

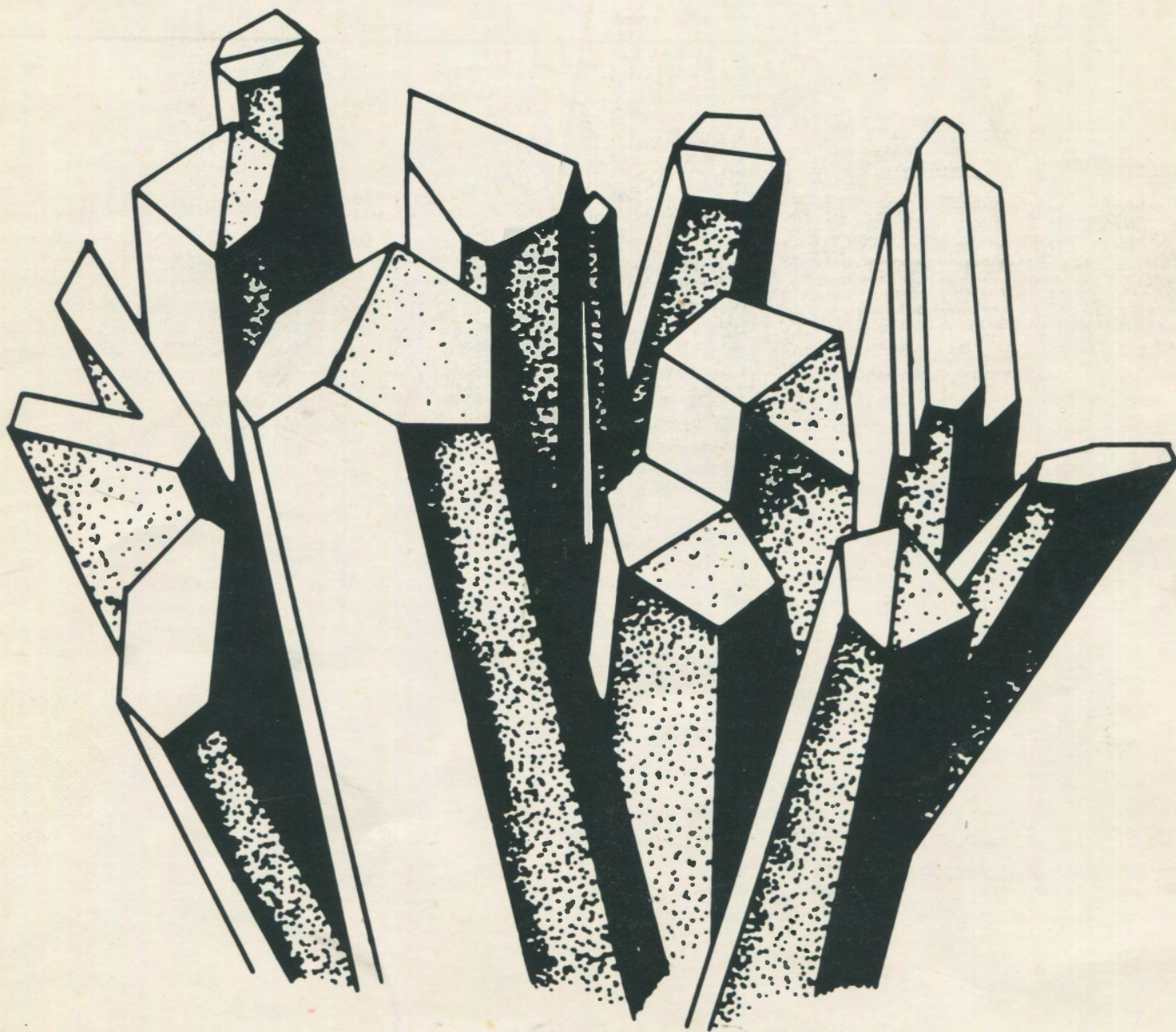
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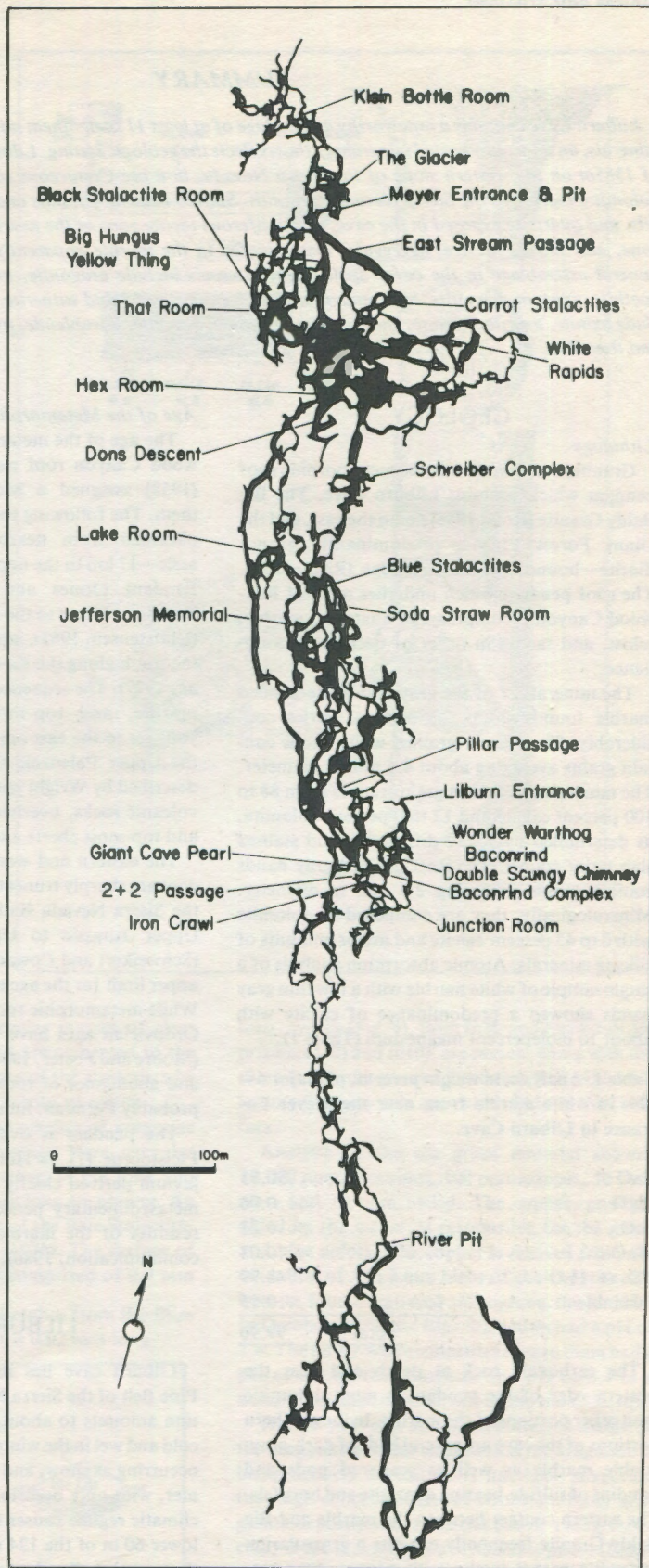
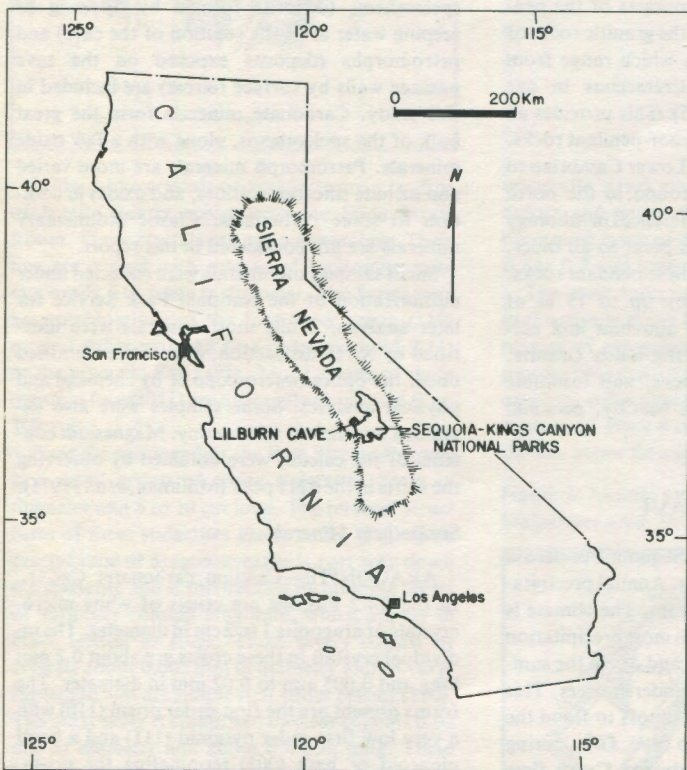
MINERALOGY OF LILBURN CAVE KINGS CANYON NATIONAL PARK CALIFORNIA*

BRUCE W. ROGERS and KATHLEEN M. WILLIAMS
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LILBURN CAVE is located at an elevation of 1585m on the western slope of the southern Sierra Nevada, in the Grant Grove section of Kings Canyon National Park (Fig. 1). The cave lies within Redwood Canyon, a southward-draining tributary of the North Fork of the Kaweah River. Approximately 12 km of passageways have been mapped within the cave. (Fig. 2).

Although the regional geology of this area has been reasonably well studied (Durell, 1940; Ross, 1958; Saleeby, 1978), the only reports concerning the cave have been on its general geology (Des Marais, *et al.*, 1980).

Figure 1. (below) Map showing location of Lilburn Cave in Sequoia and Kings Canyon national parks, California. Figure 2. (right) Map of Lilburn Cave showing localities referred to in text.



*A contribution of the Cave Research Foundation.

SUMMARY

Lilburn Cave contains a noteworthy assemblage of at least 11 speleothem minerals and 11 petromorph minerals, an unusually varied mineralogy that reflects the geologic setting. Lilburn Cave lies at an altitude of 1585 m on the western slope of the Sierra Nevada, in a pre-Cretaceous roof-pendant of calcitic to dolomitic marble in the Sierra Nevada batholith. Sulfide-bearing boudins and partings of schist, hornfels, and quartzite exposed in the cave, a metaliferous tactite zone at the nearby granite-marble contact zone, and sulfide mineral aggregates disseminated in the marble apparently account for the diverse mineral assemblage in the cave. Speleothem minerals include aragonite, azurite, birnessite, calcite, goethite, gypsum, hematite, hydromagnesite, malachite, 'wad,' and witherite. Petromorph minerals include axinite, azurite, bornite, chalcocopyrite, diopside, goethite, hornblende, pyrite, sepiolite, sphalerite, and tremolite.

GEOLOGY

Lithology

Granitic rock surrounds the metamorphic roof pendant which contains Lilburn Cave. The Big Baldy Granite (Ross, 1958) lies to the east, and the Giant Forest Pluton—predominantly granodiorite—bounds the western edge (Ross, 1958). The roof pendant which underlies most of Redwood Canyon is comprised of quartzite, marble, schist, and tactite in order of decreasing abundance.

The mineralogy of the gray-and-white-banded marble found within the pendant varies considerably. The coarser-grained white bands contain grains averaging about 4.5 mm in diameter. The mineralogy of these grains ranges from 88 to 100 percent calcite and 12 to 0 percent dolomite, as determined by X-ray diffraction and stained slab point counts. The finer-grained gray bands contain grains averaging 2.5 mm in diameter. Mineralogically, they are composed of dolomite with 0 to 45 percent calcite and minor amounts of silicate minerals. Atomic absorption analysis of a single sample of white marble with a few thin gray bands showed a predominance of calcite with about 10 molepercent magnesium (Table 1).

Table 1. Analysis, in weight percent, of major oxides in white marble from near the Meyer Entrance to Lilburn Cave.

CaO	50.53
MgO	0.06
FeO	0.22
MnO	0.03
CO ₂ + H ₂ O	48.97
Insoluble	0.15
Total	99.96

The carbonate rock at depth and near the western edge of the pendant is more dolomitic than other portions of the marble. In the northern portions of the cave are several beds of dark-gray, friable marble as well as scattered pods and boudins of sulfide-bearing quartzite and hornfels. The eastern contact between the marble and Big Baldy Granite frequently exhibits a grossularite-andradite garnet tactite with copper, tungsten, and silver mineralization.

