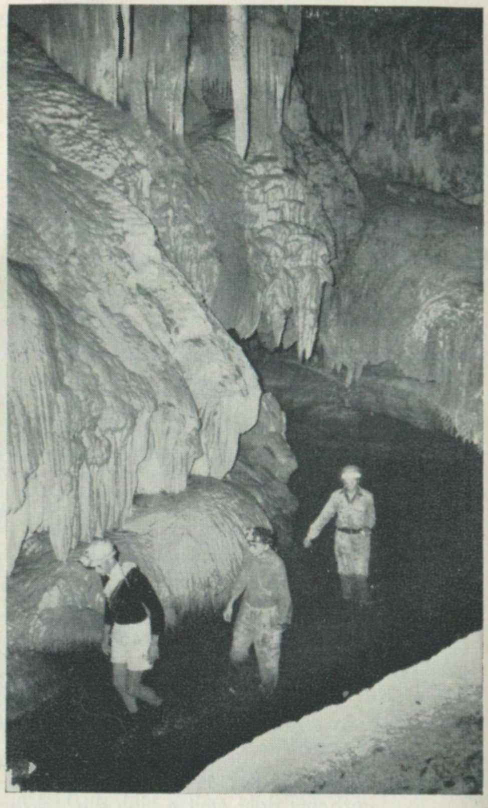

Figure 7
Waipuna, stream passage. The calcite formations decorate the 1 mile length of this cave. Photo by S. A. Rumsey.

area of a geological map was descended to see if it "went." Unfortunately, there is no topographical map of the main Waitomo area and the only maps readily available are those of the Geological Survey. However, where "topo" maps were published, these were used with advantage to trace stream submergences and resurgences. A recent technique is the use of aerial stereoscopic photos to locate possible caves. The photos can be put under a viewer and a three dimensional picture of any part of the country can be obtained. In this way, a map showing the positions of all depressions and streams in a prospecting area can be sketched and much hiking time can be saved.

Many New Zealand caves have vertical tomo entrances and for that reason ladders have always been an essential part of the caver's equipment. They are made from steel wire with tubular aluminum alloy rungs. A variety of methods have been used to secure the rungs to the wire, the latest being to fit an alloy plug to each end of the rung, drill a hole for the wire and then pressure weld the plug to the wire with a pressure of about 10 tons per square inch. This has been found to give a very strong but light ladder. Each end the ladder is fitted with sister clips for joining consecutive lengths. A Hamilton member has now produced a set of dies and jigs which make simple and quick work of ladder construction. Ropes used have been manila, but this is being replaced by nylon and terylene. Climbing poles made of light alloy sections fitted together with sleeves are used for reaching high level leads.

Another piece of Society equipment that has become important is the motor winch. It was designed and constructed by Richard Scott, for use by the N.Z.S.S. expedition to the 610 foot tomo of Harwood Hole. The drum has a hand brake at each end for controlling the free descent, and a ratchet for safety on the ascent. It is driven through chain drive reductions and a motorcycle gearbox and clutch, by a 225 cc four-stroke stationary engine. It is designed to be dismantled into easily portable parts. The time of just on 2 hours that it took to assemble it for operation on the 1958 expedition speaks for the efficiency of the design. The record descent of 550 feet was 3½ minutes and for the ascent, 15 minutes. The advantages of the winch in handling large parties were shown when, one day, 21 sightseers were lowered into the Lost World and returned to the surface after their trip through the cave.

Nowadays, New Zealand speleos, when confronted by a sump, generally attack it with aqualungs and waterproof suits, spotlights and telephones. Siphon diving, although at present attracting only a small following will, I think, gain in popularity and become another challenge to enterprising cavers. The equipment used is simple. The diver, wearing an aqualung, mask and waterproof suit, is lifelined with a rope and either this or an underwater telephone is used for communication. Light is supplied by a waterproof torch. The most notable success has been the forcing of the Cold Creek sump. This was proved by fluorescine to be the resurgence of the stream in the Rumbling Gut system, west of Te Kuiti. The underwater passage, 180 feet long, varied between 2 feet and 15 feet high and, in the narrowest parts, the divers had to turn on their sides to proceed. Although no great extension to the cave was found, the participants gained much in experience.

Personal equipment for New Zealand cavers always makes a good subject for discussion. Wearers of fibre helmets argue their advantages with owners of plastic types; steel shod boots vie with rubber commando

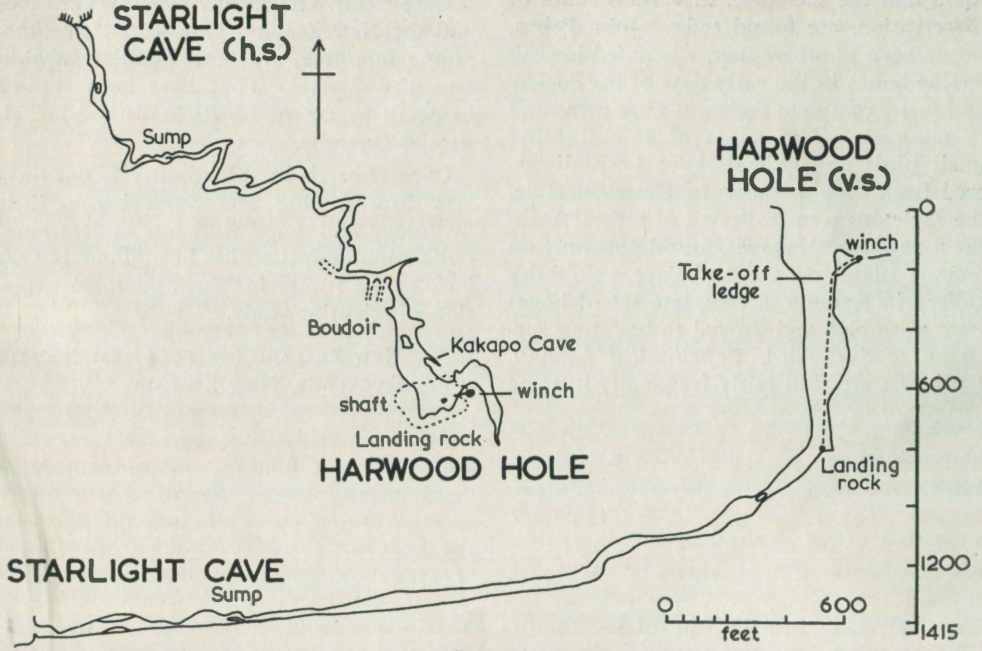

Figure 8
Map of Harwood Hole, New Zealand's deepest cave.

soles for popularity and wearers of boiler suits are quick to point out the disadvantages of shorts and vice versa. The only subject on which most are agreed is lighting. Most experienced cavers use the helmet type carbide lamp and some use both carbide and electric. The general opinion is that the carbide lamp gives a softer, friendlier, more even light, as well as being far cheaper. A spare electric torch is carried and used to spotlight distant objects.

Scientific Work

It is only comparatively recently that cavers here have started to look at caves from a scientific as well as a sporting angle. The earliest scientific work undertaken by members was the collection of moa bones. The moa, now extinct, was a flightless bird, something like an emu, of which the largest species stood 12 feet or more in height. The early Maori inhabitants used to hunt these for food and feathers, and being large and defenseless, the moa was eventually eradicated. During their existence, many fell into tomos or crawled into caves to die, and it is there that the skeletons, in various states of preservation, are found today. John Pybus, now a keen photographer, was noted for collecting bones in the early days of the Society and many complete skeletons were presented to museums. The bones of several other small birds and animals have been discovered from time to time. In Harwood Hole, the skeletons were collected of several kakapo, a native bush parrot, found now only on Stewart Island. In the Bird Cave, an old dry gallery in Karamu, a complete set of bones were assembled and proved to be a new species of extinct bird, *Capellirallus karamu.* Bat bones are seen fairly frequently in some Waitomo caves. They are usually single specimens and one gains the impression that they did not live in colonies. The bat, although common in most countries, is rare in New Zealand and has never been seen alive in caves.

To the Maori people, caves were sacred and forbidden. The only use they made of them was as burial places. Many such caves are known but are usually avoided because of the objections raised by the Maoris to people entering them. Early man, whose drawings and living quarters are found in European caves, does not appear to have visited our part of the world. The only rock drawings discovered have been of recent origin and are in small rock shelters.

A recent discovery is the existence of ground beetles, partly or wholly adapted to cave life. These are trechines of the genus *Duvaliomimus.* Various modifications have been found from Port Waikato southwards. Our librarian, Brenda May, is still working on them as well as on our cave fauna in general.

Cave wetas, known in America as crickets, and the New Zealand glow-worm, *Arachnocampa luminosa,* are both familiar inhabitants of our caves. They have been studied in detail by Dr. A. M. Richards and Dr. H. Brontë Gatenby.

Cave research in this country is not on a very firm footing yet. Surveying, a little hydrology and some work on underground radio communication has been done, but we look to the future for a considerable extension of scientific study.

New Zealand Speleological Society
Auckland, New Zealand

A Stream Piracy Theory of Cave Formation

by HERBERT P. WOODWARD

Abstract—This theory attributes all caves to the sudden rearrangement of a specific drainage system, either by the piracy of a higher-level system by a lower-level system, or by the capture of surface drainage by underground circulation. Its distinctive feature is its association of the cave-forming process with the history of the adjacent surface drainage system, and that it regards a cave as a transitory or impermanent feature of stream development in the same category as a waterfall, a lake, or a river gorge.

The theory postulates a single stage (not cycle) of cave development although there must have been a necessary pre-cave epoch in which the bedrock acquired an incipient structural porosity along joints and fractures. The trigger which initiates cave development is the activation of swift flow at the water-table level, a situation which is normally absent and is likely to be brought about only by some relatively sudden event. Such causative events might be the fall of sealevel; glaciation and ice melting; a major climatic change; acceleration or relocation of surface streams; or the break-through of some impervious barrier or retaining wall.

Although these causative events seem to be widely different, each one effects a significant change in the surface drainage pattern, resulting in stream rearrangement, rejuvenation, diversion, or capture. On this account the theory is termed the "Stream Piracy" theory.

Introduction

The writer is neither a speleologist nor an authority on caves. Yet in the course of 40 years' field work in the Appalachian country he has entered and examined many caves, several of which—such as Luray Caverns, in Virginia—he made a special effort to explain in terms of present surface topography and drainage. He also studied Natural Bridge and Natural Tunnel in Virginia, describing in 1936 the similarity between these features and suggesting a common type of origin.

He was then impressed with the somewhat contrasting theories of Malott and Schrock (1930) and of Wright (1934) for the origin of the bridge, and observed that unlike these hypotheses, his own theory connected the bridge with stream piracy as a specific event in the surface drainage development. He noted for the bridge and tunnel, as well as with all caves he had then examined, that the operation of stream piracy was either the initial causative factor or an early result of cave formation. Indeed, when referred to in the literature (Thornbury, 1954, p. 332) his theory is usually called the Stream Piracy theory.

In 1959 he was invited by the North Jersey Grotto of the National Speleological Society to present a paper on cave formation for which he prepared and distributed a 5-page mimeographed outline. It was later suggested that this outline could be expanded into a descriptive essay, and after correspondence with William E. Davies, the present article was submitted to the Bulletin of the Society early in 1961. At the time his outline was prepared in 1959, the writer had not seen the excellent symposium on cave origin published January 1960 as Part 1 of Bulletin 22 of the National Speleological Society. Its careful subsequent study has effectively improved the present manuscript.

General Statement

Cave formation or speleogenesis is an excellent exercise in four dimensions wherein the familiar three dimensions of solid geometry must be translated through time. As with certain other four dimensional matters, one may reduce the problem to only three dimensions—vertical, horizontal, and chronologic—but the conversion is incomplete and the omission serious. In particular the geologist is plagued with the difficulty of constructing sketches or diagrams that correctly employ the dimension of time. This paper and its illustrations represent one compromise to the geometrics of the problem.

The entire topic has been clouded by uncertain terminology and an unnecessary rigidity of characterization. An example is the prevalent concept that there are several "cycles" in cave formation, whereas in fact there is nothing at all cyclic about the process. A cave moves forward in the time dimension from inception to destruction and in nowise is a circular event. There may be stages, epochs, or phases in its history but the latter is orthogenetic, progressing in a straight line from beginning to end.

Nearly every essay on cave formation invokes "uplift" of the land, an event treated without specification. Yet there is no genuine evidence for the actual occurrence of either local uplift or subsidence of the earth's crust in the sense that a somewhat restricted area is elevated or depressed with respect to its surroundings. Nevertheless the uplift postulated for cave genesis must be both local and differential, or it would not create the circumstances required. As a matter of fact, almost the only genuine type of non-orogenic uplift, namely the rebound of northeastern North America after the melting of Pleistocene glaciers, is never invoked in cave formation.

Next, after realization of the possibility of deep-seated solution, there has been much discussion of insignia that will distinguish between cave features formed in deep and in shallow zones. Thus various students have pointed to certain criteria as indicating one of these environments and excluding the other. The writer suspects that reliance on this type of evidence may be misleading, and that perhaps the point at issue is not the depth or site of production but quite different features later to be discussed in this article.

He believes, too, that confusion arises from efforts to assemble all cave structures in any single category such as "speleofacts," for this places side-by-side features of deposition (speleothems) and those of solution (speleogens), whereas they were produced quite differently, at different times, and by different processes. To give them similar status is somewhat like placing in the same category such antithetical land features as river canyons and deltas, both of which belong in the stream system but at different places and for different reasons. Finally, much emphasis has recently been placed upon "free-surface" flowing water at or near the water table. This mechanism or agent certainly enters into speleogenesis and is employed in the present theory. But the medium is generally introduced into the argument without considering (1) how such velocities can be generated in a zone where the maximal flow without acceleration may be only a few feet per day; and (2) how such movement can be translated from a broad laminar drift into a channeled or directed flow.

If nothing else, this article will discuss speleogenesis from a viewpoint not lately presented and without "cycles" or "uplift" of the land. If it needs to be characterized in a particular category, it can be thought of as primarily depending upon the entry and work of vadose water in a pre-cave solution network.

Not to define a cave is to mislead the reader, and in this paper a cave is regarded as a natural enlarged underground limestone conduit capable of carrying free-flowing water from an upper to a lower level. In the time dimension it has a beginning and an ultimate end and there are recognizable stages in its history. Many caves can be entered and explored but this is not a technical requirement. The cave is three-dimensional in the usual geometric sense but it also occupies a position that may shift vertically from time to time in terms of ground or water levels that also may be shifting (a) in the same direction but at different speeds, or (b) in an opposite direction.

The critical definitive element is the mature integration of solution openings into a conduit capable of carrying flowing water. In simpler terms, there is no cave until there is a continuous opening from entrance to exit and the cave-producing process begins at this point. Also, in the sense that it is blocked by unopened bedrock, a cave may not "end," for it must be able to carry drainage to some outlet. Cave maps that show only passages and chambers explorable by man may not reveal the full extent of the actual openings. Thus there may be considerable variation between the true dimensions of any cave and a tracing of what can be explored.