The strike of the foliation of the marbles found within the pendant is about N15E with a dip of about 85E. This follows the regional structure of other metamorphic roof-pendant rocks in the southern Sierra Nevada.

Age of the Metamorphic Rocks

The age of the metamorphic rocks of the Redwood Canyon roof pendant is unknown. Ross (1958) assigned a Mesozoic-Paleozoic age to them. The following fossil-based dates have been obtained from nearby pendant rocks: Jurassic—17 km to the northeast in the Boyden Cave Pendant (Jones and Moore, 1973), Upper Triassic—44 km to the southeast in Mineral King (Christensen, 1963), and Upper Permian 10 km to the south along the Kaweah River (Schweikert, *et al.*, 1977). The sequence of basal schist, overlying marble, and top-most quartzite becoming younger to the east appears to be comparable to the Upper Paleozoic Calaveras Complex rocks described by Wright and Schweikert (1977): basal volcanic rocks, overlying argillites and marbles, and top-most cherts and quartzites.

The eastern and western contacts of the pendant are sharply truncated by the granitic rocks of the Sierra Nevada Batholith, which range from Upper Jurassic to Upper Cretaceous in age (Schweikert and Cowan, 1975). This provides an upper limit for the age of the roof-pendant rocks. While metamorphic rocks of Lower Cambrian to Ordovician ages have been found to the north (Moore and Foster, 1980), differences in lithology and abundance of rock types point to an older, probably Permian, limit for these pendant rocks.

The pendant is overlain by up to 15 m of Pleistocene (?) to Holocene alluvium and colluvium derived chiefly from Big Baldy Granite, metasedimentary pendant rocks, and insoluble residues of the marble (Gail McCoy, personal communication, 1980).

LILBURN CAVE

Lilburn cave lies in the Sequoia-Ponderosa Pine Belt of the Sierra Nevada. Annual precipitation amounts to about 1400 mm. The climate is cold and wet in the winter, with most precipitation occurring as snow, and warm and dry in the summer, with only occasional thundershowers. This climatic regime causes spring runoff to flood the lower 60 m of the 124 m deep cave. Only during these spring floods does Redwood Creek flow through the entire canyon on the surface. During summer months, the creek sinks in a large area of alluviated sinkholes about 1 km north of the presently known north end of the cave and flows southward through the cave. The water resurges at Big Spring, a Vaclousian spring about 1 km

south of the known south end of the cave. Big Spring behaves as an ebb-and-flow spring during heavy spring runoff or especially heavy summer thundershowers.

The morphology of Lilburn Cave is that of a 3-dimensional maze. Over 12 km of passageways are contained in an area about 1.5 km long, 0.5 km wide, and 124 m deep. Joints and, to a lesser degree, faults have determined the orientations of many of the major passages. The initial stage of phreatic solution produced passages that now have a strong vadose overprint. Underwater passages more than 34 m below the exposed water table suggest that phreatic solution is active today, primarily along the southern and western margins of the marble body.

Carbon isotopic measurements of CO₂ from the cave soil, cave air, bedrock, and cave water indicate that the CO₂ is nearly exclusively derived from biological activity in the forest soil. Carbon dioxide produced at Lilburn Cave peaks in later summer, when percent volumes range from 0.17 to 0.30 with a mean of 0.23, and ebbs in late winter, when a percent volume range of from 0.12 to 0.13 with a mean of 0.13 has been recorded. Poor air circulation accounts for the high concentrations in the cave (DesMarais, *et al.*, 1980).

MINERALOGY

Due to the geologic setting, an unusually varied mineralogy is present in Lilburn Cave. Both speleothems (deposits formed by dripping or seeping water after the solution of the cave) and petromorphs (deposits exposed on the cave passage walls by surface retreat) are included in this study. Carbonate minerals form the great bulk of the speleothems, along with a few oxide minerals. Petromorph minerals are more varied and include silicates, sulfides, and oxides in addition to some carbonates. Clastic sedimentary minerals are not considered in this report.

Small samples of minerals were collected under authorization of the National Park Service for later analysis. While most minerals were identified by X-ray diffraction, a few were identified under the optical microscope or by chemical and physical analyses. Some samples were also examined by electron microscopy. Magnesium contents of the calcites were obtained by observing the shifts in the d211 peak (Milliman, *et al.*, 1971).

Speleothem Minerals

ARAGONITE—Calcium carbonate; CaCO₃. In the 2+2 Passage are crusts of white microcrystals of aragonite 1 to 2 cm in diameter. The individual crystals in these crusts are about 0.2 mm long and 0.005 mm to 0.02 mm in diameter. The forms present are the first-order prism (110) with a very low first-order pyramid (111) and a basal pinacoid or base (001) terminating the prism. These crusts fluoresce pale blue under shortwave ultraviolet light and phosphoresce pale sea green up to 5 or 6 seconds either after the ultraviolet light has been removed or after having been excited by the discharge of an electronic flash unit held to their surface.

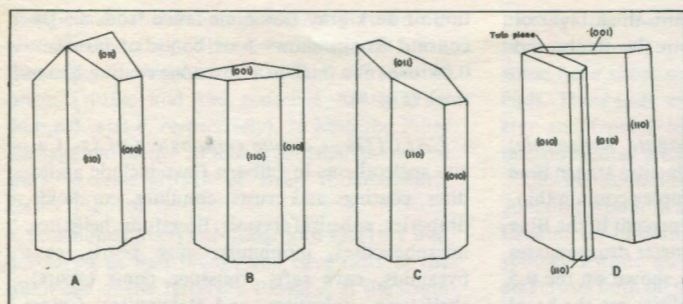
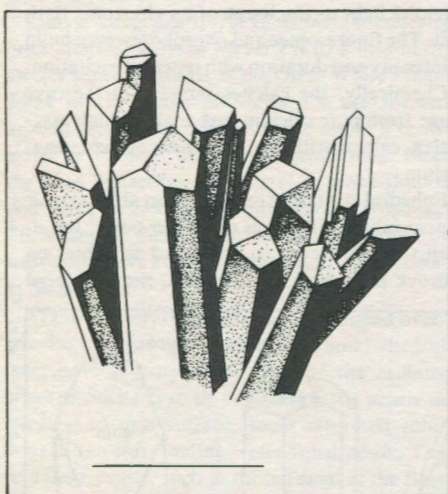
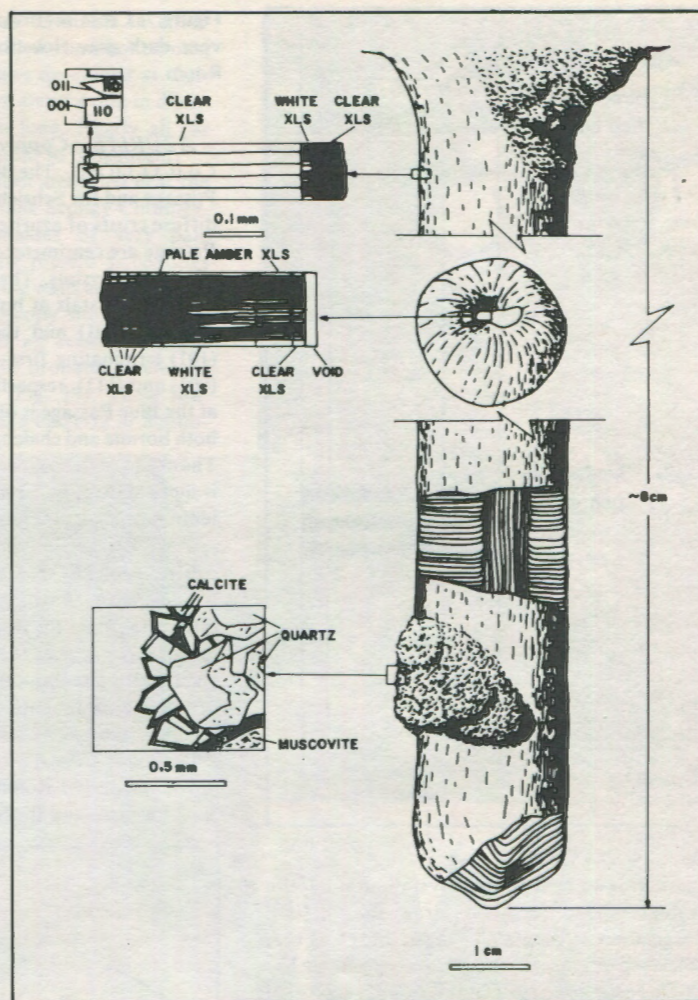


Figure 3. (above) Sketches showing crystal forms of aragonite found in Lilburn Cave. Figure 4. (right) Sketch of aragonite stalactite found in the East Stream Passage. Figure 5. (right) Sketch of aragonite crystals from the pale green patch of flowstone adjacent to the Blue Stalactites. Scale bar is 0.5 mm long.



Milky-white crystals of aragonite grow on fins of biotite quartz schist near the Soda Straw Room. These crystals are up to 8 mm long. Their tips are coated with masses of hydromagnesite moonmilk 6 to 8 mm in diameter. The forms here are combinations of the first-order prism (110) capped either with the first-order pyramid (011) or the pinacoid (001) (Fig. 3A,B). Some of these pyramid faces (011) are unequally developed (Fig. 3C).

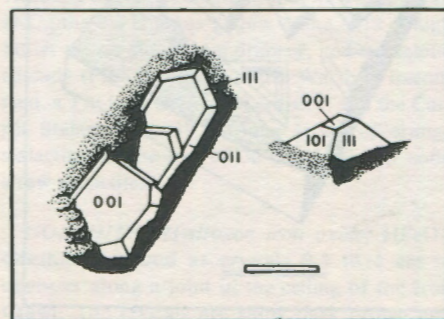
Near the south end of the East Stream Passage is a small group of white stalactites 2 cm in diameter and 8 to 10 cm long. The internal structures of these stalactites are complex (Fig. 4). A central tube of aragonite extends part way down the stalactite and is surrounded by multiple layers of variously colored aragonite, which appear in cross section as rings. These layers consist of crystals about 0.005 mm in diameter and of varying length and are simple first-order prisms (110). The outer layer is comprised of clear crystals 0.02 mm in diameter and about 0.4 mm long. These crystals are first-order prisms (011) and are tipped with combinations of first-order pyramids (011) and pinacoids (001). As in the forms found near the Soda Straw Room, some of the pyramids are



unequally developed. Irregular masses of clear quartz and muscovite sand are cemented to the outermost layer of aragonite of the stalactites by 0.1 to 0.3 mm long clear rhombs of calcite.

The most spectacular occurrence of aragonite in the cave is in the Blue Passage. Here, irregular masses of sea green flowstone 14 cm long and powder blue stalactites 30 cm long are present. An excellent color photograph of the Blue Stalactites is given as Plate 6 of Hill (1976). The surface of the sea green flowstone is comprised of 0.7 mm

Figure 6. Azurite crystal sketches from the Blue Stalactites area. Scale bar is 0.02 mm long.



long crystals (Fig. 5). Both first- and second-order prisms, (110) and (010), are present along with the (011) first-order pyramid and the (001) pinacoid. Some of the crystals are twinned along the (110) face.

Analysis of the sea green material showed 10,000 ppm strontium, 100 ppm copper, 50 ppm zinc, and 10 ppm nickel. The copper, possibly aided by the nickel, is responsible for the green and blue colors. The copper is derived from the oxidation of 1 to 2 mm blebs of chalcopyrite and bornite found scattered throughout the marble. In October, 1977, the Blue Stalactites had a pH of 7.4. The milky-white stalactites next to them had a pH of 6.2 on their surfaces and pH of 6.4 in a water drop suspended on one of the stalactite tips.

The low pH value and the uncorroded nature of the aragonite crystals suggest that the aragonite is being actively deposited. It has been suggested that high concentrations of strontium favor aragonite deposition over calcite (Curl, 1962), especially if the aragonite is a metastable phase (Lippman, 1973). The amount of strontium present in the Blue Stalactites closely approaches the values Murray (1951) suggested favor aragonite deposition.