One last point: There are thousands of caves in hundreds of localities. Is it reasonable to expect a single theory to account for them all? The writer follows Davies (1960) in assigning a basic congruence to the formation of all caves and caverns. Certainly an individual cave may possess features not precisely duplicated anywhere else; but these differences are believed to mask a much greater concordance for which a harmonious explanation can be made that will account for the features in common without preventing appropriate differences.

It is the thesis of this paper that underground drainage—of which a cave is only one feature—is genetically related to surface drainage and is explainable in terms of this interrelationship; that just as lakes and waterfalls are transitory features of a surface stream pattern, each with its own history of development, so caverns are transitory features of underground drainage with their sequential development and a common primary causation. If evidence is required of the association of cavern systems and surface drainage, it should be noted that cave passageways invariably dip outward toward major stream valleys with slopes that are concordant with those of the surface pattern. Only if stream incision has continued after cave development will there be a steep threshold from the inner cave to the outer valley.

It should be unnecessary to remark that all theories of cave formation including the present theory, postulate cave genesis by some action of cold meteoric (surface-derived) water. This article deals primarily with the production of limestone caves.

Further Discussion and Definition

So that the reader may better follow the argument, a few additional paragraphs of discussion and definition are introduced.

When rain falls on the land surface some of it evaporates; another portion runs off as surface drainage, while a third portion enters the ground. Part of the last third remains below ground, but much of it returns to surface circulation; hence there is a real and important relation between surface and subsurface drainage. In many significant ways they are parts of the same system.

On its way downward, water that sinks into the earth passes through a *Zone of Aeration*, or the *Vadose Zone*, until it reaches that part of the earth's crust which is water saturated. The *Zone of Saturation* has an interface with the overlying zone of aeration that is called the *Water Table*, and the upper part of the zone of saturation is termed the *Phreatic Zone* by some speleologists. In this paper, therefore, the water table is a true boundary between an upper vadose zone (through which water descends from the surface) and an underlying phreatic zone wherein all open spaces are water filled.

The exact position of the water table varies with rainfall, climate, rock porosity, permeability, and time, but in any area (for purposes of this argument consider a township or a county, 75 to 150 square miles in area), the water table is adjusted to the level of streams draining that area, being mostly above the surface of nearby streams. Each stream is adjusted to a *Local Base Level* which is the elevation of the body of water into which the stream flows, and is a horizon below which the stream may not cut its valley. Local streams have local base levels; the surface of the master stream (or a lake or the ocean) into which they flow is a *Regional Base Level*.

As rivers erode their valleys, local base levels are correspondingly lowered and this will depress the water table in the inter-

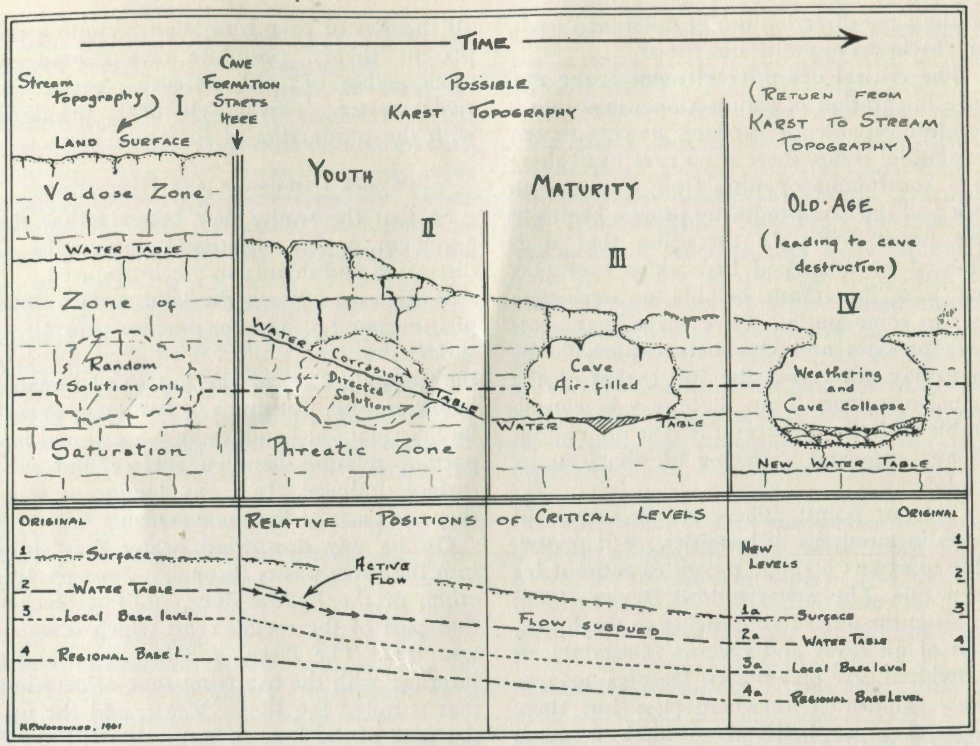

Figure I

In this figure, the cave location is shown at a constant horizontal position through four stages of development, each given Roman numerals. The first is the pre-cave stage of random solution in the phreatic zone and initial water entry in the vadose zones. The next stage (II) shows the steep gradient of the water table needed to accomplish corrasion and produce directed solution. In stage III the cave becomes air-filled, speleothems appear, and the cave grows old with roof collapse and rock fill in the final stage. Note in this representation that the critical levels descend through time as indicated in the lower third of the diagram. This descent is a genuine decrease of elevation with respect to the center of the terrestrial geoid.

stream areas. Even the regional base level will gradually drop but it descends slowly and must become stationary when it reaches sea level, the universal base level.

The picture here drawn shows four horizons or levels that are interrelated: the land surface, the water table, the local base level, and the regional base level. They do not maintain fixed elevations and the vertical intervals between them will vary through the time dimension. But in the normal geomorphic sequence the underground relations between these several horizons tend to become and remain graded or gradational, one level evenly descending to the next lower level (fig. 1).

Within this graded pattern, the water table is usually a movable level lying somewhere between the ground surface and the local base level; mostly it is being depressed as surface streams downcut their valleys. It fluctuates temporarily but rarely rises permanently. If it does rise, water will flood the lower part of the vadose zone; when it sinks parts of the phreatic zone are drained of water that saturated them.

The water table is not horizontal but is usually much more level than the land surface above it. Along the line or thalweg of any drainage system, the water table will slope gradually downstream and there will be a slow down-slope drift of underground

water near or along this horizon. Although this flow is gravity determined, its speed is so retarded by friction and rock density as to be very gradual in comparison with the velocities of surface drainage. Probably it customarily falls between a few feet of movement per day and a few inches of flow per year. This flow is laminar rather than closely channeled and there is normally no free-surface turbulent flow such as that of water sliding down an open inclined conduit.

In the inter-stream areas there may be local water-table fronts (steeper gradients) between minor territories controlled by different branches of a single drainage system or between headwater tributaries and the master stream. Little or no underground water shifts laterally down the slopes of these fronts from one basin to another, for underground divides keep the movement of water in essentially the same patterns as those of surface streams.

Yet a topographic situation may develop along a steep front between two nearby areas in which the act of stream piracy may suddenly divert water from one surface basin to the other. Such a situation rarely occurs in the lower or middle portions of a mature river system while it is common along the upper reaches, particularly near the margins of physiographic or topographic subprovinces. The situation is specially common in regions of folded strata and areas of trellis drainage, where a headwater tributary may extend parallel to and not far from its master stream although the two are flowing at discordant levels (and possibly in different directions).

Even here there is no cross flow along the water table from one basin to the other until piracy actually occurs, for there is a subsurface divide that separates the two water basins. Once the surface capture has taken place, however, and this is commonly a relatively sudden event, then the underground drainage from the upper level will be activated into swifter flow, and this is the trigger for cave genesis to occur.

These remarks can now be generalized into a few sentences. The local water table is a subdued reflection of the land surface which is controlled by a local base level that is a function of a regional base level. Mostly there are graded relations between these surfaces, one level sloping gradually toward another. Inasmuch as the flow of underground water is gravity controlled along surfaces that are not far from horizontal, water movement is slow and poorly channeled. If a sudden interference alters the graded relations of the several horizons, opportunity for rapid, even turbulent, movement along the water table results, in which case speleogenesis commences. If the interference is non-sudden but is gradational, then adjustments between the several horizons will take place slowly and no rapid underground flow will be brought into action.

A word is required at this point to explain what is meant by "sudden" as a requirement for the process under consideration. In the sense implied here, the word "sudden" connotes anything from an essentially instantaneous event (such as a landslide or avalanche that might occur within a few hours or days) to something that might extend as long as a few thousand years but still be essentially hasty in comparison with the length of geologic time. A good example of the latter is Niagara Falls, produced relatively suddenly by retreat of the southern margin of the Wisconsin glacier which opened thereby a simple downstream passageway to the Atlantic Ocean along what is now the St. Lawrence River.

Thus the trigger for the initiation of cave formation is some kind of swift acceleration of water at the water-table level. This can only occur as the result of a rapid dislocation of one part of the water table with respect to another part, or of one water table with respect to another water table. Such dislocation reflects a corresponding sudden dislocation of local base levels or of one base level with respect to another. In nearly every instance the event will first set in motion the diversion of surface water from one drainage basin to another or from a surface to a subsurface position. As these diversions are commonly described as stream piracy, the subjoined theory of cave formation is called the "Stream Piracy Theory." The production of caves, therefore, is directly tied in this theory to some type of surface interference

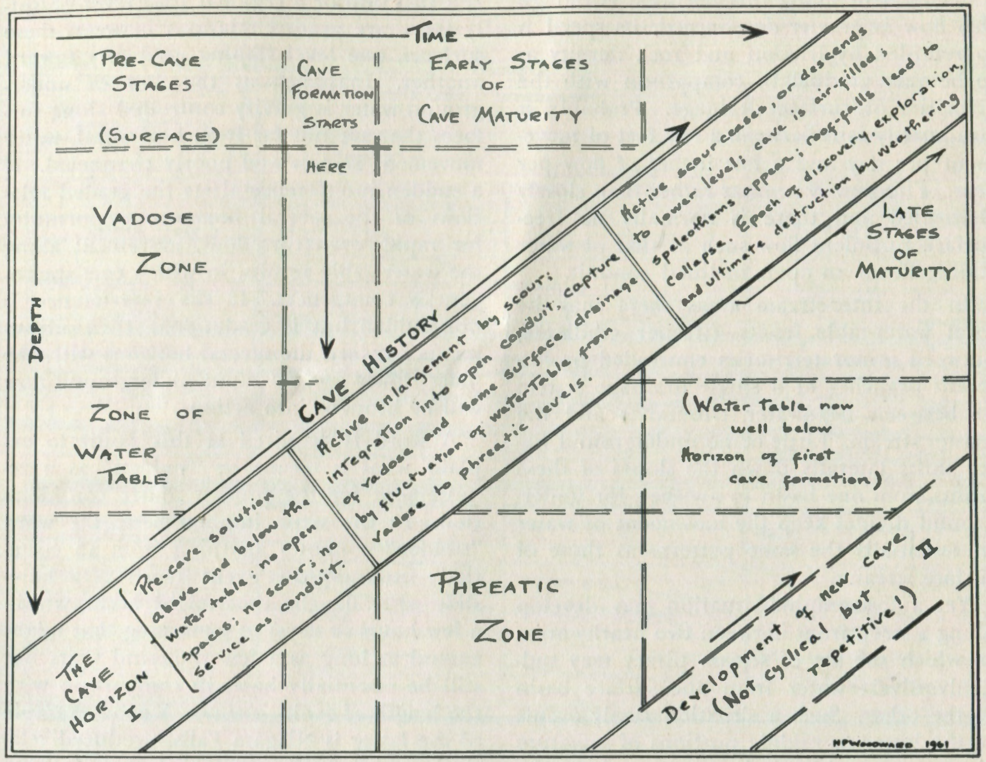

Figure 2

In this figure, the several water horizons or zones are shown in the horizontal plane, while the cave horizon is seen to ascend toward the ground surface as cave history proceeds in the central diagonal block of the diagram. Note that this representation equates the water levels of the initial stage with those of the later stages, whereas in fact they may be quite differently developed. Thus the water table at the right of the diagram may be that of an entirely different stream system from that of the pre-cave stages. Note the possible development in this diagram of a new cave system that is not at all cyclical, but rather is a repetition of speleogenesis in the new environment. For comparison with Figure I, tilt this diagram so that the central block becomes horizontal.

with the drainage pattern, and it is not believed that crustal "uplift" is an actual causative process in the development of more than a very few caves. Also, there is nothing cyclic or circular about the events in question (fig. 2).

All of this article so far has been preliminary and introductory, and the author hopes that the setting has been adequately laid so that the text can now move forward in defense of the main thesis. The next two sections deal with the characteristics of the cave-favorable environment and with cave features bearing upon cave formation. A short résumé of this and other theories follow, while the last two sections first describe the zonal characteristics of pre-cave solution levels (events just preceding speleogenesis), and finally the activation and completion of the cave-forming process.

Characteristics of the Cave-Favorable Environment

A locality containing caves must have certain characteristics that bear upon the presence of those caverns. For example, there must be soluble bedrock near or at the surface—preferably limestone, less appropriately dolomite, chalk or marl. The limestone must be dense and not texturally porous, otherwise water would ooze through it as through sandstone. It must be highly jointed and preferably thin bedded; probably it should have some dip or inclination rather than be precisely horizontal.

The size (width or length) of the limestone outcrop does not affect the size or number of caves; rather, its location with respect to the drainage pattern and particularly the elevation of its outcrop with respect to base level are important in cave history. It is wise to remember, too, that although the present location of the limestone outcrop affects the discovery and explorability of a cave, it is the favorability of the outcrop with respect to the original cave formation with which we are primarily concerned.

There must be sufficient rainfall to provide both flowing surface drainage and a residue that will sink into the vadose zone; rainfall should thus be moderate to abundant, preferably in an erratic pattern rather than steady precipitation the year round. Uneven rainfall induces fluctuations of the water table, a feature that assists—but does not alone produce—enlargement of joints and accessways along the water-table zone. Aridity does not favor cave formation; but a stage in the development of karst topography simulates arid conditions by channeling most surface water underground.

Topographically there must be deep surface valleys below uplands containing the soluble bedrock. For continued cave development there must either be rapid deepening or widening of these valleys or some corresponding change in relative position of the critical water levels—surface, water table, local base level and regional base level. Marginal rather than central locations with respect to topographic subprovinces are characteristics of most cave regions.

With a curious inversion of reasoning, Davies (1960) remarks that the abundance of caves and the occurrence of large caves along the headwaters of river basins result from the "stability" of those areas, while he attributes the absence of large or small caves in the lower reaches of river systems to the greater frequency of "geomorphic fluctuations."

The exact reverse, of course, is much more reasonable. It is along the headwaters of river systems where conditions are in flux, with down-cutting, shifting of divides, stream capture and diversion, valley widening, and possible "land uplift" being the rule rather than the exception. In the middle and lower reaches of a river system, both the surface and subsurface drainage have become graded and adjusted to conditions that change very slowly. In consequence, the geologic and physiographic factors that promote the development of caves are less common, even unlikely, along the middle and lower portions of the master drainage system. An exception to this generalization is the case of a mature river system that has become rejuvenated with old meanders now deeply incised below former erosion planes. But in the strict sense of the term, such a system is no longer mature, rather it is in a second stage of youth.