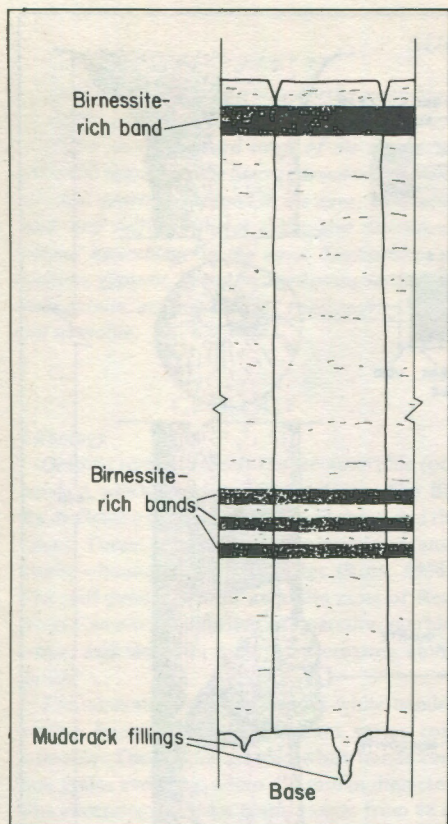


Figure 7. Cross section of 20 mm thick layer of very dark gray flowstone from the Baconrind Room.

AZURITE—Copper carbonate hydroxide; $Cu_3(CO_3)_2(OH)_2$. The Blue Stalactites area in Blue Passage and the Schrieber Complex contain thin, diffuse crusts of azurite. Also present in the Blue Passage are centimeter-in-diameter drusy masses of azurite crystals. The forms shown on the 0.5 mm long crystals at both localities are the basal pinacoid (001) and the second-order pinacoid (101) terminating first- and fourth-order prisms (001) and (111), respectively (Fig. 6). The copper at the Blue Passage is obtained from oxidation of both bornite and chalcopyrite blebs in the marble. The origin of the copper in the Schrieber Complex is more elusive, but seems to be derived from oxidation of chalcopyrite.

BIRNESSITE—Hydrous sodium calcium heptamanganese dioxide; $(Na,Ca)Mn_7O_{14} \cdot 3H_2O$. Birnessite covers the floor of a portion of the Jefferson Passage near the Soda Straw Room. The black coating is about 0.01 mm thick over a base of clastic sediments ranging from clay to boulders.

Dark gray to nearly black flowstone is present in the Baconrind Room, the Pillar Passage, the 2+2 Passage, and the Soda Straw Room. A sec-

tion of dark gray flowstone taken from the Baconrind Room shows four bands of birnessite 0.04 to 0.1 mm thick in a flowstone coating 20 mm thick (Fig. 7).

CALCITE—Calcium carbonate; $CaCO_3$. Calcite speleothems in Lilburn Cave include anthodites, coatings and crusts, conulites, coralloids, draperies, euhedral crystals, flowstone, helictites, microhelictites, moonmilk, cave pearls, cave pyramids, cave rafts, rimstone dams (gours), shelfstone, stalactites, and stalagmites. Colors range from nearly clear through milky white, white, yellow, tan, orange, red, brown, and gray to nearly black. Crystal sizes range from micron-sized moonmilk to 20 cm-long monocrystalline stalactites (Fig. 8).

Much of the milky gray calcite fluoresces pale powder blue under shortwave ultraviolet light and phosphoresces pale green upon removal of the ultraviolet light or discharge of an electronic flash unit. The fluorescence and phosphorescence build in intensity and duration with repeated excitation.

Chemically, the calcites sampled in the cave range from pure calcium carbonate to high magnesian calcite with up to 9 molepercent magnesian.

Euhedral crystals of calcite almost always occur in association with pools or former pools. In Lilburn Cave, the crystals are found as linings on bedrock pools and as cave rafts, rimstone pool

Figure 8. Sketches of monocrystalline stalactite fragment from the Soda Straw Room. (left) Sketch showing single cleavage surface at top, transverse ridges, and soda straw core. Scale bar is 1 cm long. (top right) Detail of etch figure on surface of stalactite. Also note parasite crystal at top center. (lower right) Approximate orientation of calcite rhomb in enlarged detail above.

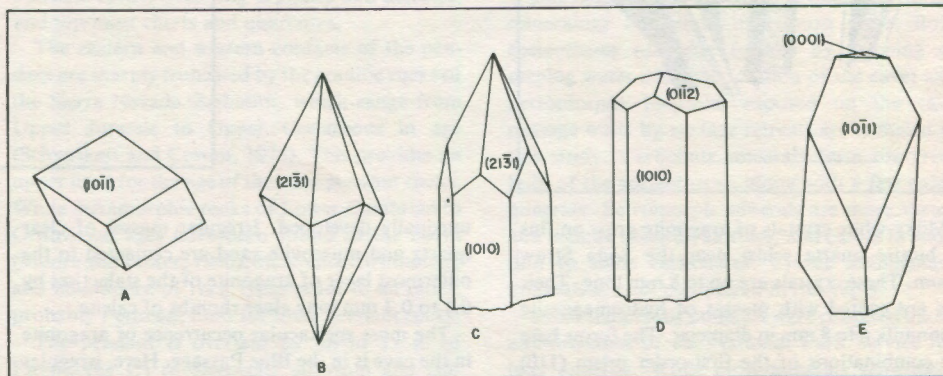
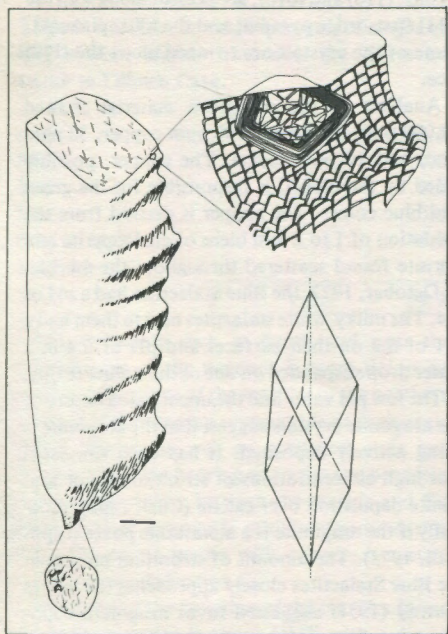
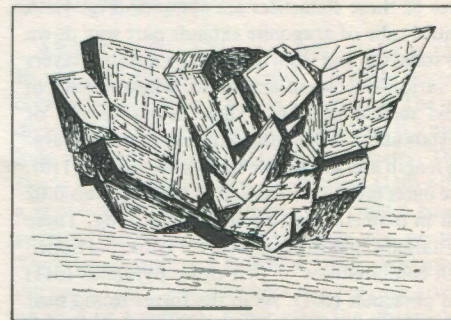
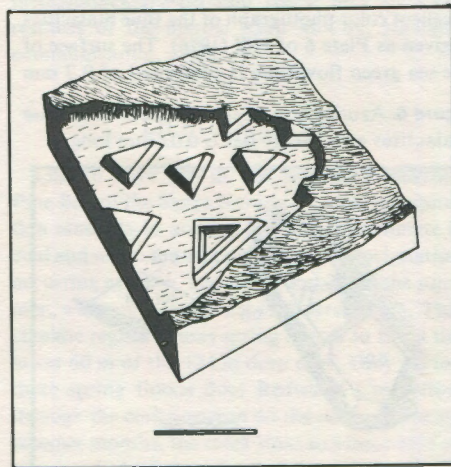


Figure 9. (above) Sketches of crystal forms of calcite found in Lilburn Cave. Figure 10. (left) Sketch of skeleton growth of calcite crystals in Pillar Passage. Scale bar is 1 cm long. Figure 11. (below) Sketch of calcite crystal masses found in a dry pool in Glacier Hall. Scale Bar is 1 cm long.



linings, and conulite linings. Common forms observed include the positive rhombohedron (10 $\bar{1}$ 1), the positive scalenohedron (2131), the first-order prism (1010), and the pinacoid (0001) (Fig. 9a,b,c,d, and e, respectively). In both the Pillar Passage and the 2 + 2 Passage are small pools that show skeletal growth of steep rhombohedral forms (Fig. 10).

Scalenohedral crystals (dogtooth spar) are well developed as wall linings and cave rafts at the south end of the Jefferson Passage, at the south end of the Crystal Crawl, and in the area of the Big Hungus Yellow Thing. Rhombohedral masses of 2 to 5 mm-wide crystals are present in an alcove of Glacier Hall (Fig. 11). Masses of what appear to be moonmilk in Glacier Hall are actually felted masses of minute prisms of calcite 0.005 mm in diameter and 0.12 mm long. The two common forms here are the first-order prism (0101) and the pinacoid (0001).

Calcite cave pearls range from 18 cm-long brick-shaped pearls in Meyer Pit to 2 mm-in-diameter spherical pearls at the Great White Pillar. Some of the pearls at Meyer Pit are formed around squirrel leg bones and are about a centimeter in diameter and 4 centimeters long. Near the Blue Stalactites are several cupcake-shaped and -sized yellow pearls with brown 'frosting.' The cores of these pearls are small pebbles of weathered biotite quartz schist about a centimeter in diameter.

At the Glacier, the pearls have developed overgrowths on their upper surfaces. Rhombohedral faces have grown on the ends of the radially oriented calcite crystals comprising the pearls in response to near-surface, super-saturated solutions in the surrounding water-filled pools. The very large pearls, such as those found at the Blue Stalactites and at Meyer Pit, tend to be irregular in shape, perhaps reflecting the irregular nuclei around which they formed. Large pearls, those up to about a centimeter in diameter, tend to be almost perfectly spherical. The largest of these spherical pearls, the Giant Cave Pearl, is about 3.5 cm in diameter (Fig. 12). Pearls half a centimeter in diameter and smaller tend to be tightly packed into their nests and, thus, are frequently irregular or cubical.

Helictites are not common. Scattered patches of up to 8 cm-long clear calcite helictites occur locally in the upper portions of the cave, especially in the northern and central areas. Many of these show rhombohedral cleavage patterns along their length. Among the speleothems present in the Baconrind Room and Complex are several helictites up to 17 cm long, stained bright orange with goethite (?) inclusions. One such helictite, 7 mm in diameter, makes 7 spirals in 9 cm, each spiral being approximately 15 mm in diameter. Several straight helictites a centimeter in diameter and 20 cm long are present at the top of Meyer Pit.

Microhelictites have been found in both the Black Stalactite Room and along the East Stream Passage. They average about 0.5 to 1 mm in diameter and range up to 1 centimeter in length. While

most of the microhelictites terminate in either scalenohedrons or steep-sided rhombohedrons, some have short soda straws developed at their ends. These soda straws are about 4 mm in diameter and from 2 to 4 mm long. Nearly all the microhelictites are transparent to translucent.

Calcite moonmilk has been identified near the Junction Room in the Double Scungy Chimney. Centimeter-in-diameter masses of very pale yellowish-white material are present as coatings and crusts both on the marble walls and on clastic fills. Electron photomicroscopy shows the typical, lath-like structure of *en echelon* stacked rhombohedrons which have probably nucleated around organic filaments (Fig. 13). These filaments may be either rod-like bacteria or actino-

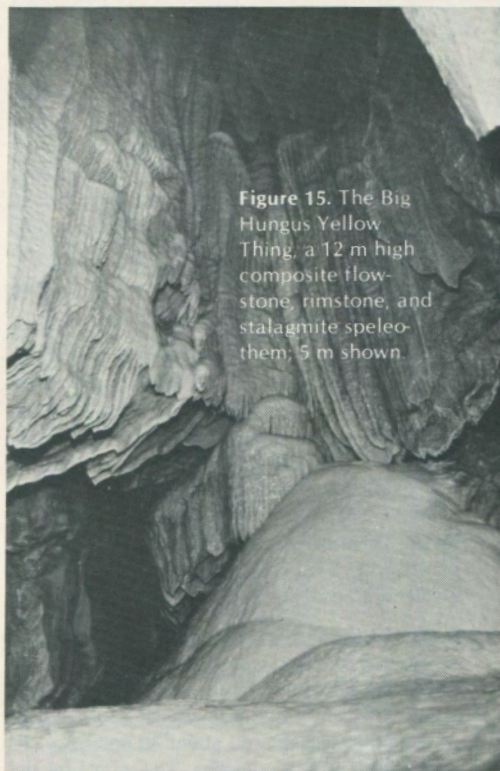


Figure 15. The Big Hungus Yellow Thing, a 12 m high composite flowstone, rimstone, and stalagmite speleothem; 5 m shown.



Figure 12. The Giant Cave Pearl. Note second pearl buried in rimstone. Toy bus is 3.7 m long.

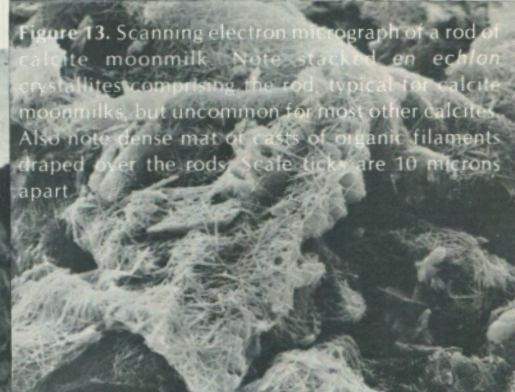


Figure 13. Scanning electron micrograph of a rod of calcite moonmilk. Note stacked *en echelon* crystallites comprising the rod, typical for calcite moonmilk, but uncommon for most other calcites. Also note dense mat of casts of organic filaments draped over the rods. Scale ticks are 10 microns apart.

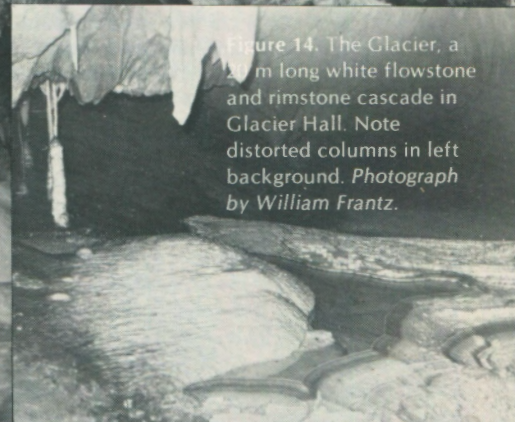


Figure 14. The Glacier, a 20 m long white flowstone and rimstone cascade in Glacier Hall. Note distorted columns in left background. Photograph by William Frantz.

mycetes (Rogers and Moore, 1976; Hill, 1976; Moore and Sullivan, 1978).

The outstanding calcite speleothems in Lilburn Cave are: the Glacier, a 20 m-long white rimstone and flowstone cascade (Fig. 14); the Jefferson Memorial, a 3 m-high, 2 m-thick white column resembling the Jefferson Memorial in Washington, D.C.; the Big Hungus Yellow Thing, a 12 m-high butter-yellow flowstone, drapery, and stalagmite cascade (Fig. 15); the Wonder Warthog Baconrind, a 3 m-long baconrind drapery; and the Carrot Stalactites, a 10 cm-long group of orange stalactites at the tips of 30 cm-long clear soda straw stalactites.

GOETHITE—Hydrogen iron oxide; HFeO_2 . Goethite is found as crystals 0.5 to 1 cm in diameter along a joint in the ceiling of the Iron Crawl. The crystals are shiny dark brown and

about 2 mm thick (Fig. 16). Forms noted include first-order prisms (011), second-order prisms (101), third-order prisms (110), and side pinacoid (010). The iron is derived from oxidation of chalcocopyrite blebs in the marble.

Shiny black stalactites 7 mm in diameter and 4.5 cm long and several-centimeter-square sheets of shiny black flowstone are present in the Black Stalactite Room. The stalactites have 0.1 mm-thick growth rings of goethite with rounded tips, but no central canal. The bases of the stalactites and the interiors of the flowstone masses consist of powdery rust-red hematite layers with a few shiny black layers (Fig. 17).

Millimeter-sized grains of a detrital silvery sulfide mineral are scattered sparsely throughout the flowstone. This sulfide may be arsenopyrite, which occurs in the nearby granitic rocks of the Giant Forest Pluton. The ceiling of the Black Sta-

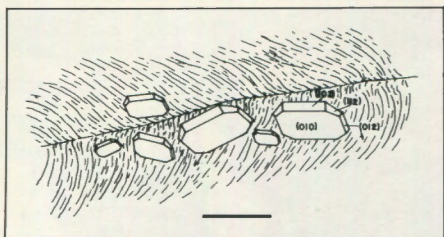


Figure 16. Sketch of tabular goethite crystals found along a joint in the ceiling of the Iron Crawl. Scale bar in 1 cm long.

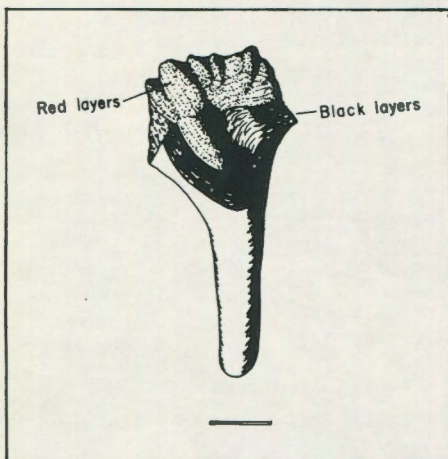


Figure 17. Sketch of 4 cm long goethite stalactite, showing the external shiny black layer and internal earthy, red layers. From the Black Stalactite Room. Scale bar is 1 cm long.

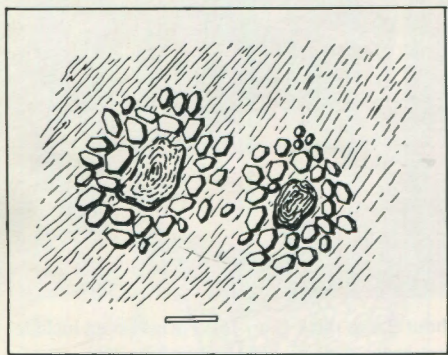
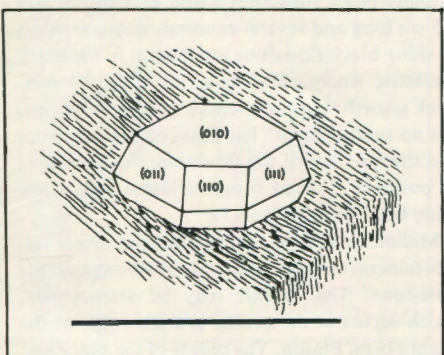


Figure 18. Sketch of centimeter in diameter gypsum crystals found in the Iron Crawl. Scale bar is 1 cm long.



lactite Room has several square meters of very fine-grained quartzite with small patches of sulfide minerals exposed. Oxidation of these sulfides is the source of the iron for the goethite and hematite in the speleothems.

On 2 to 3 m-long boudins of similar fine-grained quartzite in the Klein Bottle Room are small patches of flowstone, shiny black in color. While the bulk of the flowstone is goethite, small portions of the edges are reddish and may be hematite. As in the Black Stalactite Room, the oxidation of sulfide minerals is the source for the iron.

GYPSUM—*Hydrous calcium sulfate*; $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Gypsum flowers 0.1 mm thick and several mm long occur on a weathered pod of sphalerite and goethite in the wall of the Junction Room. In the nearby Iron Crawl, two forms of gypsum are found. The first consists of white, 0.2 to 10 mm-long tabular crystals that cluster around 10 to 15 mm-in-diameter patches of dried silt on the passage wall (Fig. 18). The crystals are flattened along the side pinacoid (010) with two fourth-order prisms, (110) and (111) (Fig. 19). The second form present in this passage are white, 1 to 3 cm-long and about 7 mm-thick crusts formed along ceiling joints.

In the Black Stalactite Room, gypsum fibers 0.04 mm thick and 1 mm long occur as 2 to 3 mm-diameter masses within the layers of goethite flowstone covering the quartzite. Evidently, the forms are greatly elongated first-order prisms (011), with front pinacoid terminations (100).

The source for the gypsum in each locality is the oxidation of sulfide minerals contained in the wall rocks. The Junction Room contains sphalerite; the Iron Crawl, chalcopyrite; and the Black Stalactite Room, arsenopyrite.

HEMATITE—*Ferric oxide*; Fe_2O_3 . A small amount of the dark gray flowstone found in the Baconrind Complex is colored by very fine-grained black hematite. Analysis of a bulk sample of the flowstone showed about 20 ppm iron, 10 ppm nickel, and 10 ppm zinc. The source for the hematite is unknown.

In the upper portions of the Baconrind Complex and near the Lilburn Entrance, earthy, red, ocherous varieties of hematite color many of the orange and red calcite flowstone cascades. Hematite also colors the spectacular Wonder Warthog Baconrind and the baconrind draperies that give the Baconrind Room its name.

As previously mentioned, hematite may be present in flowstone in the Klein Bottle Room and in stalactites in the Black Stalactite Room.

HYDROMAGNESITE—*Hydrous magnesium carbonate hydroxide*; $\text{Mg}_3(\text{CO}_3)_2(\text{OH}) \cdot 4\text{H}_2\text{O}$. Near the Soda Straw Room, hydromagnesite occurs as white masses of moonmilk 15 mm in diam-

Figure 19. (left) Detailed sketch of gypsum crystal found in the Iron Crawl, showing the faces present. Scale bar is 1 cm long.

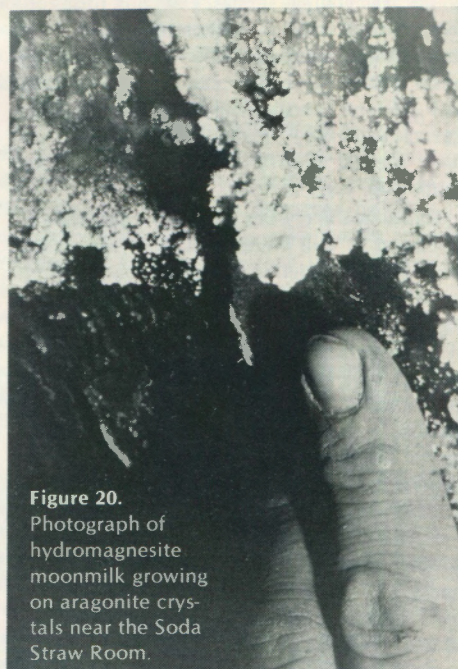


Figure 20. Photograph of hydromagnesite moonmilk growing on aragonite crystals near the Soda Straw Room.

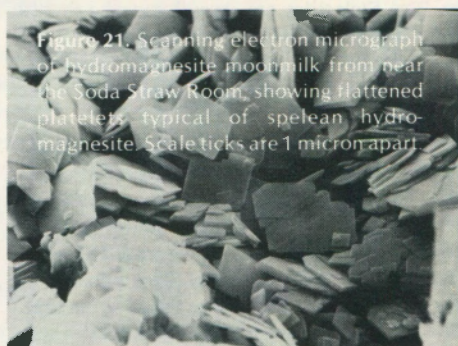


Figure 21. Scanning electron micrograph of hydromagnesite moonmilk from near the Soda Straw Room, showing flattened platelets typical of spelean hydromagnesite. Scale ticks are 1 micron apart.



Figure 22. Photograph of malachite angel hair located near the Blue Stalactites. Individual fibers are up to 2 cm long. One water droplet at the end of the fiber at center, it is approximately 3 mm in diameter.

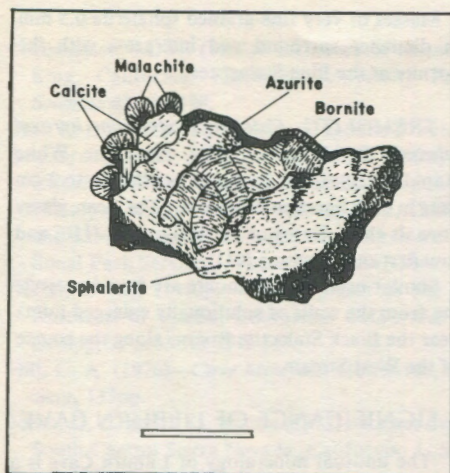


Figure 23. Sketch of a mass of sphalerite and bornite with encrusting malachite and azurite from near the Blue Stalactites. Scale bar is 0.5 mm long.

Figure 24. Malachite at Dons Descent. Note diffuse stain and fins of malachite formed along near vertical joint. Tip of ball-point pen provides scale.



Figure 25. Sketches of axinite crystals in the Lake Room showing forms present.