Gardner made (1935) and Davies has pursued (1960) the suggestion that a sequential relation can be established between cave levels and nearby stream terraces or erosion levels. This logical interrelation should be studied in terms of the regional geomorphology of any particular cave. For the theory being described in this article, such a relation is almost a necessity, as the process of cave formation is here linked to the dislocation of previously graded relations between surface, water table and base level, all of which are tied to sudden epochs of valley deepening or widening. Obviously the latter are factors in the development and incision of lateral stream terraces, so that cave levels should be related to particular stands of the base level, while such base-level positions may be reflected in the topography.

The relation of cave levels to stream terraces resembles the analogous relation of certain residual ore accumulations to terraces, a good example being the case of the so-called "Oriskany" limonite deposits that also occur in the Appalachian Valley and Ridge province. These ore deposits can be reliably found along the margins of incised valleys at horizons where a previous water table intersected the sandstone outcrop that now contains the limonite accumulations.

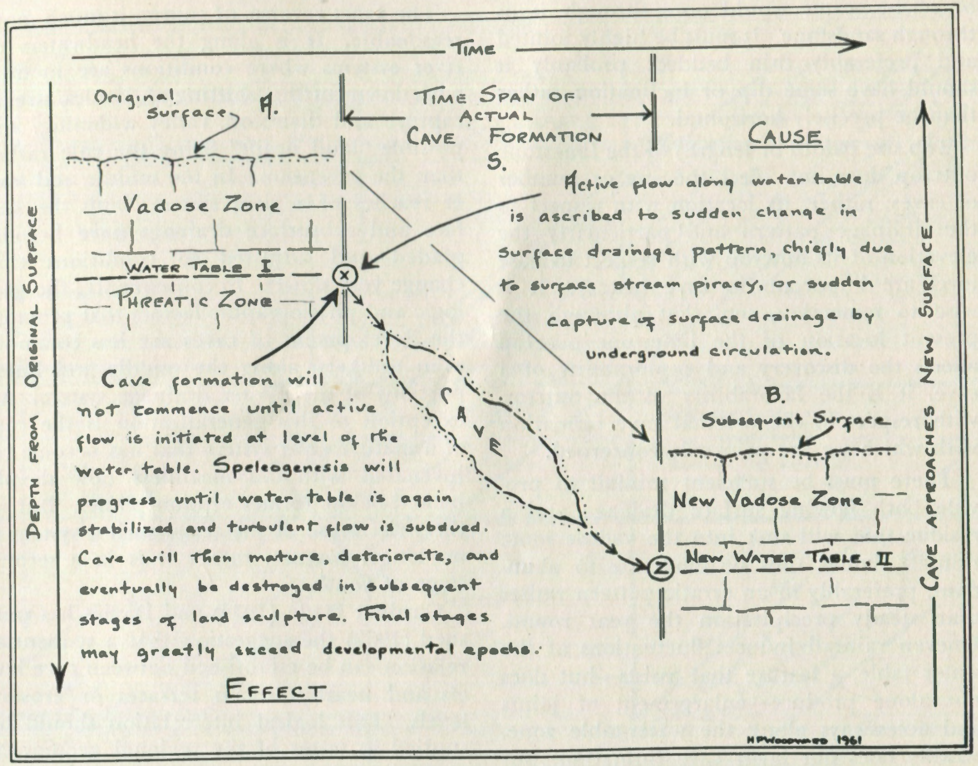

Figure 3

This figure not only orients the cave-favorable environment between the original land surface and its water horizons (A) and those following cave formations (B), but also locates the time span of the true speleogenetic process (S). The latter commences when the steep gradient between X and Z is created, and ends when the new water table (II) and its supporting levels have become graded and stable. The vertical arrow at the right indicates the approach of the cave toward and above the new ground surface, and represents what many previous authors have regarded as "uplift." The descending arrow at the left shows the direction pursued by speleogenesis in relation to the original land surface. The inclined central horizons represent the flow of kinetic energy. As indicated here the cave itself is a transient, non-permanent phenomenon to be eliminated as its horizon approaches and ultimately rises above the ultimate land surface.

No one has yet associated residual limonite deposits and the nearby limestone caves of the Valley and Ridge region, yet they are controlled by similar circumstances, namely the horizon of a former water table in the history of stream down-cutting.

It is important to affix clearly the nature of these interrelations. Both the cave levels and the ore deposits are associated with stream terraces, and there may be similar vertical intervals between a given set of terraces and the elevations of nearby cave levels and ore deposits. But the controlling factor in the production of all three features is a sudden renewed incision of the stream pattern after an epoch of lateral planation. This renewal can be blandly ascribed to "uplift," but more specifically it relates to a rapid drop in the local base level, and the ultimate cause of the latter must be traced to some sudden event in the progress of land drainage. Rarely, if ever, is crustal movement involved (fig. 3).

Two other observations may be noted. Most caves occur on the upstream (often updip) side of a deep river valley or canyon that descends below cave level; and more caves occur on the flanks of major geologic structures than on their crests.

Cave Features Bearing on Cave Formation

The pattern of cave passageways bears on the manner in which they were formed. Most caves are simple linear conduits leading surface water directly from an upper entrance to a lower exit; the majority are single-level openings having floors which slope gently down-grade. This essential horizontality may be masked by sedimentary debris and rock falls, or by local scouring and incidental deposition; but the level of most caves is an even profile closely corresponding in grade to the profiles of nearby surface streams.

Where the containing limestone is flat or only moderately inclined the course of the cave may be sinuous or irregular; if the rocks have steeper inclination the pattern is likely to be linear or angular. More complicated patterns are usually trellis-like, often with an evenly rectangular or reticulate spacing. Side passages and angular branches increase as the speleologist follows the cave headward from its termination, and these channels and accessways grow narrower and more inaccessible up from the lower ends of the cave. This has the effect of giving the cavern a candelabra-like pattern, not unlike—save for its angular aspect—the dendritic pattern of a surface stream.

Some caves are three-dimensional where the bedrock is horizontal or gently inclined and show multiple levels with passageways that lie above or below the mainway; here and there these are interconnected by various vertical or sloping ladders or ramps. In many such multilevel caves, analogy can be made with the cellular space lattice of a mineral crystal that may have a pseudo-cubic (rectangular) or monoclinal (inclined) arrangement. In a few caves this network is so indistinct or non-linear that the pattern is more spongelike than geometric.

Thus a simple classification of caves in terms of patterns may be developed as follows:

One-Level Caves	*Multilevel Caves*
A. Linear	C. Latticework
B. Rectangular, leading to reticulate	D. Spongework, leading to irregular

The linear extension of most caves is along joints, particularly strike joints, and save in regions of very low dip there is no conspicuous development along the rock dip. Indeed most openings that extend either up-dip or down-dip from the mainways pinch out or terminate in side fissures in a short distance. Even in zones of steep dip where one might expect ready delivery of water along bedding planes, there is small tendency for cave development to follow these planes from one level to another.

Narrow passageways are common in steeply dipping beds where the cross-section of the opening may be triangular due to the intersection of joints and the bedding. Correspondingly, rock horizontality often permits lateral expansion into wide chambers or rooms beneath competent ceiling beds or a structurally strong hanging wall. In vertical beds the ceiling may be correspondingly higher and narrower if there are variations in the solubility or resistance of portions of the bedrock. Where the latter is uniform, however, there is very little difference in the shape of chambers in flat or vertical beds.

As elsewhere noted, most caves have a horizontal profile at any point even though the bedrock may exhibit steep dips. It seems certain that this horizontality must be traced to a similarly horizontal original water table; hence the significance of the latter in cave formation becomes evident.

Almost all caves show evidence of both solution and scour, the latter term standing for abrasive processes involving free-flowing water. There is, of course, a sequential relation between these two processes, and it is clear both from the general restriction of caves to water-soluble limestone and from the evidence of intersecting solution and abrasion surfaces, that solution invariably antedates scour or corrasion. This does not exclude additional solution after a period of scour, but this is a second or even a tertiary epoch of solution.

From this evidence one must reason that the initial water entry into any accessway was effected by solution, to be followed at a later stage by corrasion. With fluctuations of the water table, solution may again take place if the water table is temporarily elevated so as to flood openways previously enlarged by flowing water and now subject to solution in standing or slowly circulating water. This alternation may occur several times, but the sequence is invariably started with solution followed by scour. Note that the sequence ends with neither but with ordinary rock weathering as the cave becomes air filled.

In the deeper portions of many cave systems, or in sections of the cave that were once at a deep level with respect to the original water table, there are wall recesses, tubes, ceiling pockets, and dead-end openings that cannot be attributed to any type of stream scour and must be entirely solution-formed. Some of these seem to be unrelated to joints, although some structural weakness must have localized their development. This type of speleogen is the result of long-continued solution and these are products of the pre-cave epoch that failed to become integrated after the true cave-forming process commenced. Although they have no prevailing orientation, most of them now point upward toward the original position of the water table at the time cave formation commenced, and they have escaped integration because water-flow is a gravity-controlled process leading toward an outlet, and these could not be so followed. In this aspect, at least, the solution accessways originally developed in the deep zone of saturation branch upward toward the old water table, much as the accessways in the vadose zone coalesce downward toward that level.

Almost every cave contains more or less rock debris transported by surface water flowing through the cave. As free-flowing streams cannot circulate through the cave until the mainways have become integrated into a continuous conduit from entrance (or entrances) to exit (or exits), the deposition of fill must follow stream scour and be a tertiary step in cave formation—(1) initial solution, followed by (2) scour, followed by (3) fill.

The source of sedimentary cave fill is the load carried by surface streams in suspension or rolled along by saltation. Thus the initial deposit will be fine silt introduced as the waters first enter a continuous channel. This will be followed by increasingly coarser material as the stream gathers strength and speed. Ultimately when the flow slackens off, the size of transported material will grow smaller and the last type of deposit will be fine silt and red clay representing the total burden of slow moving, almost stationary, water. The red clay (terra rossa) represents in-washed red soils common to most limestone outcrops in temperate latitudes that slip into the caves directly or are carried down by local floods and heavy rain wash.

As in a surface valley and perhaps even more frequently, the tempo of water flowing through the cave will change, and with lowering of the water table (base level) the cave stream may reverse its role of depositing debris and start to incise an inter-cave channel in material previously deposited. This process may be repeatedly changed, so that an alternation of interrupted deposition and channel cutting can generally be deciphered in the study of sedimentary cave deposits. In some passageways material previously deposited may be completely swept away; in others the entire opening can become packed roof-high with silt, sand and clay.

Roof collapse resulting in rock falls is usually a late stage in cave formation. Although it cannot be certainly inserted in the time schedule of developmental stages, it is more likely to occur when the cave is air-filled than water-filled. The ingenious possibility that earthquakes create simultaneous rock falls in nearby caves should be considered; but any evidence linking specific rock falls to particular earthquakes has not been advanced. Doubtless once the cave is air-filled the spalling of rocks from a cave roof is immensely assisted by weathering.

The pattern deposition of calcium from solution is also one of the late phases of cave development, for such features as stalactites and stalagmites can form only when there is open air-filled space. Their possible early counterpart—precipitation from solution in the pre-cave epoch or early cavern stages—are much less common, although crystal formation, distinct from amorphous deposition, can develop in standing or slowly moving water during a later stage of flooding. Minor vein-filling is possible in the pre-cave epoch.

Locale of Cave Formation \ Theories	Swinnerton 1929, '32	Davis 1930	Bretz 1938, '53	Davies 1957, '60	White 1960	Matson 1909	Malott 1937	Gardner 1935	Woodward 1934, '61
Vadose Zone	1	2	2	4	2 / 0	1	1	2	1
Zone of Water Table	2			2, 3	1				
Upper Phreatic Zone		0	0		X	0	X	1	
Lower Phreatic Zone	0	1	1, 1a	1	0	0	0		0
The Triggering or Activating Process	These theories require the enlargement of earlier solution channels formed during initial cave formation. All rely on uplift to activate cave formation. None ties Speleogenesis to surface streams.					These theories involve capture of surface waters by vadose flow into solution channels. Woodward specifies such sudden diversion and capture as primary cause of cave formation.			
Legend	1, 2, 3, 4 = Stages or cycles; Blank does not specify; X specifies cave solution here; 0 excludes such								

H. P. Woodward 1961

Figure 4
Various theories of cave formation arranged for comparison and contrast. This figure shows one interpretation and the relation of the present theory to its predecessors.

Theories of Cave Formation (Speleogenesis)

A good many theories have been offered for the process of cave formation, mostly dealing with the place of origin and the number of stages or "cycles." Most assume the ultimate causative process to be land uplift (figure 4). Four types may be selected as having certain essential differences; the present theory is outlined as the fifth type.

1. *Early Theories, relying upon vadose water.*

   As a type example, one may mention the theory of Matson (1909) who held that all caves are formed in the vadose zone by the action of surface water diverted into solution channels previously developed by descending vadose water. He did not postulate any major circulation or cave formation at or below the water table.

2. *The "Two-Cycle" theories of Grund (1903), Davis (1930), and Bretz (1938, 1942).*

   These theories attribute cave formation to an initial cycle (epoch) of deep solution under hydrostatic head below a peneplane or a mature landscape. There is a second cycle (epoch, stage) resulting from uplift that permits enlargement and occupancy by vadose or surface waters. Bretz adds a subsidiary phase involving the deposition of red clay as the last event of the first epoch (cycle).

3. *The Water Table theories of Swinnerton (1929), 1932), Davies (1960) and White (1960).*

   These theories restrict cave formation to a relatively narrow horizon at or just below the water table along which laterally flowing turbulent streams of water provide an agent for either solution or abrasion. Swinnerton implies an initial development of solution channels in the vadose zone and discounts cave formation in the deeper phreatic zone. Davies reverses this and suggests initial random solution in the deep phreatic zone with ultimate uplift and cave destruction in the vadose zone. White sees no evidence for solution channels in either the vadose or deep phreatic zones and believes caves represent a subterranean drainage net with streams flowing along the water table having finite velocities. He likewise relies on uplift to provide a later stage of enlargement, fill removal, and destruction.

4. *The Invasion Theories of Gardner (1935) and Malott (1937)*

These theories recreate with modifications the older ideas typified by Matson's diversion of surface waters into solution channels. Malott believes that all caves are formed in the vadose zone by the invasion of surface drainage into an underground solution network developed above the water table. He thinks there may be slight circulation and/or solution below the water table but it is not critical to his theory. Gardner assumes that static underground water in an elevated phreatic zone is activated into movement downdip by valley widening or deepening that permits surface escape of trapped water. When the latter has drained out, it is replaced by vadose water and subsequently by surface water diverted underground. He accepts some quiet solution along saturated joints but regards the main action as a gravity flow down dip.

5. *The Stream Piracy Theory of Woodward (1936, 1959, 1961)*

A. A cave is here considered to be an underground conduit capable of carrying flowing water from a higher surface entrance to a lower exit. In another sense it is a maturely integrated system of openings in calcareous bedrock initially developed from a pre-existing network of solution accessways that are enlarged and coordinated by various processes.