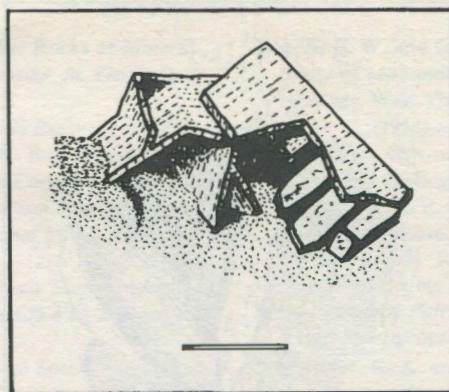
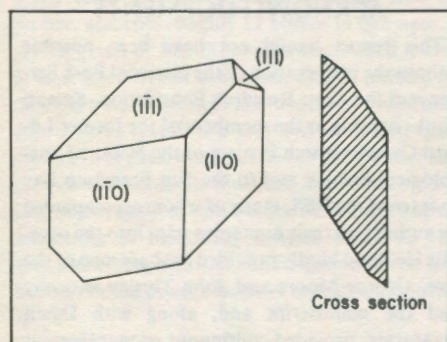
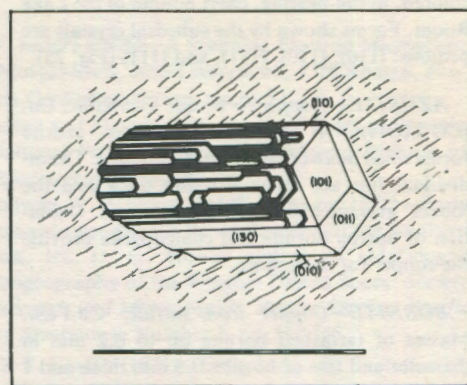


Figure 26. (left) Sketch of azurite boxwork at the Blue Stalactites. Note larger masses of azurite crystals at right edge of boxwork. Scale bar is 1 mm long. **Figure 27.** (right) Sketch of hornblende crystal from the Pillar Passage. Scale bar is 5 mm long.



eter. These colliform masses are perched on the tips of aragonite crystal groups (Fig. 20). Under the electron microscope, rectangular plates 0.04 to 0.1 micrometers thick and 0.5 to 4 micrometers long are seen. These plates show the forms of a front pinacoid (100), side pinacoid (010), and the second-order pinacoid (101) with flattening parallel to the (010) face (Fig. 21). The dark bands of the marble upon which the aragonite crystals and hydromagnesite moonmilk grow are more dolomitic than the white marble and may have provided the magnesium needed for the formation of the hydromagnesite.

MALACHITE—Copper carbonate hydroxide; $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$. The ceiling of the Iron Crawl exhibits diffuse stains of malachite a centimeter in diameter. The walls of Blue Passage display the following forms of malachite in localized areas: less than 1 mm-thick crusts, poorly formed crystals about 0.1 mm in length, and 6 cm-long masses of fibers up to 0.5 mm thick and 2 cm long. Some of these fibers may be malachite microhelictites, as water droplets hang from their ends (Fig. 22). Tiny pale bluish-green malachite fibers 0.05 mm thick and 1 mm long occur at this locality. One of these fibers makes two 360 degree turns in its 1 mm length. It may be that some of the pale fibers are rosaite - $(\text{Cu}, \text{Zn})_2(\text{CO}_3)_2(\text{OH})_2$. Malachite also forms 0.04 mm diameter spherical aggregates of crystals on corroded calcite grains adjacent to masses of sphalerite and bornite at this locality. The sulfide masses are about 1.5 mm in diameter (Fig. 23).

On a pendant overhanging the lake in the Lake Room, malachite forms a thin film extending over a diffuse maze of cracks in the marble. Pale green malachite on a pendant near the lake shore forms a circular, thin film mimicking a doubly plunging fold in the marble which is outlined by a dark band. At Dons Descent, a circle of malachite about 5 cm in diameter is formed along a nearly vertical joint in the marble. Below the circle of malachite, several linear fins of calcite and malachite up to a centimeter long extend 2 to 5

mm outward from the cave wall along the joint (Fig. 24). There is an area faintly stained by malachite on the silt and fine sand floor 20 cm below these fins. Diffuse stains of malachite cover an area of about 6 cm² on the surface of a pink chert boudin at River Pit (Gail McCoy, personal communication, 1980).

The source for the copper at all of these locations is 0.5 to 2 mm long blebs of chalcopyrite in the marble. Often, this chalcopyrite is concentrated along the darker bands of the marble or along joints. At the Blue Stalactites, the primary sulfide is bornite. Minor amounts of chalcopyrite are also present.

WAD—Cryptocrystalline mixtures of manganese and heavy metal oxides. Many of the passages in the upper cave, especially in the area of the Baconrind Complex, have black coatings both on marble and on clastic sediments. While most of these appear amorphous to X-ray diffraction analysis, X-ray fluorescence has shown the major constituents to be iron and manganese, thereby prompting the use of the term 'wad.' Blackish brown crusts 1 mm thick occur on dikes of Big Baldy Granite in the Contact Room. Other coatings occur in and around the Lake Room and in the Baconrind Complex.

WITHERITE—Barium carbonate; BaCO_3 . Wet chemical analysis has shown that a white crust from the wall of the East Stream Passage contains large amounts of barium and carbonate, very little calcium, and no zinc. This material could not be relocated on subsequent trips, thus precluding further identification of the mineral. However, it is assumed that the mineral is witherite, based on the chemical analysis and on the physical properties observed.

Petromorph Minerals

AXINITE—Calcium, manganese, iron, aluminum, hydroxyl boro-silicate; $(\text{Ca}, \text{Mn}, \text{Fe})_3\text{Al}_2(\text{OH})(\text{BO}_3)\text{Si}_4\text{O}_{12}$. Axinite is found as 2 to 4 mm-long, amber-colored crystals on a lavender-

colored, pyrite-bearing, chert boudin in the Lake Room. Forms shown by the euhedral crystals are pedions: (110), ($\bar{1}\bar{1}0$), (111), and ($\bar{1}\bar{1}\bar{1}$) (Fig. 25).

AZURITE—Copper carbonate hydroxide; $\text{Cu}_2(\text{CO}_3)_2(\text{OH})_2$. At the Blue Stalactites, azurite forms small boxwork complexes (Fig. 26). The individual fins are about 0.1 mm thick and the 'boxes' average about 1 to 2 mm across. Oxidation of nearby bornite and chalcopyrite provide the copper for the azurite.

BORNITE—Copper iron sulfide; Cu_5FeS_4 . Masses of tarnished bornite up to 0.2 mm in diameter and fins of bornite 0.5 mm thick and 1 centimeter long are present in the area of the Blue Stalactites. The small masses of bornite are intergrown with sphalerite and are covered by secondary copper carbonate minerals (Fig. 23).

CHALCOPYRITE—Copper iron sulfide; CuFeS_2 . Blebs of chalcopyrite 0.1 to 2 mm in diameter are present in areas of the cave that contain secondary copper carbonate minerals. Much of the chalcopyrite is concentrated along darker, more dolomitic bands in the marble. Although most of the blebs are colliform structures, some of the larger blebs in the Iron Crawl show partial sphenoid forms (112) up to 0.1 mm long.

DIOPSIDE—Calcium magnesium silicate; $\text{CaMgSi}_2\text{O}_6$. Fins of diopside 0.5 mm thick support the fibrous malachite near the Blue Stalactites.

GOETHITE—Hydrogen iron oxide; HFeO_2 . A pod of goethite 2 cm thick in the wall of the Junction Room carries many corroded sphalerite crystals. The goethite remaining after the zinc is removed is earthy-ocherous-red in color and has an earthy-to-spongy texture.

HEMATITE—Ferric iron oxide; Fe_2O_3 . Near the Soda Straw Room, a band of white marble is stained pale pink by polysynthetic twinned crystals of partly oxidized specular hematite ('Iron Roses'). Forms observed on the crystals, which are 0.08 to 0.2 mm in diameter and 0.02 to 0.04 mm thick, include the pinacoid (0001) and the rhombohedrons ($10\bar{1}1$) and ($1\bar{1}01$).

HORNBLLENDE—Complex hydroxyl aluminosilicate; $(\text{Na}, \text{Cl})_{2-3}(\text{Mg}, \text{Fe}^{2+}, \text{Fe}^{3+}, \text{Al})_3(\text{Al}, \text{Si})_5\text{O}_{12}(\text{OH})_2$. In the Pillar Passage, black hornblende crystals in a mass 15 cm long occur near thin pods of biotite quartz schist (Fig. 27). The crystals are up to 6 mm long and show forms including the side pinacoid (010), second-order pinacoid (101), first-order prism (011), and third-order prisms (110) and (130). X-ray diffraction shows that the crystals are a mixture of both hornblende and traces of grunerite, $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$.

PYRITE—Iron disulfide; FeS_2 . Small masses of pyrite up to 3 mm long exist in the lavender-colored chert pods found in both the Lake Room and River Pit. No crystal faces are present.

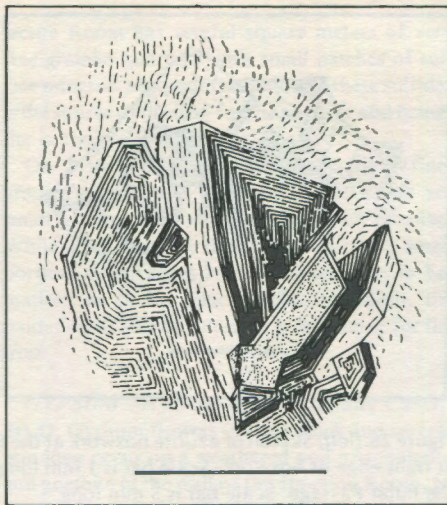


Figure 28. Sketch of sphalerite crystals from pod of goethite in the Junction Room. Note that some of the crystals are solid sphalerite throughout, while some have had their internal portions replaced with earthy, red goethite. Scale bar is 1 cm long.

SEPIOLITE—Hydrous magnesium silicate hydroxide; $\text{Mg}_3\text{Si}_6\text{O}_{15}\cdot 6\text{H}_2\text{O}$. A block of marble 3 m square near the north end of That Room has dropped about 12 cm from a nearly horizontal joint. The joint is filled with sepiolite 'mountain leather.' The sepiolite sheet averages about 1 mm thick, although it locally thickens to nearly a centimeter. Portions of the mountain leather hang down as much as 4 to 5 cm into the opened joint. Individual platelets of sepiolite about 0.8 mm in diameter and 0.06 mm thick are formed of sheets of sepiolite crystals about 0.002 to 0.005 mm in diameter. The platelets have formed around grains of marble and have retained their folded shape after solution of the marble.

In a side canyon near the Klein Bottle Room, pods of white, flexible sepiolite 12 mm thick are covered by small, linear masses of calcite crystals up to 2 mm long.

A nearly horizontal sheet of sepiolite near the middle of the East Stream Passage is 2 mm thick and covered with a thin film of dark gray wad.

SPHALERITE—Zinc sulfide; $(\text{Zn}, \text{Fe})\text{S}$. Dark, ruby-red to black crystals of sphalerite occur in the goethite pod in the wall of the Junction Room. The crystals have highly corroded margins and range from 2 to 25 mm long (Fig. 28). Analysis of a bulk sample of the pod shows nearly 30 percent by weight zinc. Goethite present between the sphalerite crystals has banding that mimicks the outlines of the crystals, suggesting that nearly 50 percent of the volume of the crystals has been altered to goethite by removal of the zinc. A single sphalerite crystal was analysed for other elements and found to contain 4 percent iron and 0.1 percent manganese. Forms shown by the corroded crystals include cubes (001) and tetrahedrons (111).

Masses of very fine-grained sphalerite 0.5 mm in diameter surround and intergrow with the bornite at the Blue Stalactites.

TREMOLITE—Calcium magnesium hydroxyl silicate; $\text{Ca}_2\text{Mg}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$. Near the White Rapids, tremolite is found as needles up to 1 cm long in dark bands in the marble. The clear, glassy crystals show forms of vertical prisms (110) and low first-order prisms (011).

Similar needles of tremolite are found projecting from the walls of solutionally enlarged joints near the Black Stalactite Room, along the course of the West Stream.

SIGNIFICANCE OF LILBURN CAVE

The unusual mineralogy of Lilburn Cave is a reflection of the complex geologic setting at the cave. The interface of metamorphic and igneous rocks and their attendant solutions has allowed the formation of the varied minerals present in the cave.

Little has been written on the occurrence of copper-bearing speleothems. In Lilburn Cave, however, observations may be made on both the resulting forms and on the mechanisms responsible for them.