B. In any cave-favorable area, there must be a pre-cave epoch of solution wherein a non-integrated system of fissures, crevices, or other accessways is established (a) by semi-selective solution of water descending through the vadose zone and (b) by random solution in the slow drift of water through the totally saturated phreatic zone. This preliminary epoch of solution is distinct from, but a necessary prerequisite for, the subsequent process of cave formation.

C. Lateral flow at the water table is usually very slow, and cave formation does not commence until there is active turbulent flow at this level. Almost all previous authors regard this change of status as the result of "uplift," whereas it should properly be assigned to the sudden creation of a discordance between two nearby local base levels or between a local base level and a regional base level. The critical element is abruptness and the process is interference with a previously graded stream system.

D. Geologic events qualified to provide such sudden change include the sudden penetration of a barrier or retaining wall; a rapid increase in runoff or sink-in due to climatic changes, stream rearrangements, or ice melting; and in rarer instances, accelerated stream incision resulting from local sudden diversions of surface drainage. An important factor commonly disregarded is the relatively sudden fall or rise of sea level, the universal base level. All develop surface conditions of stream piracy and drainage diversion.

E. The sudden increase of flow at the water table activates capture of surface water by its diversion into the vadose zone, while the new turbulence along the water table initiates an epoch of rapid fissure or channel enlargement by directed flow rather than laminar drift.

F. Climatic or seasonal fluctuations of the water table will bring the horizon of lateral cave enlargement either up into the lower vadose zone or down into the upper phreatic zone, in either instance modifying and incorporating pre-cave solution networks already present.

G. As the entire process is part of the drainage of the area and therefore constitutes an operation moving downward toward regional base level, in time the horizon of cave development may descend through rocks previously well below the original water table, while higher levels will be evacuated, may partially collapse, or will be destroyed by erosion. Deposition and erosion of fill; rock falls; and the deposition of speleothems are common phases of cave development as the water table drops below zones of earlier enlargement. Note also the introduction of weathering as an enlarging agent.

H. The process will cease and cave destruction will commence when quiet flow is restored and maintained at a new water table. By this time the drainage system (both surface and underground) will have resumed or attained a new graded profile, and the cave system will be largely air-filled, only on occasion channeling drainage from a higher surface level to a lower surface exit.

Note that the theory presented here draws upon all of the older theories but coordinates their features, in its author's opinion, in a more logical and sequential pattern. Emphasis is placed, as by Swinnerton, Davies, and White, upon flowing water at the water-table level for solution, enlargement, and selection (integration) of accessways transformed into cave openings. Everything prior to this directed flow at the water table is stripped from actual speleogenesis as also postulated by Davies. Diversion (invasion) of surface waters through capture is assumed in much the same fashion as conceived by Matson, Malott, and Gardner. Pre-cave solution both in the vadose and deeper phreatic zones is called upon, somewhat as described by Davis, Bretz, Davies, and Gardner, although it is not regarded as a "cycle" or phase of cave formation as considered by some of them. Stages of cave destruction in the vadose zone are similar to those of Davies and White.

The essential point of difference between the stream piracy theory and its predecessors is the insistence that activation of swift circulation at the water table must itself come from a sudden event which is reflected below ground from a rapid dislocation of surface drainage. Plus, of course, a denial that "uplift" *per se* has any proven genetic relation to any particular cave.

There are two other points of divergence. One is the author's belief that a cave is a "normal" feature of land drainage in the same category as a lake or waterfall; it is formed and is ultimately destroyed as a transitory feature of land drainage. The other point is that for any particular cave, there is a specific relation with a particular surface stream, and that with careful study the underground feature can be tied into the surface system by which the area has been or is being drained. In other words, like a lake or a waterfall, a cave is part of a particular drainage line.

Zonal Characteristics of Pre-Cave Solution Levels

By definition a cave is a maturely integrated system of solution openings (Davies, 1960). This concept predicates a pre-existing series or network of non-integrated or random solution openings that precede or antedate the epoch of cave formation. Although clearly contributory to the later development of caves and caverns they constitute nevertheless a separate and independent activity of underground water. Not until some continuous line of passage has been selected and enlarged by the directed turbulent flow of swift-moving water through such a pre-existing solution network, does a cave develop or the true process of speleogenesis commence.

It is plain that this pre-cave solution network erects a sort of inverted scaffolding within which the cave itself may ultimately be constructed. Thus the actual process of cave formation may inherit patterns, trends, and traits that were cultivated or initiated in the pre-cave period. Indeed, unless some such characteristics are then initiated, there may be no subsequent cave.

There are two zones in which this pre-cave solution takes place, the vadose zone above the water table, and the phreatic zone below the water table. These zones are gradational at the level of the water table as the latter fluctuates up and down with changes in rainfall, sink-in, and base level. This fluctuation may amount to several tens of feet; hence one could designate a third, or intermediate, zone in which pre-cave solution may occur—the vadose zone, an intermediate water-table zone, and the phreatic zone. By some writers, the intermediate zone is regarded as a "shallow phreatic" zone in contrast to the deeper phreatic zone.

It should also be noted that in terms of geologic time these three zones may shift up or down in a pattern controlled by such external factors as the down-cutting or rearrangement of the surface drainage system or any sudden alteration of the vertical differences between the several water or base levels. In the next-following discussion, however, the three zones will be described in terms of an essentially stationary pattern, in which the only fluctuation is that of the water table.

Water entering the ground moves downward until it reaches the water table or is impeded by some impermeable barrier. In rocks that contain voids or interstices like those of a sandstone, the downward movement takes advantage of a textural porosity of the rock. In massive tightly compacted rocks, the water can move only along fractures, joints, or other separable surfaces inherent to the type of rock or transmitted to it by tension and strain. If the rock is not only dense and massive but also soluble, original or acquired lines of water circulation will be opened and enlarged by solution. After the latter has occurred and there is opportunity for swifter flow as the surface water descends, the possibility of corrasion or abrasion by friction should be considered in the vadose zone.

This downward flow of water through the vadose zone is controlled by gravity, so that seepages along hundreds of tiny joints and channels near the surface tend to coalesce downward as the water gets farther away (deeper) from the actual surface where relief of pressure and processes of weathering will have provided more joints and openings than at depth. Hence vadose circulation channels will funnel downward from an upper highly branching pattern to a more selective or less complicated pattern below.

Openings followed by vadose water will always descend and many will end downward by horizontal shift to another down-leading channel. There can be no development of dead-end channels leading upward, for the flow-energy is controlled by gravity. Soil or fine earth in suspension may be carried downward to block some lines of travel; but the water will carry little material in solution and any mineral deposition in the vadose zone is rare during the pre-cave epoch.

As indicated elsewhere in this article, unless activated by some special sudden event, water movement along the water table is very slow, perhaps only a few feet per day or month as a lateral laminar flow or seepage along the thalweg of the water table. This rate is far slower than the downward water passage through the vadose zone and there should be more genuine opportunity for solution along the water table than in the overlying vadose zone. On the other hand, as the slow circulation along the water table will already carry some mineral material previously dissolved from its vadose passage, this load may retard—perhaps even prevent—any additional solvent action along the water table.

Doubtless there is also an interface near the water table between processes of oxidation and reduction, as well as between aeration and saturation. The presence of carbonic or organic acids near this interface should not be discounted as other agents adding solvent power to water circulation at this horizon. While the precise sum of these positive and negative factors is not yet known, there is no doubt that the water-table level is a critical horizon in speleogenesis, being the site of early solution in the pre-cave period, and of erosive scour once water movement has become accelerated.

The entire environment in the phreatic zone is water-saturated save for impermeable, wholly non-porous, islands. There also is a slow down-grade water migration that is also gravity controlled, but there is little or no selectivity of one channel in preference to another. Solution of water-soluble rock will take place slowly and may be directed upward as well as laterally or downward. As the flow is extremely slow, water molecules will stay longer near any given point and will thus have longer solution opportunity; but once saturated they will cease to promote solution and the process will slow to a halt.

Solution in the deep phreatic zone is essentially controlled by differences in the permeability and solubility of the bedrock and results in simple widening of joints and fracture planes. There is no active flow, usually no high hydrostatic head, no abrasion and corrasion, and no possibility of enlargement into open or air-filled cavities. There is no indication or evidence, in the writer's opinion, of the systematic development of connected openings by solution in the deep phreatic zone. On the other hand, of course, the random enlargement of joints, bedding planes, and other surfaces into a solution network or spongework is a preliminary stage favorable for cave development if the necessary triggering action is accomplished to initiate the process.

To summarize the zonal characteristics of pre-cave solution:

Vadose Zone: Enlargement of joint and fracture surfaces by down-seeping surface water; network pattern converges downward or branches upward; no dead-end upward passages; no deposition from solution; small erosion if any.

Zone of Water Table: Possible solution along horizontal plane by slow-moving water; no upward or downward development; solution possibly enhanced along interface between aeration and solution and between oxidation and reduction.

Phreatic Zone: Random non-selective solution by slowly drifting water in completely saturated environment; no corrasion or erosion, but minor deposition from solution is possible; upward dead-end solution pipes are possible; network or spongework should branch upward toward old water table.

Activation of the Cave-Forming Process

The essential requirements for cave production can be reduced to a simple model that becomes activated by an appropriate event. The basic situation is (A) an upper drainage system or intake area; (B) a lower drainage system or outlet area; and (C) an intermediate limestone basement as indicated in the accompanying sketch (fig. 5).

YZ is the vertical distance between the two systems; the lateral or horizontal dis-

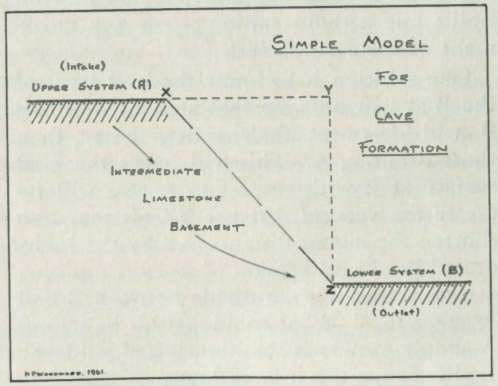

Figure 5
Simple geometric model for cave formation.

tance is XY. A and B may be different streams or different parts of the same river system; the chief requirements are that they are close together and that there is no direct present surface or subsurface flow between them. For effective results, the vertical distance (YZ) might be several hundred feet; the lateral distance (XY) might be a few miles.

Any geologic event or process that can create or increase the vertical distance YZ or, if YZ remains constant, can shorten the horizontal distance XY, is favorable to cave formation. This is because either change increases the gradient (XZ) between the water tables of the two systems, and this in turn will activate underground flow at the water-table level from the upper system (intake) to the lower system (outlet).

As the required change could be caused by the actual uplift of A with respect to B, or by the sinking of B with respect to A, almost all speleologists have assumed that such land movement genuinely occurs. The present writer regards this as far from the truth, for he is at a loss to explain any isostatic or other up-and-down crustal movement on a small enough and localized scale actually to cause such uplift or submergence. Thus he believes the causing process must be sought among those events that will give the effects of land uplift without creating any actual vertical movement of the bedrock. If this is true, we should next consider what will alter the above diagram in the same fashion as land uplift but without calling upon any movement of the earth's crust.

One solution is to lower the base level of the B system only, so that streams draining B will down-cut their valleys faster than those draining A. This will lower the land surface at B with respect to A and will increase the vertical distance YZ. It may also shorten the lateral distance XY by the invigorated headward erosion of streams draining across B, pushing the divide between B and A closer to A. What could set this in action? A simple answer is the lowering of sea level. I will pursue this a little later.

Supposing there is a perched water table under A, held up by an impervious layer that intersects the sloping surface between A and B. If this layer is cut by a rejuvenated stream of the B system, the perched water may escape into B drainage by simple gravity flow, evacuating the vadose area under A and inducing surface water from the A level also to channel underground to the B level. This process will be an underground capture of A by B, or the subterranean diversion of water from the higher to the lower system. Active flow will be encouraged at the water table with opportunity for solution and scour. A cave system may thus be initiated that will continue to develop so long as the model remains without change. Let's call this situation Type I in which speleogenesis is activated from below by the discovery of a lower outlet from which vadose and other water can pour out. In essence, this is the situation envisioned by Gardner (1935).

Now suppose a slightly different situation. The headward-moving streams tributary to B manage to push back and down-cut the actual surface divide that separates them from the less active (higher but slower) streams on the A surface. There may come a point when some of the A streams are diverted into the vigorous B tributaries, and an actual stream capture or example of surface piracy takes place. Surface drainage from A will now flow directly to the B level across the shortest possible direction.

But whereas the A water table was a function of A drainage before the capture, it must now adjust to the lower levels of the B system. This will suddenly give it a steep gradient along which active water flow may take place underground. Such directed movement likewise provides opportunity for scour and channeled solution, and a cave system may start without having any overt surface intake or actual open outlet. This might be called Type II. Later, however, surface-connected accessways may draw surface water into the maturing underground conduit and ultimately the cave system will closely resemble Type I.

Perhaps the barrier holding the perched water table is not cut until after stream capture (leading to Type II) has taken place at

the surface, so that the exposure of an open outlet (as in Type I) takes place while the Type II process is in operation. In this case the two types of cave formation may progress apace with one another, or may coalesce in the ultimate production of a more complex cavern system.

Still another type is possible. An increased volume of water in the A system or a favorable rearrangement of surface drainage lines on the upper surface may magnify the volume of intake and/or enable surface waters faster to enter the vadose zone of the A surface. If this should take place after capture has occurred, or at a favorable point in imminent piracy, a cave system can be initiated or encouraged simply by volume increase at the intake end of the conduit (Type III).

The present theory, therefore, contemplates three types of cave systems (I) initiated by the sudden discovery of a new outlet; (II) created by a sudden steepening of the water-table slope; and (III) activated by a sudden increase in water volume at the intake, plus, of course, composite and transitional varieties in which one or more types may be combined. It is believed that all caves will be found to fit into one or the other of these simple categories, each of which is associated with some type of stream diversion—either the underground capture of surface water, or the shift of surface drainage from one basin to another. The small diagram shown above explains the setting; only some triggering event is required. Further consideration is now in order of geologic processes that might have this ability.

I return to the matter of a lowered sea level. It is now well known that the surface of the ocean was greatly depressed during the period of Pleistocene continental glaciers. A calculation that sea level may then have been 300 to 400 feet lower than its present stand is generally accepted as reasonable. Such a depression of sea level would lower the regional base level everywhere, and in such coastal regions as California or Dalmatia; on peninsular regions such as Florida or Yucatan; or on islands like Okinawa or Bermuda, what had previously been phreatic zones well below the water table would then stand far above base level. Thus phreatic water would drain down and outward by gravity flow, to be replaced by vadose and ultimately surface water. Cave formation would commence and would continue as long as the situation remained without major change. The process would be the capture of surface drainage by the development of a hitherto concealed outlet; and in terms of geologic time this would have been a sudden development.