The gypsum speleothems in the cave, while not large or varied, allow observations on their development via a somewhat different route than at most other limestone caves. In most other accounts, the origin of the gypsum is ascribed to ground water solution charged with sulfates travelling from a source to the cave where speleothem development occurs. In Lilburn Cave, we can see that direct development of speleothems has taken place on the sources of the sulfate-bearing solutions.

The occurrence of actively forming aragonite in a cool (9°C) cave environment and in the presence of large amounts of strontium lends support to an origin controlled largely by chemistry rather than by temperature (Moore and Sullivan, 1978).

The tentative identification of the barium mineral, witherite, marks its first occurrence in spelean environments.

Finally, the listing of petromorphic minerals found in the cave is presented with the hope that other researchers will be encouraged to study this neglected facet of spelean mineralogy.

ACKNOWLEDGEMENTS

This report would not have been possible without the cooperation of the National Park Service and the Cave Research Foundation. Special thanks are due to the members of the former Lilburn Cave Research Project of the National Speleological Society and to the San Francisco Bay Chapter of the NSS, many of whom accompanied the authors on their numerous trips into the cave. Ellis Hedlund kindly provided the base map of the cave. George Moore and John Tinsley critically read the manuscript and, along with David DesMarais, provided continuous encouragement during all phases of this study.

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The Recovery of Mount St. Helens

Principal Investigators:

Dr. Virginia D. Adams &
Dr. A. B. Adams

Site: Mount St. Helens, Washington

Disciplines: Botany, ecology, population biology

Mt. St. Helens erupted May 18, 1980, spewing more than a cubic mile (400 million tons) of 1200°F volcanic ash over twelve miles into the air. The eruption shortened Mt. St. Helens' peak by 1,200 feet, downed 3.2-million-board feet of timber, and cost roughly \$1 billion in damages.

Every part of Mt. St. Helens was buried under at least one layer of ash, mud, debris, pumice or downed trees. Although the mountain's mud and debris flows resemble a grey-brown desert, they are rich in organic matter. The ash and pumice are packed with minerals (but lack usable nitrogen). Life begins again as rain washes off the ash and as wandering or burrowing animals break up the ash, promoting aeration and irrigation of the soil and providing minute hollows to trap windborne seeds.

Immediately after the eruption, ecologist Dr. Virginia Adams and her husband, botanist Dr. A. B. Adams, both of the University of Washington, started monitoring life's renewal on a littered and muddied blowdown area in the "Red Zone" northwest of the devastated mountain. Their goal for this year is to discover and document the mechanisms of species turnover as plants repopulate the razed area around Mt. St. Helens.

Field Conditions: The Adamases, experts on Mt. St. Helens, will lead EARTHWATCH teams into the "Red (devastation) Zone" to map and monitor the progress of existing vegetation plots, stake out new ones, and trap windborn seeds for analysis. Volunteers will also measure leaf transpiration and water pressure in plant stems to determine how fast and efficiently different plants are making food and to observe whether the fast-growing plants dominate.

Teams will camp and share chores in rural Kid Valley—120 miles from Seattle and a thirty minute's drive to the work site. Facilities are primitive (no running water or electricity), but meals are varied and plentiful. Mosquitoes, blowing ash, and rough terrain (rubble, fallen trees) are the main hazards. Volunteers will work on a rough 9-to-5 schedule with evenings and the middle weekend free to explore this striking landscape.

EARTHWATCH®

10 Juniper Road
Box 127
Belmont, Massachusetts 02178
(617) 489-3030

Team I: Jun 6-19, 1982
Team II: Jul 25-Aug 7
Team III: Sep 5-18

Staging Area: Seattle, Washington
Share of Costs: \$835

ZOÖGEOGRAPHY of CAVE COLLEMBOLA East of the Great Plains

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WOLFRAM DUNGER in 1969 pointed out that the relative immobility, ubiquity, antiquity, and dietary flexibility of Collembola should make them excellent tools for zoögeographic analysis. In spite of this, relatively little has been written on the biogeography of the group. Salmon (1949) and Delamare (1951, pp. 278-305) give brief general views of the topic. Dunger (1972) and Szeptycki (1967) both examine European faunas with regard to glacial relict distributions. Two other major works are by Rapoport (1968, 1971), who examined Neotropical and Antarctic faunas in the light of modern acceptance of the reality of continental drift. Other authors have looked briefly at biogeography as addenda to systematic studies (Massoud 1967a, Stach 1951). An interesting recent work by Blackith and Blackith (1975) uses principal coordinates to study collembolan distribution. This work depends upon two totally unreliable U.S. species lists, making its utility for the Nearctic region very questionable.

There are several good reasons for the short bibliography above. In the first place, the collembolan fossil record is very poor. The oldest fossils are of one species of Devonian age (Massoud, 1967b), but the taxonomic position of this species, as well as that of a single Cretaceous fossil (Delamare and Massoud, 1968), is uncertain. The more abundant Tertiary fossils all belong to extant genera occurring at present in the same regions (Handschin, 1926; Christiansen, 1971), and the same may even be true of a recently discovered Lower Permian entomobryid (Riek, 1976). This meager fossil record strongly suggests a generally bradytelic and conservative group. Secondly, the phylogenetic relationships between genera and families are still not completely clear, and phylogeny within extant genera has been treated only for *Xenylla* (da Gama, 1969, 1976) and *Triancantheta* (Najt, 1974). The final problem is that the present distribution of Collembola is still poorly known. If we concentrate on one habitat, caves, we can manage to avoid many of these problems.

The cave Collembola east of the Great Plains are far better known than those of any other Nearctic group of the order, thanks to the efforts of Tom Barr, Stewart Peck, John Holsinger, James Gardner, and a host of other speleologists. In addition, other authors have done some analysis of phylogeny of a number of groups. Thus, this is a fertile field for zoögeographic study.

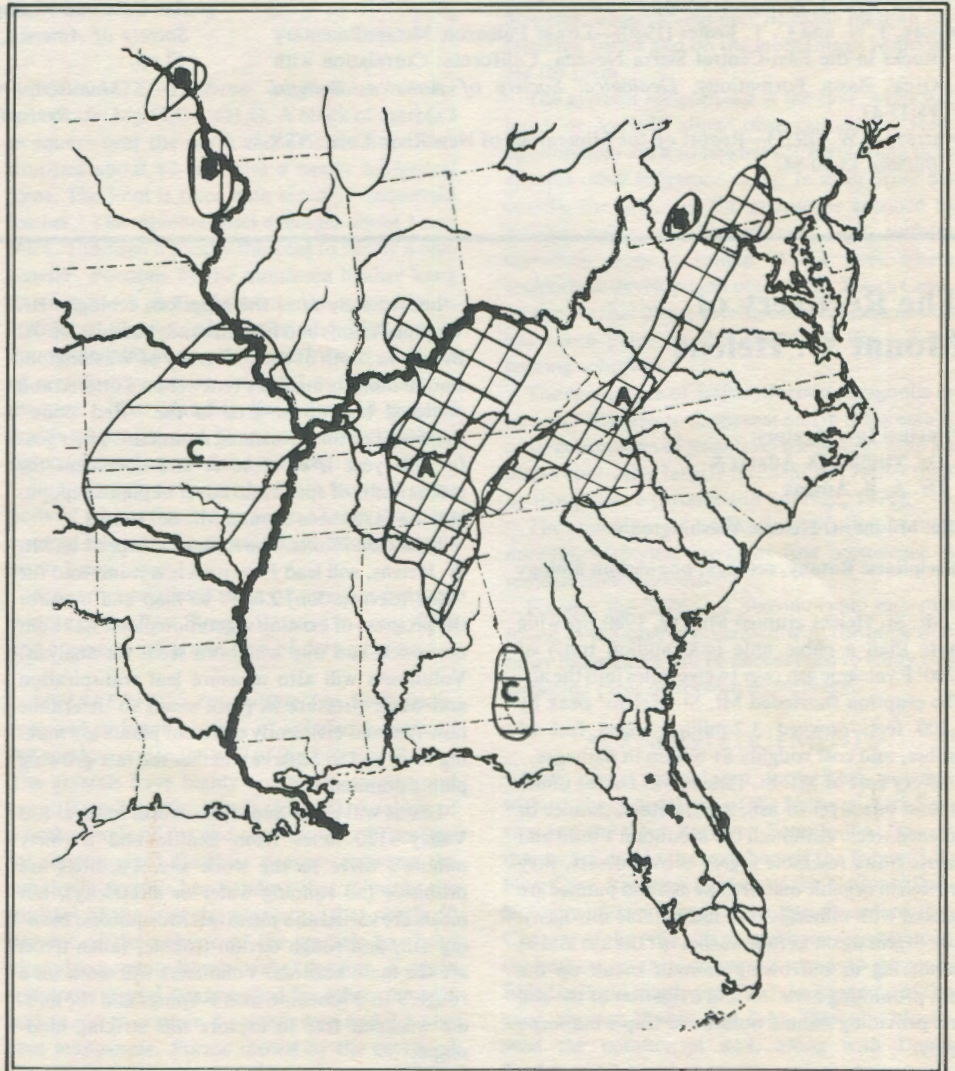
SUMMARY

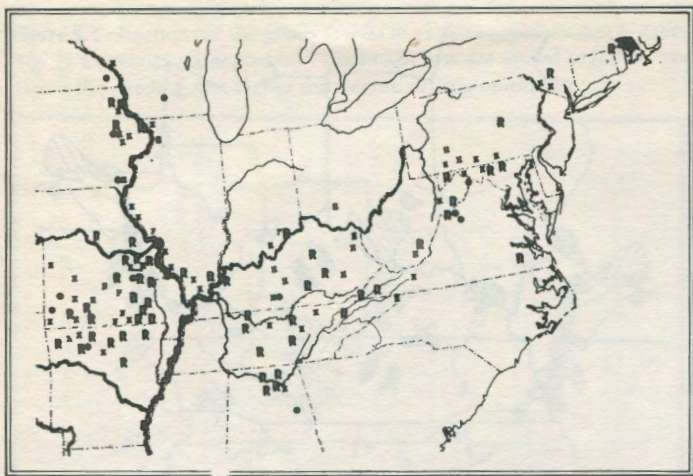
The distribution patterns of 92 species of collembola found in North American caves can be classified in 5 categories: 1) Epigeic species with rare opportunistic cave occupation, 2) Trogliphilic species with opportunistic cave occupation, 3) Trogliphilic species with scattered pockets of cave occupation and adaptations, 4) Troglotitic species with a single successful cave invasion and subsequent largely underground spread, and 5) Troglotitic species which have evolved separately in different systems by parallel speciation. Troglomorphy tends to increase from pattern 1 to patterns 4 or 5.

The caves occupied by these species can be broken into 3 major categories: A) Glaciated-area caves, B) Heartland caves, and C) Non-glaciated, non-heartland caves. The 3 cave areas show very different patterns in cave occupation and in major taxonomic groups. Thus, distribution pattern 2 dominates in A and C caves and patterns 4 and 5 in B caves. Taxonomic groups show similar differences. The subfamily Entomobryinae, which shows the greatest troglomorphy, dominates in B caves, while the families Isotomidae and Onychiuridae, which show the least troglomorphy, dominate in A caves. Type C caves are intermediate and have the highest percentages of Tomocerinae and Sminthuridae, which are intermediate in degree of troglomorphy.

Figure 1. Major cave areas in eastern United States with known collembolan faunas.

A Heartland and adjunct regions. B Glaciated region caves. C Non-glaciated, non-heartland caves.





▲ *Arrhopalites pygmaeus*. × *Tomocerus flavescens*. ● *Sinella caeca*.

Figure 2. Cave distributions. Each symbol represents one county (the number of recorded caves in each varies from 1 to 9).

CAVES STUDIED

The caves in the area under consideration fall into 3 major groups. The first group, which I will call the heartland (see Fig. 1), includes the caves of the 6 major Southeastern systems outlined by Barr (1968). The second is the glaciated region. Even though many of these caves are substantially unmodified by glaciation, it is unlikely for many reasons that their present fauna entered much before Late Pleistocene time. The last group includes southern caves outside the heartland. Most of these in the present study are in Missouri and Arkansas. Troglotic forms are largely limited to caves of this and the heartland areas.