Also as already explained above, streams entering the ocean would be suddenly invigorated because of the added vertical differential between local and regional base levels, and there would be headward erosion, deeper incision and faster rivalry between tributaries for control of local basins. Surface piracy, the beheading of a sluggish tributary by an active rival and other types of interbasinal drainage exchange would ensue. These in turn would introduce steep water-table gradients between adjacent basins, and if the difference in elevation was sufficient, would make possible the development of caves of Type II. The process would be halted, of course, if a return of ice melt should restore sea level to a higher or its original stand.

It is suggested that caves in the specific areas noted above are related to the Pleistocene depression of sea level. The latest such lowering has been eradicated by the return of ice-locked water; but there may have been several such epochs in the million years of the Pleistocene. Some of the caves previously formed are at levels now flooded by sea or fresh water depending upon local circumstances. Further cave formation has largely halted and cave destruction is retarded because of flooding. In other instances where cave formation occurred high above sea level, it may still be taking place under somewhat subdued conditions.

There is, I think, no merit in repeating the sequence of cave-forming events that occurs when a barrier retaining a perched water table is penetrated, but it should be noted that something of the same kind of event can take place by the narrowing of two incised loops or meander curves of a stream, in which water from an upper river level may find access through the intervening wall as the two curves approach one another by lateral erosion. Examples of underground drainage diversion by this method are common in many limestone regions, although there should be a marked vertical differential for much development of channeled openings.

How about continental glaciation itself, particularly the retreat of the ice margin? The latter will uncover valleys previously graded and adjusted but recently ice-grooved and perhaps now blocked with moraine or drift. There will be a great volume of excess water to be carried away; stream rearrangement is certain; and the ice margin may serve as a temporary dam for one stream and a valley wall for another. Innumerable temporary and permanent stream captures or diversions will take place, and drainage rearrangements of many kinds will occur. These will inevitably create discrepancies in the relations of surface, water table, and base levels, and water flow will surely be initiated along portions of the water table. Piracy, stream capture, and sudden drainage diversion multiply in such conditions and cave formations should be an outcome. As elsewhere suggested, following the melting of Pleistocene land glaciers there has actually been a crustal rebound of the previously weighted land surface in some areas, a factor that could supply actual crustal uplift as often postulated by speleologists.

A similar stream invigoration could occur with a sudden shift of climatic zones or of rainfall, bringing changes in the volume of surface waters or affecting the proportion of run-off and sink-in. Stream incision is possible under these conditions with its concurrent effect on the slopes of the water table. If sufficient this flow will tap vadose zones and ultimately surface drainage, with diversion or piracy as a concomitant effect if not the initial trigger of cave formation.

Suppose a limestone basement has been previously concealed from active stream erosion by thick soil or glacial debris not yet scoured off. Or is located on a plateau covered by a lava flow about to be cut through by valleys. Or occupies a position not breached by stream erosion until some particular event takes place or a particular erosional stage occurs. The previously concealed limestone is then suddenly uncovered by erosion as streams commence to cut into it. The former water table will be lowered, and phreatic water from the nearby uplands will drain out. Or the ingress of stream water into the limestone may be encouraged if the water table below the limestone is controlled by a base level lower than that of the incising stream. Again the process starts either with the outflow of phreatic water into the stream or the inflow of stream water underground, both processes resulting in the shifting of drainage from one basin or position to another in some type of piracy or subterranean diversion.

The descent of an avalanche, an outpouring of lava from a volcanic cone, a surface-rending earthquake, may each create a local point of stream diversion from one basin to another, and in each case—if other circumstances are favorable—may result in sudden activation of water flow at water table level.

It is not necessary to list every possible agent or process favoring cave formation; but it must be plain that they all have several factors in common:

1. In the geologic sense, they are sudden rather than gradual processes.
2. Their primary effect is to increase the effective gradient between two adjacent drainage systems.
3. This is accomplished either by invigorated surface erosion; by stream rearrangement; or by the sudden introduction of elements not previously present that themselves do one or the other of these things.
4. One of two factors is invariably present: drainage shift from one surface basin to another, or the diversion of surface flowing water underground.
5. Each of the latter is competent to activate a sudden down-grade flow at the level of the water table. Once this has been initiated, speleogenesis commences.

Finally the process halts and the cave grows old. Why? In the case of the Florida or Bermuda caves it is because sea level returned to its former stand and the cave environment became flooded. In most other cases it is because the local base level has again become graded with respect to the regional base level; the water table has been depressed to the point of essential horizontality and there is no longer any rush of water through the underground conduit. Surface streams have established surface courses, and the underground channels are drained save for local and spasmodic invasion in time of flood.

In some instances a stream may adopt an underground passage and incorporate it in its course, in which instance the several stages in roof collapse may first produce a natural tunnel, later a natural bridge, and finally a steep-sided limestone gorge to be widened and ultimately brought to maturity by erosion and weathering.

In time the water table will drop below early cave horizons and there may be secondary cave development at levels well underneath the original mainways. But these will be *new* caves dependent upon the development of different streams or upon the different development of the same stream. Although the cave-forming process may continue at the new, lower, levels, this is not *cyclic* in any sense. Rather it is repetitive, while the former caves, now high and dry, will ultimately collapse, be filled with deposits and fill, and will ultimately disappear as such.

A lake is the ponding of stream water behind a dam. Ultimately the dam gives way and the lake drains out, whereupon the stream continues the valley deepening temporarily halted. A resistant ledge or hard rock layer crossing a valley will retard erosion while it is being undermined at softer levels. A stream cascades over this ledge in falls that may grow in height as the base level of the stream below the falls descends. Ultimately, however, the stream cuts into the ledge, and the lip of the fall moves headward until either the hard layer is entirely cut through, or the declivity has been brought to a smooth gradient. In time the falls will disappear.

Caves belong in the same category—transient features connected with the flow of surface drainage. Ultimately the reasons for their existence disappear and they become subject to destructive erosion and weathering. Finally no trace is left save what can be deciphered from the physiography of the region.* But the reasons for cave development are not obscure, and each cave can be traced to a series of circumstances involving a particular stream — either the one now flowing through it or one that occupied it in a previous stage.

If tomorrow's caves are today being formed along concealed water tables deep below ground, far above in caverns measurable by man, the speleologist should be able to establish a relation between old cave systems and particular drainage patterns, and his new discoveries should add fundamentally to our knowledge of caves and their causes. But I do not think these discoveries will carry the cave far from the process of stream piracy as its ultimate causative factor.

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Particular mention should be made of the excellent symposium on the "Origin of Limestone Caves" in Vol. 22, Part I, of the Bulletin of the National Speleological Society, published January 1960.

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*Although it is a matter for another report, the writer can point to a number of stream gorges or deep channels in the Appalachian region where there is now no cave but where one must once have been. An interesting example is the deep course of South Branch of South Fork of Potomac River near Upper Tract, Pendleton County, West Virginia, where a former underground diversion carried the stream from a high-level valley to one at a much lower local base level. The resulting collapse and destruction of the former cave is now complete, and only the deep gorge known as "Smoke Hole" and one or two side passages are left to show the position and dimensions of the original underground capture and the cave (or caves) it created.

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The Collembola of Hunters Cave

by KENNETH A. CHRISTIANSEN

With a Preliminary Study of the Microarthropod Ecology of Hunters Cave

by K. CHRISTIANSEN, MARY WILLSON AND JERRY TECKLIN

Abstract—Two new species of Collembola have been described from Hunters Cave, northeastern Iowa. The new Species *Onychiurus reluctus* and *Oncopodura iowae* also occur in other caves in the Maquoketa region of Iowa.

In Hunters Cave collembolan fauna is sharply affected by linear distance from the cave mouth, and the fauna is apparently divided into two groups. Within the cave, distribution of both categories and of all cave microarthropods is widespread but spotty and sparse. The distribution of forms appears to be unaffected by air moisture or temperature variations within the cave, but is greatly affected by, but not entirely limited nor determined by, a conjunction of at least 3 optimal conditions of soil moisture, particle size, and organic content. Of these the last appears to be most restrictive since it is found in optimal concentration very rarely in the cave, while the others are normally in acceptable conditions; however, suitable organic content is totally ineffective by itself. The number of exceptions found indicate that additional factors exert some influences in distribution and abundance of these animals, but the number of these exceptions is so small that it is likely that only a few additional factors play any significant role.

In the winter of 1958-59 a group of speleologists from Iowa City, Davenport, and Grinnell, Iowa, initiated a detailed survey of the physical conditions and fauna of Hunters Cave. The cave is located northeast of Maquoketa in the Galena Limestone (Ordovician), which is prevalent in the Kansan Drift area of northeastern Iowa. At the base of the entrance, a ten foot vertical drop in a sink hole, a passage continues south into the main room of the cave, which measures 120 feet long, 60 feet wide, and 15 feet high and contains considerable breakdown on all sides (fig. 1). To the right of the entrance room is a long wide room, only 2 feet high. To the left of the main room is a series of interconnecting passages, including the "Paradise Room." This room or series of rooms contains the best speleothems of the cave (calcium carbonate stalactites and soda straws); few speleothems remain in the rest of the cave because of vandalism. Across from the entrance of the main room is an area called the "Pit Room" which connects with the section of the cave referred to as the "Maze" (a series of interconnecting passages, mostly crawlways). The "Pit Room" measures 40 feet long, 50 feet wide, and 30 feet high, resembling a huge drain. A passage between the Main Room and the Pit Room leads to the jumpoff spot leading to the canyon area. The actual entrance to the canyon is through a corkscrew and a 15 foot drop. The canyon measures 40 feet long, 20 feet wide, and 40 feet high. Beyond the canyon the passage continues to several silted rooms after which it is blocked. Silting in the cave seems to be rather rapid and in a short period of time, perhaps 10 to 20 years, considerable changes have been made in the traversable area.

The survey of Hunters Cave was started in June, 1959, and at present the physical data is fairly complete, but in biological

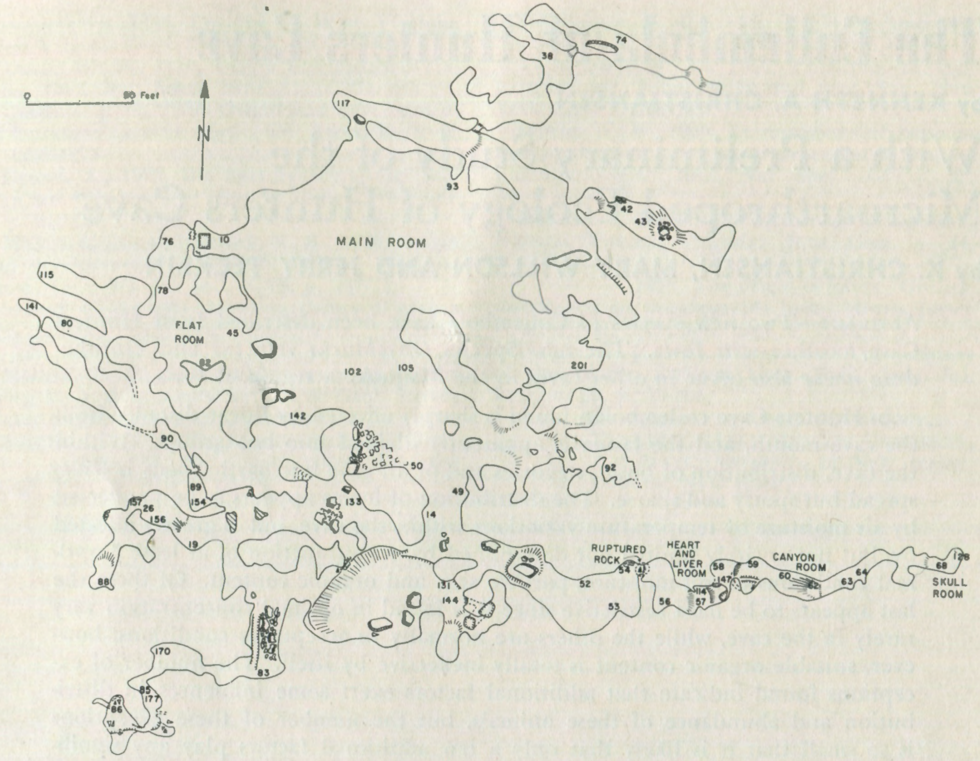

Figure I
Map of Hunters Cave prepared by Hedges, Darland et al showing location of collecting sites.

studies only the collembolan fauna has been investigated in detail.

The physical conditions of the cave are uniform. The temperature fluctuates in time and location between 43° and 54° F. with the majority of readings between 47° and 50°. The average temperatures are somewhat higher in the winter than in the summer and certain areas have persistently higher temperatures. Relative humidity is virtually constant at 99% with no areas below 95%. The cave fill varies from clay to sand with loam; flowstone is common.

Many different animals are found within Hunters Cave, but the majority of these can be classified as accidentals or trogloxene forms. Of the apparently troglophile or troglobite animals only two types are abundant: the collembola and mites. Animals were captured from the cave and in the soil around the cave mouth manually and by aspiration. In addition, flotation and Tullgren funnel extraction methods were employed; over three hundred samples were analyzed by using these methods. The mites have not been analyzed, but the collembolan fauna has been studied in detail. Eight species of this fauna are true cave inhabitants with an additional four species occurring occasionally in the leaf mold at the bottom of the entrance pit. Of the species within the cave, six are troglophile forms and three troglobite; the latter include two species new to science. Soil from the epigean vicinity of the cave mouth yielded 23 species including 5 of the troglophile forms mentioned above. It is interesting to note that more than half of the species found commonly in the soil around the cave have never been found, even as accidentals, inside the cave in spite of the fact that the first portion of the cave consists of a shallow pit with rich

deposits of leaf mold at the bottom. The indication is that some physical or biotic factor of the cave structure is an extremely pervasive barrier, which repels or destroys normal epigeic forms.

The species found outside the cave, but not yet found within the cave, are as follows: *Folsomia elongata, Tetracanthella sp., Friesea claviseta, Peudachorutes subcrassus, Onychiurus armatus* gr., *O. subtenuis, Isotoma trispinata, Isotomodes productus, Anurida tullbergi, Entomobryoides purpurascens, Orchesella ainsliei, Neelides minutus, Sminthurinus sp.,* and *Sphaeridia pumilis.* The four species which are found in the surrounding soil and leaf mold near the cave entrance are: *Folsomides americanus, Hypogastrura armatus* gr., *Isotoma viridis,* and *Dicyrtoma sp.* Of these only the first mentioned is found more than a foot away from the entrance pit. The six troglophile species are: *Tullbergia granulata, T. iownsis, Isotoma notabilis, Arrhopalites caeca, Tomocerus flavescens,* and *Megalothorax minimus.* All of these except the last named are also found outside the cave in the immediate vicinity; however, the relative abundance of the species occurring in the two conditions is quite different in each case. *Megalothorax* poses a very interesting problem since it appears to be replaced outside the cave by the genus *Neelides.* It is possible that *Megalothorax* actually represents a troglobite species, but the morphology is so similar to that of the normal epigeic form that it is impossible to separate them at present. The three troglobite species are: *Onychiurus obesus, Onychiurus reluctus* (n. sp.) and *Oncopodura iowae* (n. sp.).

Onychiurus obesus has been reported outside of caves, but, since this collection was from a rich cave region and further epigeic records are lacking, it is very likely that it is a true troglobite. It is of considerable interest that although two species of *Onychiurus* also occur in the neighboring soil, neither has yet been found within the cave.