NATURE OF CAVE OCCUPATION

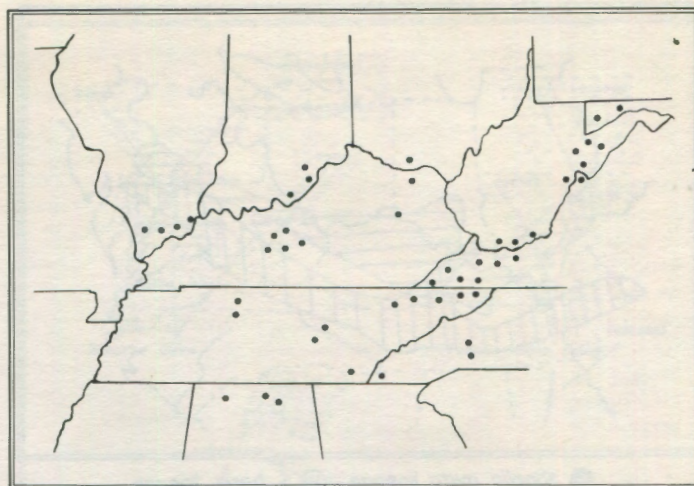
Troglotic forms are those which can reproduce only in caves, whereas trogliphilic forms can reproduce both in and out of the cave environment. Either type of animal may display varying degrees of troglomorphy, or clear specialization for cave life. Troglotites appear to spread largely underground, although short above-ground hops may occur. Trogliphilic distributions are of 2 sorts. In one type, cave invasion is opportunistic but frequent, *i.e.*, widespread and apparently limited only by suitable empty niches (Fig. 2). In the second, cave occupation is also opportunistic but is clumped and limited, suggesting rare successful cave invasions followed by underground and/or short above-ground spread (Fig. 3). In this latter type of trogliphilic distribution, as well as in many troglotic distributions, there are occasional populations in isolated caves. In some cases, this is probably the result either of isolated invasion or of parallel evolution. In other cases, it is impossible to tell whether this is the case, or whether the distribution is a vestige of a now broken but previously continuous range. Clumping of localities occurs even in patterns of opportunistic

species. In some cases, this probably is merely a reflection of very extensive opportunistic invasions in areas where little competition exists in the caves. In other situations, it appears that there are scattered pockets of successful cave adaptations in a generally opportunistic species.

In the next few sections of this paper, distributions of the major groups of Eastern Nearctic cave Collembola will be examined, and an analysis of biogeographic patterns will be presented. Throughout this work, I shall use the term 'parallel speciation.' This concept was first developed by Christiansen and Culver (1968). It refers to the independent parallel development of the same morpho-species by two separate lineages. It is, therefore, an extremely precise parallel evolution where the end products resemble each other so closely in behavior, form, and ecology that they can be called members of the same species.

Those forms, thus, are 'species' in the sense of Gisin (1964), that is, morphologically defined, phenotypically discrete units. They may also well be operational species (Doyen and Slobodchikoff, 1964), but they are not species in the classical biological species sense of a hologamodeme. I have ceased to use this generally accepted model in cave Collembola, primarily for 2 reasons: First, the concept requires data concerning interbreeding ability which are rarely available; Second, the biological species model, if rigidly applied, would make every troglomorphic, troglotic cave population a separate species. I do not feel that this would serve any useful purpose in my analyses.

In all discussions of phylogeny, I shall describe existing species as having evolved from each other or from very similar forms. That is, the more primitive extant species represent forms very similar to the historical ancestors and consist of surviving, unmodified progeny of these. An alternate view is that each species evolved from



○ *Tomocerus bidentatus*.

Figure 3. Cave distribution. Each symbol represents one county (the number of recorded caves in each varies from 1 to 14).

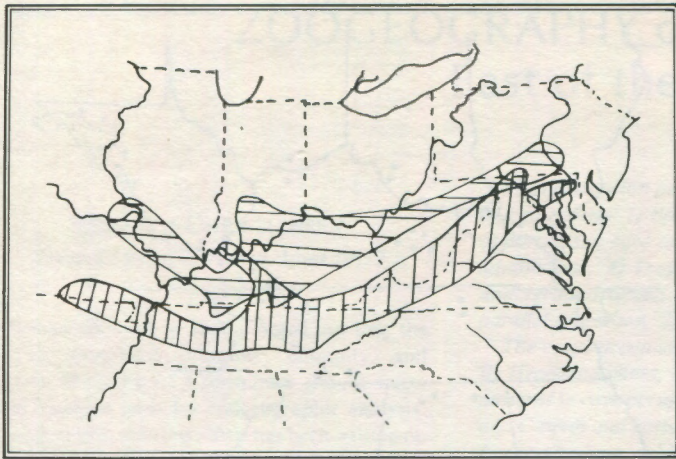
dissimilar ancestors, and one form has retained more primitive or ancestral features than the other. Neither view can at present be effectively verified; however, the former is easier to present and better satisfies the data available. The genus *Sinella* illustrates the problems involved in this study and is a good starting point for viewing the evolutionary cave zoogeography of the region.

ENTOMOBRYINAE

Genus *Sinella*

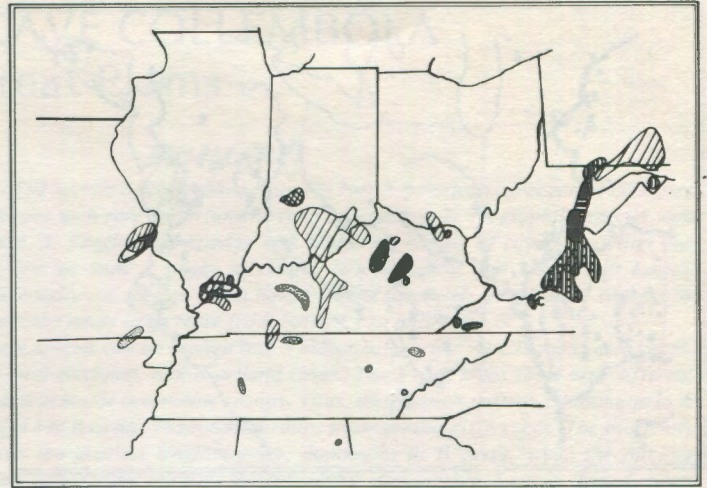
Two surface (epigeic) species of this genus are occasionally found in eastern caves. The first, *S. caeca*, is common (Fig. 2), whereas the second, *S. curviseta*, is known from only 2 caves. Both species appear to be opportunistic cavernicoles. The remaining cave species fall into 2 groups, here named the *avita* and *barri* lineages after their putative most primitive forms (Fig. 4). The species *avita*, *alata*, *cavernarum*, *basidens*, and *krekeleri* all belong to the former, while *barri*, *hoffmani*, and *agna* belong to the latter. The 2 groups occupy essentially non-overlapping ranges; the *barri* lineage is more southern and eastern than the *avita* lineage. The actual distributions of the species concerned is totally allopatric and highly subdivided (Fig. 5); however, neither group extensively occupies any central region of the heartland or unglaciated marginal caves. Rather, they seem to occupy the northern and eastern margins of the heartland and scattered caves between the Missouri-Arkansas and heartland regions. The genus is also well represented in California caves, with 2 apparently troglotic species. The distribution of the more primitive as contrasted with the more advanced species is also of interest.

The proposed phylogenies of these 2 groups, as well as that of the genus *Pseudosinella*, are shown in Figure 6 (Adapted from Christiansen [1961] and Christiansen and Culver [1968]; additions of



⊖ *Sinella avita* lineage. ⊖ *S. barri* lineage.

Figure 4. Inclusive distribution of species. The actual pockets of occupation are widely separated.



● *Sinella agna*. ● *S. alata*. ⊖ *S. avita*. ⊖ *S. barri*. ⊖ *S. basidens*. ⊖ *S. cavernarum*. ⊖ *S. curviseta*. ⊖ *S. hoffmani*. ● *S. krekeleeri*.

new species to the scheme were made using the same methods followed in those works).

Examination of figures 5 and 6 reveals some interesting phenomena. First, it can be noted that troglomorphic forms (troglomorphic or not), and non-troglomorphic forms that are known only from caves (*i.e.*, apparent troglobites), all have highly fragmented ranges. In contrast, the troglomorphic troglobites have generally compact ranges and are generally the sole Entomobryinae occupying their cave systems. An important exception to this is *Sinella basidens*, with 2 widely separated cave clusters. The development of these widely separated, highly troglomorphic troglobites is difficult to explain except as an example of parallel evolution from some *S. cavernarum*-like ancestor.

At the other extreme, the widely scattered populations of *S. barri* argue for a previously continuous range now fragmented into discrete cave refugia. The single surface collection of these species is from Fayette County, Indiana, well outside the present range of the cave forms.

S. hoffmani poses a different problem. Here, it is difficult to see whether the present fragmented distribution is the result of parallel evolution from a *barri*-like ancestor or represents the vestiges of a previously continuous range. There are 3 surface collections. The first is in West Virginia, near a cave entrance. The other two, from North Carolina, are well outside the present cave range of the species; however, the identity of these specimens is questionable.

A second feature of note is the fact that the westernmost collections of both lineages are representative of the most primitive species found in the group. The putative common ancestor of both lineages, *Sinella aera*, is a surface form found only on the west coast, as are most of the surface species of this genus.

Genus *Pseudosinella*

In contrast to *Sinella*, the surface species of *Pseudosinella* are largely eastern forms. This

genus differs from *Sinella*, also, in having a much greater variety and complexity of species groups. First, there are a number of undescribed species in this genus, some of which will be referred to here. New forms will undoubtedly continue to be uncovered as collections improve. Thus, the phylogenies presented are not at all complete. Second, numerous surface species (*P. alba*, *P. octopuncta*, *P. rolfsi*, *P. collina*, *P. sexoculata*, and *P. violenta*) are opportunistic cave forms and appear to have no derivative cave species.

In addition to these unrelated species, there are 4 clearly related groups of cave species. The first is a cluster of 3 species, *P. españa* from Arkansas, sp. z from Tennessee, and *P. certa* from West Virginia. All appear to be troglomorphic troglobites of unknown interrelationship or ancestry. The proposed phylogenies of the remaining 3 lineages are illustrated in Figure 6. *Pseudosinella folsomi* is a surface species from the South. *P. aera* and *P. argentea* are known from numerous cave and surface localities. All other species are primarily cave forms, known from 1 (rarely 2) or no surface localities. *P. aera* ranges from Texas to the Appalachians. All the other species appear to be limited to the U.S. east of the Great Plains. In the section below, I shall discuss the distribution and phylogeny of each of these 3 groups: The *argentea* group, the *orba* group, and the *hirsuta* group (each named after their most abundant species).

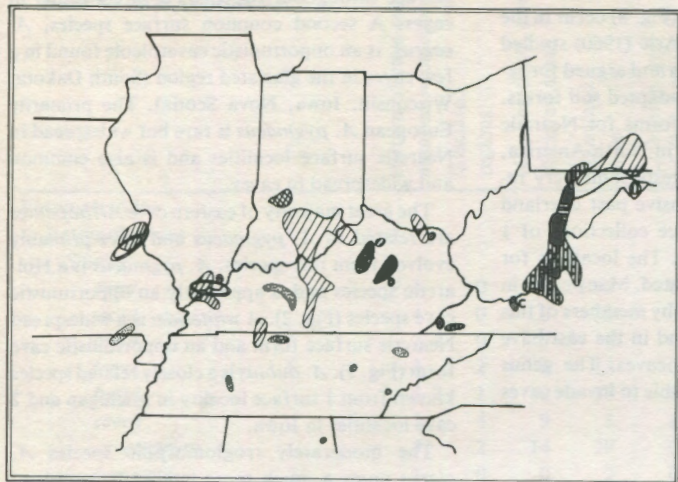
P. argentea group. *Pseudosinella aera* is similar in many respects to what one would expect of an ancestral form for this group. The labial and abdominal chaetotaxy as well as the eye and foot structure would all fit the role well. The distribution would also be apt, since this species had both the widest distribution and the largest percentage of surface localities of any species of the lineage (Christiansen and Bellinger, 1980, v. 2). The cephalic chaetotaxy, however, is different from others of the lineage, so that the question of the relationship remains open. *P. argentea* is prob-

ably a group of intricately inter-related forms (Weichsel, 1980), with the southern cluster of Arkansas cave forms differentiated from the remainder. The great majority of cave collections are from the Missouri-Arkansas cave region. Occasional, probably opportunistic, cave populations occur around the margin of the heartland. Surface collections have been made from Louisiana and Illinois to Connecticut. *P. nata*, known from a single Alabama heartland cave, is clearly related to *argentea*, but the nature of this relationship is obscure (Fig. 6). *P. pecki* is also related, but in this case it is clear that the species is more troglomorphic than *P. argentea*. There are 3 apparently discrete cave populations of *P. pecki* (Fig. 7), and the degree of troglomorphy is greatest in the southernmost of these.