Systematic Descriptions

Both of the new species found in Hunters Cave are also found in other caves in the Maquoketa region and may be widespread throughout the midwest. Descriptions of the two new species follow.

Onychiurus reluctus n. sp.
(fig. 2, nos. 1-4)

The integument is coarsely granulate with scattered patches of finer granulation upon the tergites and antennae. The coarse granulations are noticeably heavier upon the head, antennae, first thoracic tergite, lateral portions of the second and third thoracic tergites, and the posterior margin of the sixth abdominal segment. The antennae are somewhat unusual in shape with a marked constriction between the second and third segments, the second having a striking contrast in the granulation in this region (no. 2). The fourth segment has no apical bulb and bears numerous trauncate setae on the ventral surface. The post antennal organ consists of 14 highly branched papillae in a deep groove. The chaetotaxy and dorsal pseudocelli are as shown in numbers 1 and 2. The apical organ of the third antennal segment consists of two smooth basally curved oval organs with bifurcate margins as is typical of the *O. ambulans* group. These structures lie behind six granulate subequal guard pappillae. The anal horns are slightly curved, without striking papillae, and about half as long as the hind unguis. The unguis has an extremely minute internal second tooth. The Empodial appendage lacks a basal lamella, but has a small basal swelling. It is about as long as the unguis and has a distinct apical filament. The male lacks a ventral organ. The anterior pseudocelli upon the abdomen are unridged and under high magnification they can be seen to have a very finely granulate surface.

This well-marked species is clearly related to the *ambulans* group, but is readily distinguished by its peculiar pseudocellar conformation. On a number of segments, the number of pseudocelli varies, which is indicated by parentheses showing other conditions which are common. In addition to this it should be noted that the anterior abdominal pseudocelli are doubtful structures since they have a granulate surface; however, un-

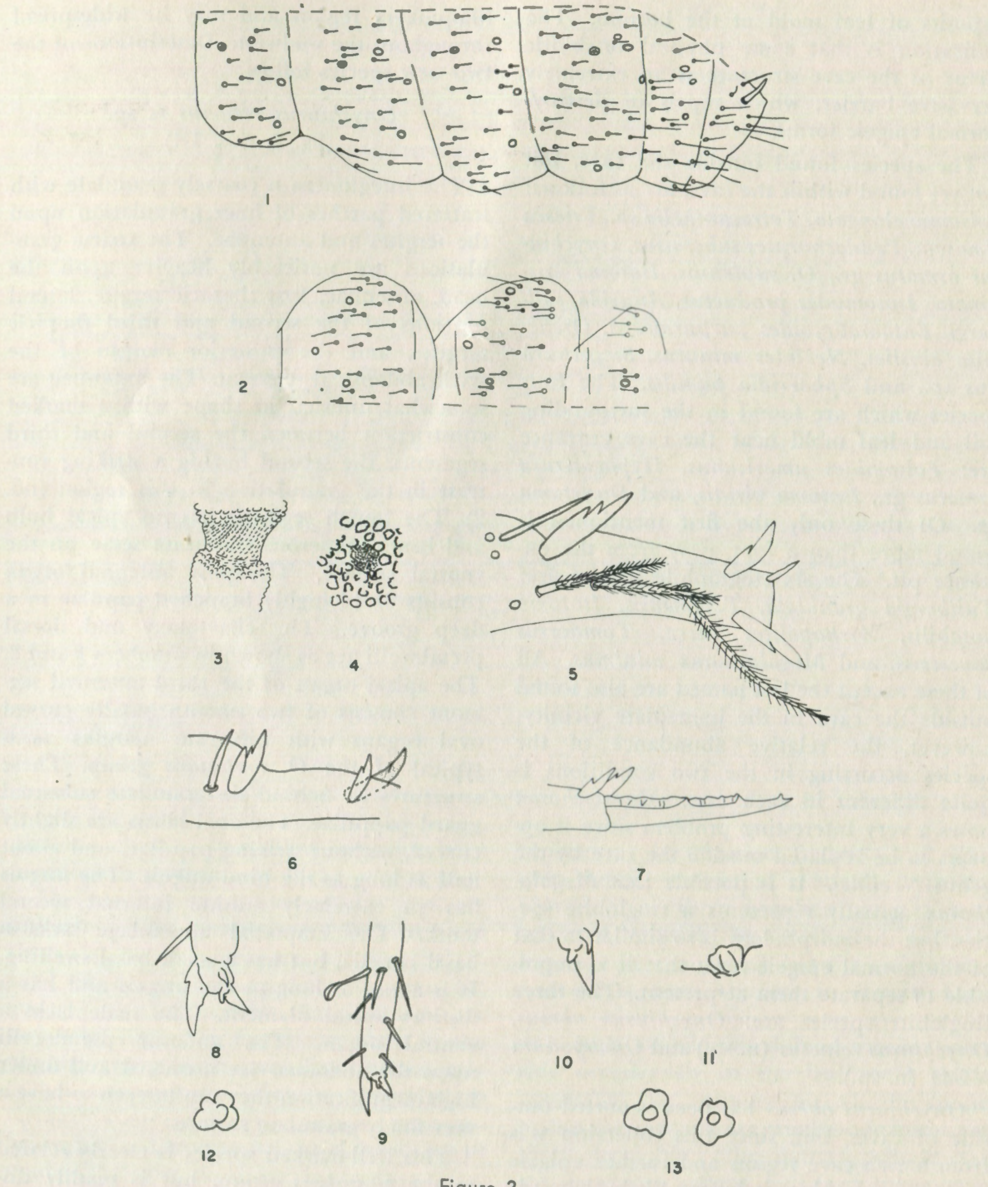

Figure 2

Numbers 1-4 Onychiurus reluctus n. sp. (1) Chaetotaxy and pseudocelli of dorsum of abdomen, Holotype, × 125. (2) Chaetotaxy and pseudocelli of dorsum of thorax, Holotype, × 125. (3) Contrast in granulation intersegment between second and third antennal segments, Holotype, × 270. (4) Anterior abdominal pseudocellus showing nature of granulation, Holotype, × 750. Numbers 5-13 Oncopodura iowae n. sp. (5) Dorsum of left dens Paratype, × 375. (6) Right dens of another Paratype, seen from side, setae omitted, × 375. (7) Lens of another Paratype, × 375. (8) Claw of same specimen as 7, × 550. (9) Middle tibiotarsus, same specimen as 7, × 375. (10) Hind empodial appendage another specimen, × 750. (11) Profile view post antennal organ, same specimen at 10, × 550. (12) Post antennal organ, other side same specimen as 10, seen from above, × 550. (13) Post antennal organs both sides of another Paratype, seen from above, × 550.

der all except the highest magnifications they clearly appear as pseudocelli. The pseudocellar formula is as follows: DORSUM Ant. base 3, Post. marg. head-2, T1-1 (0), T2-3 (2), T3-3, A1-4, A2-4, A3-4 (3), A4-5 (4), A5-3, A6-0. BASES 1-1-1. VENTER Head-2, T1-0, T2-0, T3-0, A1-1, A2-2, A3-1 (2), A4-2, A5-0, A6-0.

Type locality: Hunters Cave, Iowa, June 1959.

Oncopodura iowae n. sp.
(fig. 2, nos. 5-13)

The color in life is a dull silvery white. The facies are typical of the genus. All the segments of the antennae are sub-elliptical and the fourth segment without apical organ, but equipped with a straight row of four broad elliptical setae, along the length of the dorso external margin. No special setae lie basal to this row, but two short setae, one acuminate and one truncate, lie just distal to the row. The apical organ of the third antennal segment consists of two large unstriated, subcylindrical rods, and with one acuminate and one blunt accessory seta. The setae clothing the dorsum of the third segment are considerably thicker than those on the rest of the antennae. The post antennal organ has a large central boss from which four weakly demarcated lobes extend. The unguis has no internal teeth, but has a strong lateral tooth on one side. The tenent hair is short and acuminate, and each of the second pair of legs has a well developed clavate pretarsal seta. The empodial appendage is equipped with a well developed basal lobe, which normally projects toward the unguis. In addition there is a curved, roughly triangular, basal lamella closely appressed to the base of the appendage. The mucro is slightly longer than the dens and has four teeth. The apical tooth is slightly upturned and very close to the subapical tooth while the basal-most tooth is at about the center of the mucro. The dens is equipped with three large toothed dorsal spines, one near the inner base and the other pair near the apex, and four long ciliate setae, plus a narrow basal spine.

This species is quite close to *O. cruciata* described by Bonet from Montana caves, but it can be readily distinguished on a basis of the third antennal segment organ, the dental spination, the shape of the pretarsal seta, and P.A.O. In some of these features it resembles different European species; however, its closest resemblance is to the first named species.

Type locality: Hunters Cave, Iowa, June 1959.

Preliminary Study of the Microarthropod Ecology of Hunters Cave

by K. CHRISTIANSEN, MARY WILLSON AND JERRY TECKLIN

DISTRIBUTION AND ABUNDANCE OF COLLEMBOLA

Five of the six troplophile and three troglobite species of major occurrence in the cave show an indication of more thorough invasion of this habitat. When the average distance from the cave entrance to point of capture for all of the cave species is considered, two groups seem to be separable (fig. 3). The first group is exclusively troglophile and occurs 0-100 feet from the entrance; whereas the second group, including troglobites as well as two troglophile *tulbergia* species, are found within the cave from 0-150 feet from the entrance, with a mean over 100 feet. There appears to be a general dispersal of far ranging species, while lesser ranging species seem to have their greatest occurrence in the main room and closely adjacent regions.

It is interesting to note that members of the deeply penetrating group all are unpigmented and eyeless. *Tulbergia* has been

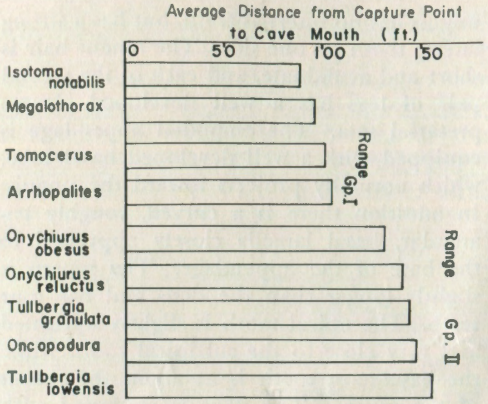

Figure 3
Average distance of capture point from cave mouth, nine cavernicole species of Collembola.

found in caves, but unlike *Oncopodura* and the *Onychiurus* no troglobite species in this genus have been described.

On the whole, collembolan fauna is extremely meager throughout the cave as compared with that of normal epigean soil or soil cover. Epigean soil samples of the size examined in the cave study (about 1500 cc.) will normally yield between 10 and 1,000 specimens. The soil outside the cave is slightly impoverished, but averages about 35 specimens per sample. In contrast to this, most soil samples from inside Hunters Cave yielded less than 5 specimens. The highest number recorded was 200 and less than 15% yielded more than 10 specimens. The average number of specimens per sample was 11.

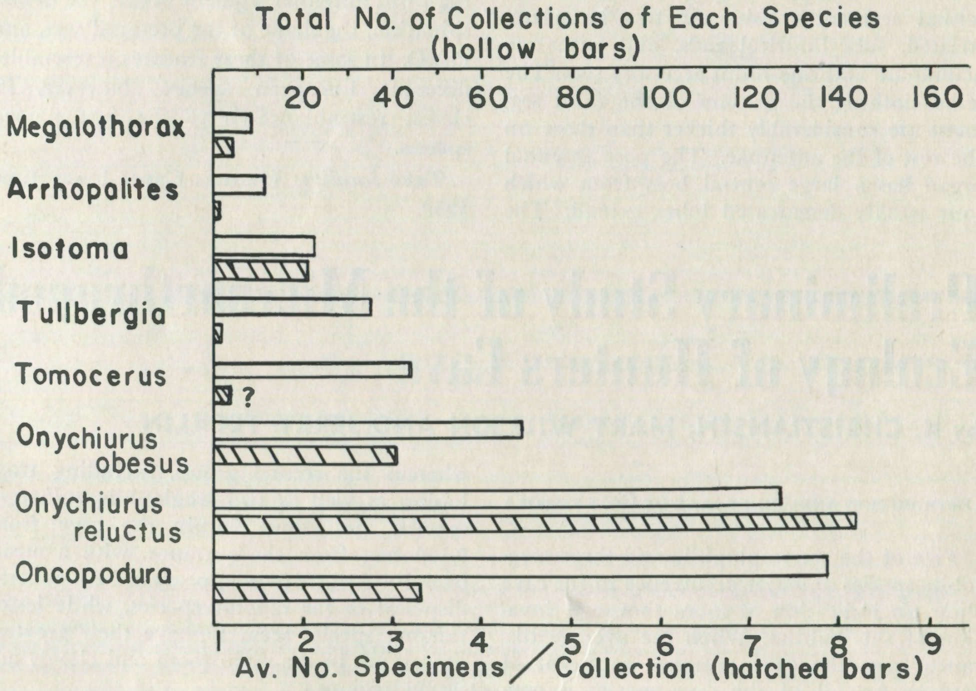

Figure 4
Total number of collections and average number of specimens per collections, nine cavernicole Collembola (two Tullbergia species grouped).

TABLE 1
NUMBER OF SAMPLES YIELDING SPECIMENS FOR EACH SPECIES

	June 1959	Sept. 1959	Oct. 1959	Nov. 1959	Feb. 1960	Apr. 1960	May 1960	Total
Oncopodura	26	34	3	39	22	6	9	139
Onychiurus (A) obesus	28	11	4	7	6	10	3	69
Onychiurus n. sp.	24	25	8	15	15	13	13	128
Tulbergia	20	1	2	1	0	4	8	36
Arrhopalites	9	0	2	7	0	2	2	13
Isotoma	11	4	0	1	1	3	3	23
Megathorax	4	1	0	0	0	3	1	9
Tomocerus	19	11	0	9	2	2	0	43
TOTAL	108	50	16	51	38	25	35	313

In view of the sparse distribution throughout the cave a remarkably large number can be seen moving over the surface of the cavern features. Thus manual collection yields results comparable to those of extraction techniques, except for the abundance of large forms and absence of extremely minute types such as *Megalothorax*. This is in strong contrast to results of epigean collection and leads to the conclusion that in caves, collembola generally lead much more of a surface life in contrast to a life in soil or plant cavities. The amount of movement must be considerable since limestone pools generally have a number of living collembola floating in them, trapped by the surrounding meniscus. The few aggregations of large numbers which do occur in the cave are always in unusually rich soil or upon pieces of debris. Table 1 summarizes the results of 313 collections. These numbers refer solely to the number of samples yielding specimens of the species concerned, but it should be noted that most samples yielded only a few specimens. The scattered distribution leads to a very high *"chance" factor* in the occurrence or absence of a species. This is particularly true for rarer forms, and most fluctuation seen in these can probably best be explained on this basis. The October collections (representing a summation of four trips) are unreliable because of the small number of collections and erratic methods.

The abundance of animals varies strikingly in terms of the numbers of collections and numbers of individuals per collection (fig. 4). The question mark in figure 4 concerning *Tomocerus* is necessary because the number of this form is not fairly reflected in mechanical extraction upon which these data are largely based. This large vagile form usually dies or escapes before extraction, and thus figures for this species are probably consistently low. Information from manual collections indicates that it is similar to the *Onychiurus* in numbers per collection. It is clear from these data that only species represented in 40 or more collections are at all abundant in the cave. All such species are troglobites.

There does not appear to be any absolute barriers or large areas unoccupiable by collembola. It was originally thought that part of the problem of studying ecology of cave forms would be careful mapping of ranges of various species within the cave. This proved to be very easy as troglobite species and *Tullbergia* occupied the whole cave in a very spotty or lattice-like pattern, while remaining species essentially occupied the main room in a similar fashion with one or two invasions into the deeper recesses. These invasions were most common in the heavily traveled canyon passage, but no area was immune. None of the genera is found in the cave in number comparable to those found in epigean soils; however, the two *Onychiurus* and *Oncopodura* are notably more numerous than other species. All of the remaining speices are rare in terms of both number of individuals per collection and number of collections in which they were found. All of these forms are normally taken as single specimens and are found in less than 10% of the total samples taken.

Seasonal Fluctuations

When the October collections are eliminated for reasons noted above and the possibility of seasonal fluctuation in populations is considered, an increase in spring is apparent in *Tulbergia, Isotoma, Megalothorax,* and the two *Onychiurus,* while a fall and winter preponderance appears to be true for populations of *Oncopodura* and *Tomocerus* (table 1). *Arhoppalites* seems to show no marked seasonal fluctuation with data at hand. The fall-winter increase in *Tomocerus* and *Oncopodura* is accompanied by a similar decrease in *Tulbergia, Isotoma,* and *Megalothorax.* More data must be accumulated to put these presently assumed fluctuations on a firmer basis. Dispersal as observed with seasonal changes was not seen to change in pattern.

Physical Factors

In the cave temperature variation with time occurs over a relatively small range; temperature as recorded by a thermograph during part of the investigation and occasional maximum-minimum thermometer readings showed a temperature range of 47°-52° F. Relative humidity was 99% to 100% at each periodic visit to the cave. Constant temperature differences between certain parts of the cave were apparent, but these were in no way correlated with any limits or variation in relative humidity, it is probable that these factors are of little importance in governing the distribution of the animals within the cave.

In many rooms the whole room is without visible life, while in others one to several areas of concentration are seen. This erratic distribution is reflected in differences in numbers obtained by mechanical extraction techniques. These results show the greatest actual number cannot always be correlated with the greatest visible number. In the cave two areas of concentration are readily seen, one on the under surface or sides of decaying organic material and the other in limestone pools. The first of these almost certainly represents a food congregation, while the second is in the nature of a meniscus trap. Both of these situations are, however, sometimes found devoid of life. In the case of organic material such occurrences are usually associated with fresh undecayed conditions which make the material unsuitable as collembolan food. In some cases this was not true, and this obviously could not explain the barren limestone pools. In the last situation the whole region immediately surrounding the pool was found to be equally lifeless, and represented a more general unsuitability of the environment. Since this was clearly not a matter of temperature, relative humid-

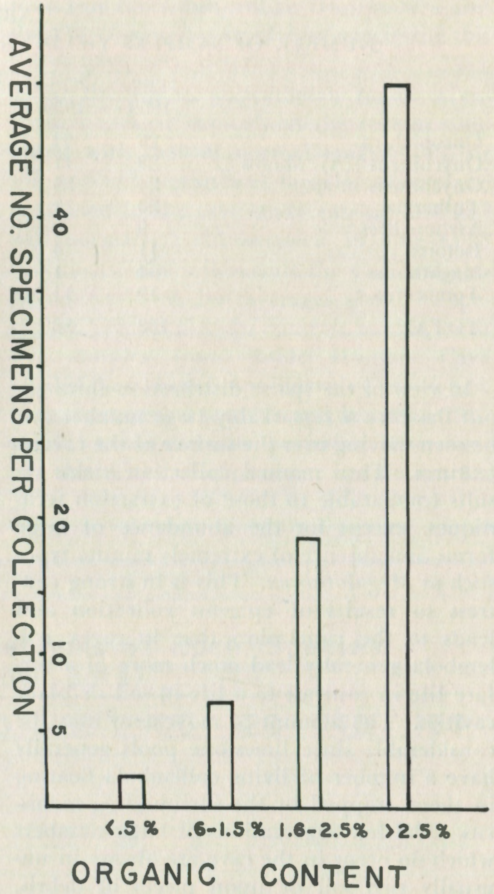

Figure 5
Average number of specimens per sample (all microarthropods) compared to organic content of sample. Numbers of collections at each organic content: 25 less than .5%, 21 between .6 and 1.5%, 8 between 1.6 and 2.5%, and 7 over 2.5%.

TABLE 2
Characteristics of Sampling Sites

Sample Location Number	Total No. Animals	% Water Content	% Organic Content	Particle Size
		APRIL 1960		
86	100	25.8	3.52	.068
156	3	4.6	.25	.096
26	1	18.2	.40	.002
68	0	13.9	.27	.090
End Maze	0	10.4	.27	.074
172	1	15.4	1.07	.106
57	1	19.0	.25	.021
90	0	19.2	.27	.005
60	2	20.7	.27	.009
93	1	22.4	.67	.026
54	0	23.7	.54	.043
20	200	27.8	4.03	.108
142	20	22.7	.92	.064
X 2	0	6.8	.27	.052
131	2	19.5	.53	.074
64	0	19.8	.40	.009
45	10	18.8	.67	.007
25	0	21.6	.13	.003
74	1	26.1	1.31	.077
80	0	22.8	1.07	.047
52	7	30.8	2.47	.012
58	2	29.3	.16	.078
105	0	45.8	1.14	.025
38	0	24.4	1.17	.008
78	1	20.5	.54	.207
92	17	25.0	.54	.150
43	0	11.8	.27	.005
92	1	14.8	.16	.050
X 1	3	10.4	.27	.030
82	4	18.2	.80	.008
49	6	17.0	1.19	.083
19	100	12.5	.94	.049
		MAY 1960		
128	0	25.68	.40	.085
201	0	28.48	.94	.061
25	4	23.89	.00	.080
114	5	19.52	.27	.097
50	12	21.64	.00	.067
83	30	28.16	4.56	.086
82	1	24.20	.67	.059
85	5	10.30	.40	.085
62	0	27.06	.54	.078
14	1	18.61	.40	.102
131	4	20.70	.27	.087
56	3	16.87	.40	.102
147	11	19.66	.67	.094
133	30	21.77	.00	.075
89	14	21.91	1.61	.090
90	70	19.60	1.88	.038
57	3	17.77	.00	.101
154	12	22.25	.40	.038
43	8	25.03	2.01	.026
76	2	20.64	.27	.038
170	12	22.11	2.68	.050
88	1	7.48	.40	.066
157	0	17.27	.00	.079
59	5	23.94	.40	.073
56	6	19.91	1.07	.122

144	4	19.02	.13	.091
53	0	14.37	.00	.115
10	10	25.53	.13	.081
141	6	25.82	1.34	.023
63	1	26.20	2.95	.093
93	4	22.74	2.01	.057
117	3	22.22	2.28	.022
42	1	29.36	4.15	.035
115	0	26.22	1.88	.024
102	0	27.27	1.61	.046

ity, or ranges, further investigations were made of soil in and upon which the organisms lived. For this purpose a series of 32 soil samples of about 1000 cc. each were taken in April and an additional 35 in May of 1960. The animals in the samples were extracted by flotation using a 3% $CaCl_2$ solution, and the particle sizes were measured using an ocular micrometer. The soil moisture was determined by evaporation and the organic content determined by the chromic acid technique. In addition to these samples, moisture, and in some cases particle size, and animal numbers were available for 39 earlier samples and organic contents for 5 others.

It was apparent that occurrence of any single species was so sporadic that significant numbers of animals could be obtained only by including all the microarthropods collected in any sample. Beyond this the virtual congruence of most of the ranges of different species made it seem likely that any apparent significant difference between species would be spurious and a result of the generally thin populations. With lumping together of all mites and collembola from 67 samples, some interesting correlations appeared (table 2). The data, on the whole, strikingly reaffirm the sparse and lattice-work nature of the distribution of animals within the cave. Of the 105 collections available for comparable population counts 34 were blank, 26 yielded 1 specimen, 11 yielded 2 specimens, 7 yielded 3 specimens, 8 yielded 4 specimens, an 7 yielded 5 specimens. Six collections yielded between 6 and 10 specimens, 6 yielded between 11 and 20, and 7 yielded more than 20 specimens. Thus more than half the samples yielded three or fewer specimens, and fewer than 10% yielded numbers at all equivalent to those found in normal epigean soils.

The average number of animals per sample and the organic content show a striking correlation (fig. 5). Most of the cave soil was very low in organic content; only 7 of the 71 collections with organic analyses yielded more than 2½% of organic matter. In addition to composition of soil there was a correlation between the amount of soil moisture and the number of animals present in the soil (fig. 6). The various average particle sizes (fig. 7) were obtained by measuring fifty particles in each case; the data here are susceptible to larger error than elsewhere, as they were taken by different people under different conditions. The distribution by particle size is one of broad limits within which the animals are uniformly successful. A striking difference from the picture seen in the soil moisture is the abundance of one of less well occupied types, i.e. particle size below .03.

If we view all of these facts, several things appear probable. First, it is likely that the majority of soils in the cave do not support arthropods. Certainly the void samples would fall into this category, and, when we consider the amount of movement already noted in the cave forms, it appears likely that samples yielding one or two specimens represent accidentally captured migrants. Such essentially non-productive areas represent more than two-thirds of the samples taken. Thus conditions which are capable of supporting micro-arthropods are relatively rare within the cave, representing no more than one-third of the available surface. Since this does not consider almost totally barren rock surface or standing water, the actual figure is probably much lower—in the order of 10-15%. When apparently suitable areas are plotted on the cave map, they appear to be widely but uniformly scattered.

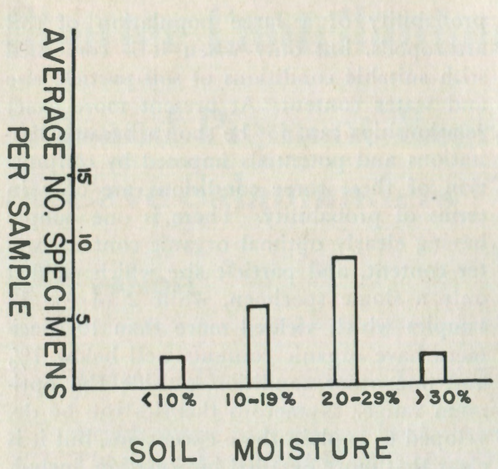

Figure 6
Average number of specimens per sample (all microarthropods) compared to soil mixture. Number of collections at each soil moisture level: 5 less than 10%, 28 between 10 and 19%, 65 between 19 and 29%, and 8 more than 30%.

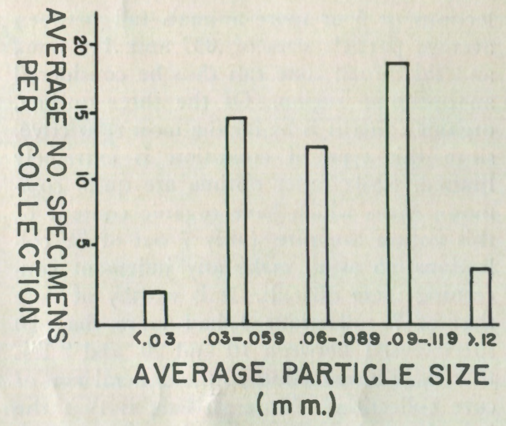

Figure 7
Average number of specimens per sample (all microarthropods) compared to the average particle size (taken from fifty random particles in each sample). Number of collections at each average particle size: 17 less than .03 mm., 14 between .03 and .059 mm., 21 between .06 and .089 mm., 13 between .090 and .119 mm., and 5 over .12 mm.

TABLE 3
ANALYSIS OF 22 SAMPLES HAVING MORE THAN 1.0% ORGANIC MATERIAL

	12 samples with particle sizes and/or soil moistures within respective optima	10 samples with particle sizes and/or soil moistures outside optimal range.
Number of samples yielding 20 or more specimens	4	0
Number of samples yielding 10-19 specimens	3	0
Number of samples yielding less than 10 specimens	5	10
Average number specimens per sample	37.0	3.8
Median number specimens per sample	12.0	3.0
All samples having known organic content		
Average number specimens per sample	11.0	
Median number specimens per sample	2.5	

The next question which arises concerns conditions which favor development of breeding populations. The graphs furnish some significant clues. If we consider these, it is possible to determine some optima for cave arthropods. First in organic matter, the best situation is clearly where organic matter is over 2.5%. The average number of animals found in such situations is much greater than that found in any other grouping and in fact such very high organic content samples, although extremely rare (less than 1% of the whole sample), contained more than half of the total animals captured. In terms of soil moisture (fig. 7) the optimum lies between 19% and 29%; this is the commonest concentration in the cave. Particle size optimum is not so easily determined; however, if all the sizes are plotted against occurrence of animals, it is clear that over 80% of collections of 5 or more animals fall between average particle sizes of .037 and .110 mm., and this broad zone can thus be considered an optimum region. Of the three optima, organic content is by far the most restrictive, since this type of condition is extremely limited, while other optima are quite common. Areas which have organic content of this nature are rare (only 7 out of 72 collections) so as to make any judgment concerning them difficult. It is worthy of note that of 7 collections 4 had more than 20 specimens, 1 between 10 and 20, and 2 less than 5. This contrasts to the general run of cave collections. More striking is that the 5 readings above 10 had moisture and particle sizes within the optimum range, while one of the two collections showing only a single specimen lacked these. If we expand the optimum of organic material to include all samples having organic content of 1% or more, such a level is found in less than one-third of the samples analyzed, yet these contain almost two-thirds of the specimens captured. These samples are more interesting if we view them in another fashion. Twelve samples with an organic content above 1% also had particle size averages and soil moistures falling within optimal ranges, while 10 had one or both of these relations falling outside the limits. Characteristics of the two series contrasted sharply (table 3).

Evidence clearly indicates that high organic content is important in increasing the probability of a large population of soil arthropods, but only when it is combined with suitable conditions of soil particle size and water content. At present more exact relationships can not be shown because limitations and potentials imposed by conjunction of these three conditions are only in terms of probability. There is one sample having clearly optimal organic content, water content, and particle size which yielded only a single specimen, while 2 of the 13 samples which yielded more than 10 specimens have organic contents well below 1% and one other condition outside the optimum range. Numerous theories can be developed to explain these exceptions, but it is clear that more detailed information, including experimentation, must be developed before the final answer is available. One of the problems which awaits further work is the role of macro-arthropod predation upon these colonies. Other problems still remain to be formulated.

ACKNOWLEDGMENTS

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The description of Hunters Cave is modified from the Quint City Grotto (National Speleological Society) preliminary report, June 15, 1958.

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Shorter Contributions

Eye and Pigment Regression of Cave Salamanders

by A. VANDEL

ABSTRACT—*Proteus anguinus* Laurenti was bred in tanks in the Subterranean Laboratory at Moulis, France. Upon hatching from their eggs, the larvae are greyish, owing to numerous black chromatophores distributed over their bodies. The eyes are very evident and strongly pigmented. After two years, the animals become entirely white, and their eyes remain only as microscopic black points. Still later, opaque skin covers the eyes. The regression of the eyes and pigmentation is thought to result from hypothyroidism which in turn is caused by lack of excitation of the pituitary gland by light.

INTRODUCTION

Proteus is undoubtedly one of the most remarkable representatives of the vertebrates. Known in Yugoslavia, its country of origin, as "olm," it was scientifically baptized by Laurenti in 1768 and called *Proteus anguinus*, the first cave-dwelling animal to have been studied. It is also the only European vertebrate which may be considered a true troglobite.

It is not surprising, therefore, that *Proteus* has been the subject of numerous notes, articles, and reports since its first mention by Baron Valvasor in 1689. Yet many problems which *Proteus* poses for naturalists are far from resolved.

For this reason it was suggested when the Subterranean Laboratory of the French National Center for Scientific Research had been established in Moulis Cave, France, that a breeding place for *Proteus* be created in the cave laboratory for the purpose of resuming the study of the mode of reproduction and development of this salamander. The project materialized when we procured 17 specimens from Gradom Cave, which lies near the town of Planina in Yugoslavia; they were obtained by Mr. Henri Coiffait, manager of the Subterranean Laboratory, who visited Yugoslavia during 1952 and 1953.

The specimens at our disposal were distributed in several concrete tanks which are supplied with a continuous flow of cave water (fig. 1). Constant renewal of the water seems indispensable in order to keep the salamanders in perfect health. The temperature of the water in the laboratory cave is 11.5°C, slightly higher than that in the *Proteus*-populated Yugoslavian caves (7-10°C).

The bottoms of the tanks were covered with a layer of sand and gravel, and a considerable quantity of clay was put at the disposal of our guests. *Proteus* digs itself into the clay, and if it finds no other shelter, it builds galleries in which all but the snout and the tip of the tail remain submerged. The breeding tanks also contain dolomite blocks piled in such a way that a gap remains which is as wide as a *Proteus* is thick. As a rule, groups of three or four of our guests bunched up in these interstices, being held there by a very marked desire to maintain contact with solid surfaces. *Proteus* leaves its shelter only when it is hungry.

The salamanders were fed regularly with water fleas, insects, and other organisms collected from a pond near Moulis. To this animal food we added wood scraps, dead leaves, moss, aquatic plants, etc., for it seems that *Proteus* derives part of its nourishment from vegetable matter.

Kammerer's publications (1907, 1912) indicate that *Proteus* bears its young alive. This is an error. The observation of egg laying in breeding tanks in the Moulis cave laboratory has shown that the reproduction of this salamander is oviparous rather than viviparous. The male stands guard near the egg-laying site, which is behavior typical of oviparous groups. Elsewhere we have described the reproduction and development of the larva in captivity (Vandel and Bouillon, 1959).

Pigmentation and Eyes

The two most notable characteristics of *Proteus* larva are the pigmentary system and the eyes.

Pigmentation of the body is remarkably developed in the newborn larva (fig. 2), in sharp contrast with the colorless full grown animals. The larva appears grayish to the naked eye. Through a magnifying glass the entire body, except for the under side, appears to be sprinkled with black chromatophores, and the pigmentation undergoes little change within 3½ months.

Zeller (1888), struck by the remarkable development of the pigmentary system of the larva, at first interpreted this dark coloration as a reaction to the light which was amply spread over his breeding tanks. He later (1889) corrected this initial interpretation. The complete darkness in the Moulis cave laboratory precludes any possibility that light is a factor in the coloration of the larvae. The larval pigmentation must be regarded as a hereditary disposition which develops in the absence of light stimuli and may persist for a long time after birth. We must conclude that the cavernicolous habit of *Proteus* is a belated development.

We have known since Zeller's observations that the larvae of *Proteus* has a very distinctly perceptible eye. It is visible even to the naked eye and becomes more so under magnification (fig. 3). The eye is covered by skin which in the living animal has the appearance of a completely transparent membrane. Under the action of histological fixing agents, the skin portion covering the eye becomes opaque, and the eye is then more difficult to discern.

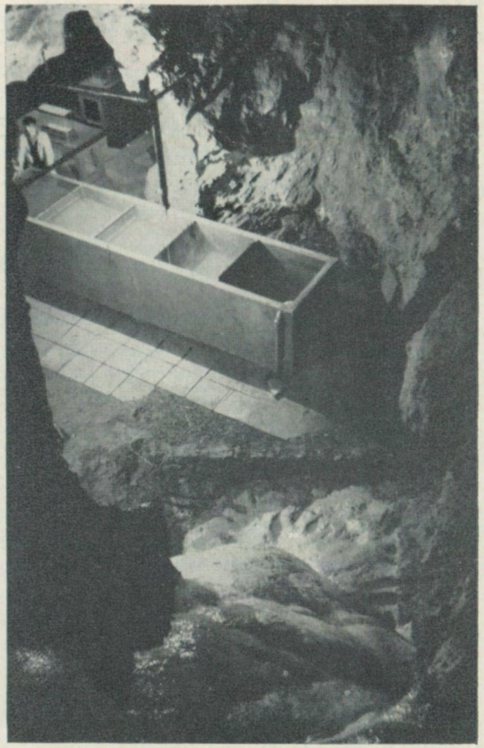

Figure 1
Salamander tank in the Moulis Subterranean Laboratory, France.

Schlampp (1892) and Hawes (1946) gave some figures regarding the growth of the *Proteus* eye. We shall be able to furnish more accurate data based on our breeding experiments. At present we can only give two sets of figures, but these are significant. Our measurements were made on greatly enlarged photographs of living animals, and are thus free of errors due to the contraction caused by fixing agents.

We see that while the animal's size has doubled in a period of 3½ months, growth

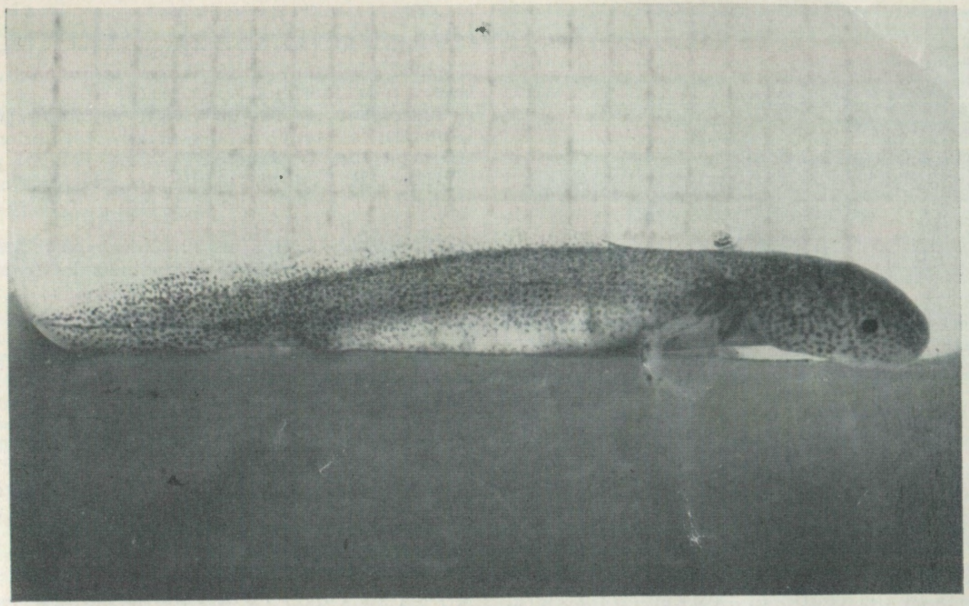

Figure 2
Pigmentation of a newly-hatched Proteus.

	Newly hatched (millimeters)	At age 3½ months (millimeters)
Length of larva	22	41-42
Length of head	4	7.4
Diameter of eye	0.37	0.40

of the eye during the same period is insignificant. Growth of the eye is highly disharmonic and constitutes a very clear example of minorant allometry. Eigenmann (1909, p. 37) observed a similar disharmony in the development of the eye of the cavernicolous salamander, *Typhlotriton spelaeus* Stejneger.

By the time the *Proteus* larvae were 26 months old, they were 110 millimeters long and had become white owing to lack of multiplication and dispersion of the chromatophores. The eye was still discernible as a microscopic black point. In full grown specimens, however, the eye is no longer visible because of the opacity of the skin covering it.

Origin of the Regression

The question is whether the regression of the *Proteus eye* is due to the animal's cave life. The answer seems so obviously "yes" that it has never been questioned. Nevertheless, we have learned some things from zoology—in spite of the fact that this is an imperfect science which is unduly neglected nowadays—that make us cautious in our judgment. It appears in fact that the eyes of salamanders which never lose their gills are usually reduced and often undergo retrogression, although all of them, with the exception of *Proteus* and *Typhlomolge rathbuni,* lead lives on the surface. The eye of another representative of the family of Proteidae, *Necturus maculosus,* is reduced; the optic nerve shows signs of degeneration, and the optic chiasma is lacking (Kingsbury, 1895). The eye of *Amphiuma means* is extremely small; its diameter is 1.5 millimeters, while the length of the body may reach a meter. The eye is covered with skin and is probably not functional (Davison, 1895). As far as can be judged from an illustration by Davison (pl. 25, fig. 15), the eye of a young animal 68 millimeters long lacks a crystalline lens. The eyes of *Crypobranchus* and *Siren* are also reduced (Herter, 1941. p. 213).

Figure 3
Head and eye of a newly-hatched Proteus.

It seems, then, that the reduction of the eyes of salamanders with permanent gills is by no means related to their cavernicolous life. The decolorization and regression of eyes in the course of post-embryonic development are contingent upon the life history of the organism and physiological factors on which our research is continuing. We know today that external factors influence the physiology of vertebrates through the intermediary of the endocrine system, especially the pituitary and tryroid glands. The regression of the eyes and pigmentation is probably due to a hyperthyroidism which is in turn the result of lack of excitation of the pituitary gland by light. In America, Breder and Rasquin arrived at similar conclusions following their experiments with the cave-dwelling fish, *Anoptichthys* (Rasquin, 1949).

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Glacier Caves in Svartisen, Norway*

by WILLIAM E. DAVIES

During the summer of 1960 the author, while enroute from Oslo to Bodø visited Svartisen, the second largest ice field in Norway. This ice field is just north of the Arctic Circle between Mo-i-Rana and Glomfjord. It is divided into two separate ice fields by Glaamaaga Valley. On the south side of the eastern part is Østerdalsisen (fig. 1), a large outlet glacier which formerly extended eastward to the lake in Svartisdalen; its eastern edge is now a kilometer west and 300 meters above the lake. Beneath the glacier is a large lake, the level of which is controlled by a manmade tunnel through bedrock. In addition to drainage through this tunnel, a surface stream drains a small lake at the front of the glacier.

The edge of the glacier contains several caves. Along the northern part of the glacier front the caves are regular melt channels (fig. 2) about 1½ meters high and as much as 3 meters wide. Their floors are bedrock with gradients of about 8 percent toward the center of the glacier. Most of these caves extend about 100 meters into the glacier, where passage is blocked by pools of water. The caves are interconnected and form a maze of passages. The ceilings and walls are fine, crystalline glacial ice with scallops about 30 cm long and high, and 3 to 10 cm deep. The ice over the cave is from 3 to 50 meters thick and transmits an eerie blue to purple light.

A different kind of cave has formed along the south part of the glacier front. Unlike most glacier caves it is cut in bedrock rather than developed within the glacier by meltwaters. The cave (fig. 3) trends southwest parallel to and 25 to 50 meters behind the glacier front. It is 3 to 5 meters wide, 2 to 5 meters high, and about 300 meters long. The cave is a declivity, a former marginal channel, that was overridden by the glacier. The west wall is bedrock; the lower part of the east wall is bedrock, and the upper part is glacier ice that has been folded back into the channel. The smooth ceiling is formed by ice that has glided across the opening. The floor is bedrock covered by cobbly sand-silt moraine. A small meltwater stream flows north along the cave.

The cave is not as beautiful as the smaller glacier caves on the north part of the glacier front. The ice is dirtier and the light transmitted is gray-green in color.

The cave is an active melt area at the front of the glacier and probably will not exist long. In many places the ceiling has collapsed; the remaining part of the cave is covered by ice only a few meters thick.

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Figure 1
East side of Osterdalsisen. Entrance to large glacier cave is at the lower left.

Figure 2
Interior of a glacier cave formed by subglacial meltwaters.

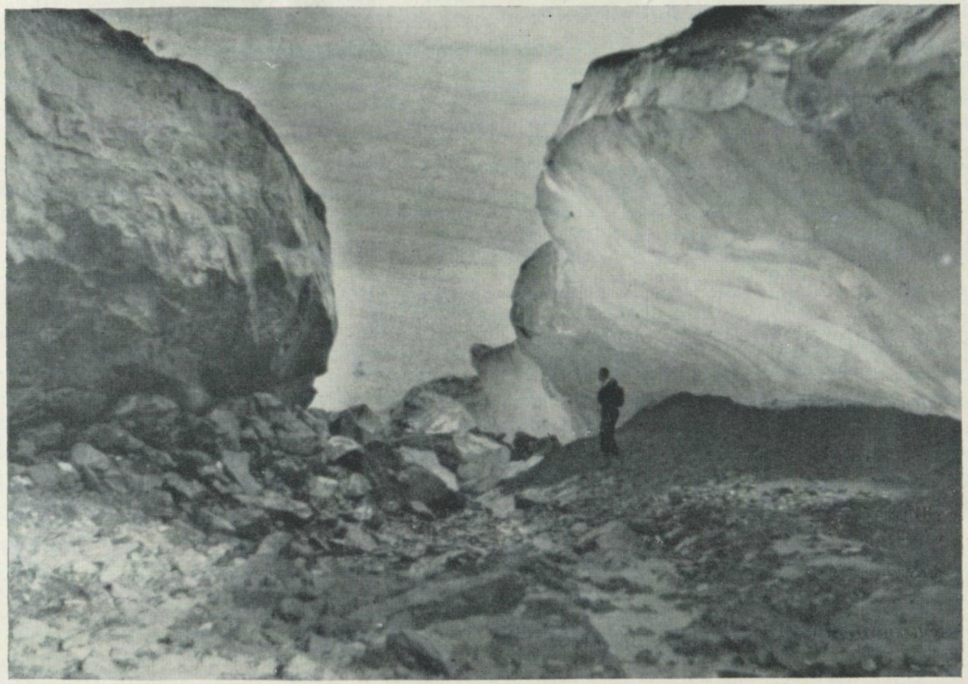

Figure 3
Interior of a cave formed by ice overriding a former marginal channel.

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ERRATA

Volume 23, Part I, page 13: Diagram for figure 12 should be placed above caption for figure 11; diagram for figure 11 should be placed above caption for figure 12.