In summary, this species group appears to show first a widespread surface form with a number of invasions of caves. Several of these invasions have resulted in local adaptation and the development of primarily troglomorphic forms. In the case of the Missouri-Arkansas region, however, this was not accompanied by clear speciation or by any great increase in troglomorphy; in the *P. pecki* cluster, it was. Whether the 3 populations of this species are remnants of a previously larger distribution or a case of parallel speciation is unclear.

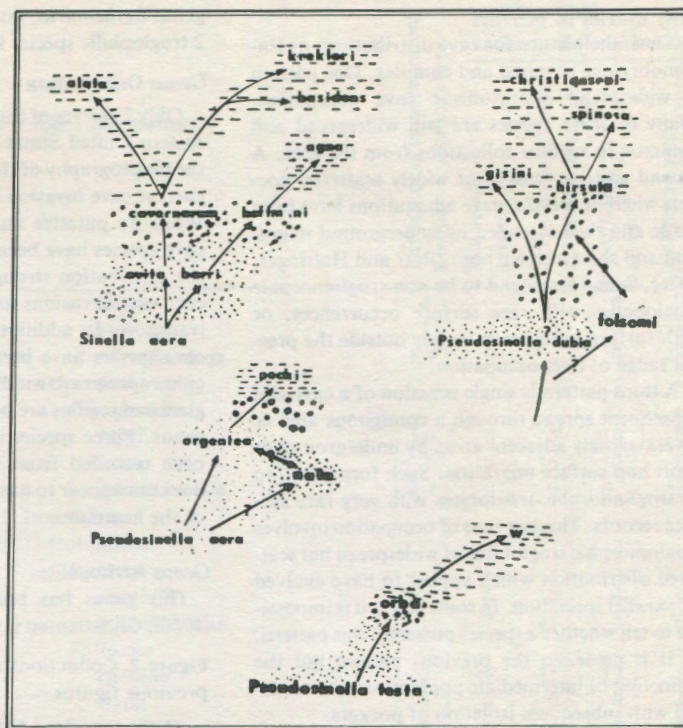
P. orba group. This group of species apparently is limited to the caves of the southeastern margin of the heartland. The relationship between *P. testa* and the other species is questionable, because there are many differences in chaetotaxy between it and the other species; however, it clearly is more similar to primitive *orba* populations than to any other Nearctic species. If they are related, then *testa*, with eyes and pigment, would clearly be more like the putative ancestor than the much more highly troglomorphic *orba* and species w. With the exception of species w, these forms appear all to be part of a single invasion and subsequently largely underground spread. An interesting note is that the form outside the group

Figure 5. Collections of the genus *Sinella* in eastern caves, except *S. caeca* (Fig. 2). Localities separated by 1 county or less are joined together. The darker the shading, the higher the degree of troglomorphy.



○ Surface (only) ● Surface (primarily) ⊙ Non-troglomorphic troglophile ⊕ Troglomorphic troglophile ⊖ Troglomorphic troglobite.

Figure 6. Proposed phylogenies for cavernicole lineages of *Sinella* and *Pseudosinella*, showing level of cave adaptation and occupation.



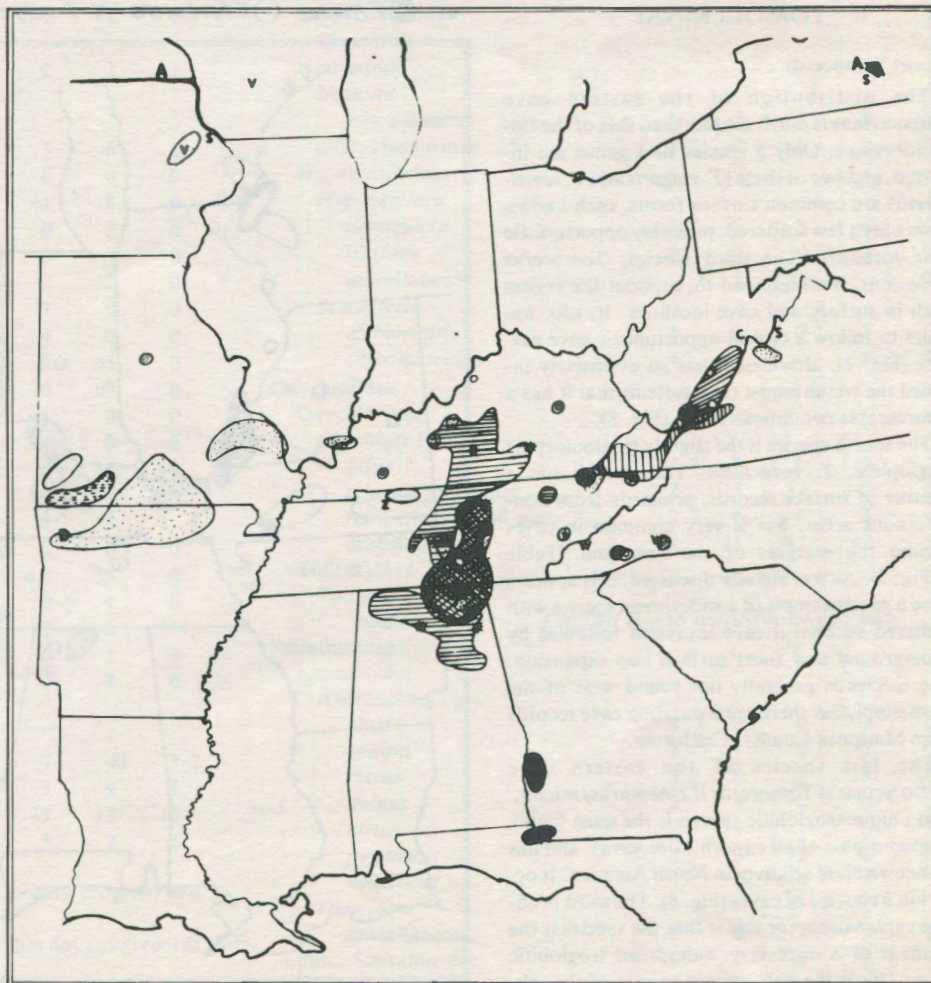
which they most resemble is a New Mexican cave species, *P. vita*.

P. hirsuta group. This is the most complex and best studied (Christiansen and Culver, 1968) of all the Nearctic cave Entomobryinae. *P. dubia*, which appears to be the most like a putative ancestor to the group, is poorly known. In addition, it has a number of features differentiating it from the other species of the group and has never been recorded on the surface. The single surface species of the group, *P. folsomi*, known from Arkansas, Louisiana, and Texas, is very different from the other species in many respects and remains in questionable phylogenetic position. The other species are all either troglobitic or nearly so (there are 2 surface records for *P. hirsuta*) and are the dominant Entomobryinae (Table 1) occupying the central heartland.

The ancestral form (*P. dubia*-like) appears once to have been widespread on the surface and to have gone underground successfully in several locations. It then spread, largely through underground routes, and went through extensive parallel speciation. In particular, it appears that *P. hirsuta* has gone through extensive precise parallel evolution (Christiansen and Culver, 1968) and has evolved the highly troglomorphic *P. christianseni* at least 4 separate times. It also appears probable that *P. gisini* has evolved at least twice.

○ *Pseudosinella aera*. A *P. alba*. ⊙ *P. argentea*. C *P. certa*. ★ *P. christianseni*. ○ *P. colina*. D *P. dubia*. ⊕ *P. española*. ⊖ *P. gisini*. ⊕ *P. hirsuta*. ⊖ *P. orba*. ● *P. pecki*. R *P. rolfsi*. S *P. sexoculata*. ⊕ *P. spinosa*. ∇ *P. violenta*. W *P. species W*. Z *P. species z*.

Figure 7. Collections of *Pseudosinella* in eastern caves; conventions as in Figure 5.



Summary, Entomobryinae

Thus, the picture for cave distributions of Entomobryinae is varied and complex. One pattern is widespread opportunistic cave occupation. Many of these species are still widespread and common in surface collections from the area. A second pattern consists of widely scattered pockets where successful cave adaptations have been made and then extended by underground migration and short surface hops (Barr and Holsinger, 1971). Such forms tend to be non-troglophobic troglomorphs with rare surface occurrences, or with surface occupation largely outside the present range of cave occupation.

A third pattern is single invasion of a cave and subsequent spread through a contiguous area or several closely adjacent areas by underground or short hop surface migration. Such forms tend to be troglomorphic troglobites with very rare surface records. This last type of occupation involves troglomorphic troglobites of widespread but scattered distribution which appear to have evolved by parallel speciation. In some cases, it is impossible to tell whether a species possesses this pattern, or if it possesses the previous pattern but the extinction of intermediate populations has occurred with subsequent isolation of pockets.

TOMOCERINAE

Genus Tomocerus

The distribution of the eastern cave Tomocerinae is much simpler than that of the Entomobryinae. Only 5 species of 1 genus are involved, and two of these (*T. vulgaris* and *T. lamelliferus*) are common surface forms, each known from only a few scattered, probably opportunistic cave localities. The third species, *Tomocerus flavescens*, is widespread throughout the region both in surface and cave localities. It, too, appears to follow a typical opportunistic cave pattern (Fig. 2), although it has so extensively invaded the westernmost cave systems that it has a considerable continuous range (Fig. 8).

The fourth species is the slightly troglomorphic troglophile, *T. bidentatus*. This species has a number of surface records, primarily from non-cavernous areas, but is very common in caves around the margins of the heartland (Table 1)(Fig. 3). As was already discussed, this appears to be a good example of a widespread species with scattered successful cave invasions followed by underground and short surface hop expansion. The species is generally not found west of the Mississippi, but there are 2 puzzling cave records from Mariposa County, California.

The last species of the eastern cave Tomocerinae is *Tomocerus (Lethemurus) missus*. This unique troglomorphic species is the most highly troglomorphic of all eastern *Tomocerus* and has no known close relatives in North America. It occurs in 3 clusters of caves (Fig. 8). The most probable explanation for this is that the species is the remnant of a once very widespread troglomorphic form. This is the only eastern species of the sub-

genus *Lethemurus*, but there are 3 troglomorphic and 2 troglophilic species known in the far west.

Genus Oncopodura

Only 2 species of this genus (Fig. 8) occur in the eastern United States caves. Arlé (1960) studied the biogeography of this group and argued for recurrent cave invasion by pre-adapted soil forms. While no putative ancestral forms for Nearctic cave species have been found in North America, the distribution strongly suggests some very recent cave invasions and extensive past overland transport. In addition, surface collections of 1 cave species have been made. The localities for either species are widely separated. Many caves in glaciated regions are occupied by members of this genus. Three species not found in the east have been recorded from western caves. The genus does not appear to have been able to invade caves of the heartland.

Genus Arrhopalites

This genus has been well studied by Yosii (1956), Christiansen (1966), and others and is the

only one of the family Sminthuridae represented by troglomorphs or troglobites in eastern Nearctic caves. *Arrhopalites benitus*, while common on the surface throughout the area, is rarely found in caves. A second common surface species, *A. caecus*, is an opportunistic cavernicole found in a few caves in the glaciated region (South Dakota, Wisconsin, Iowa, Nova Scotia). The primarily European *A. pygmaeus* is rare but widespread in Nearctic surface localities and is also common and widespread in caves.

The great majority of eastern cave *Arrhopalites* are related to *A. pygmaeus* and have probably evolved from this species. *A. pygmaeus* is a Holarctic species and is apparently an opportunistic cave species (Fig. 2). *A. whitesidei* is a widespread Nearctic surface form and an opportunistic cave form (Fig. 9). *A. dubius* is a closely related species known from 1 surface locality in Michigan and 2 cave localities in Iowa.

The moderately troglomorphic species *A. clarus* poses a much more interesting problem. Unknown outside of caves, it is widespread in the Missouri-Arkansas cave region, where it com-

Figure 8. Collections of the genera *Oncopodura* and *Tomocerus* in eastern caves; conventions as in previous figures.

H *Oncopodura hoffi*. * *O. iowae*. ● *Tomocerus bidentatus*. ○ *T. dubius*. L *T. lamelliferus*. ⊙ *T. missus*. ○ *T. flavescens*. ▼ *T. vulgaris*.

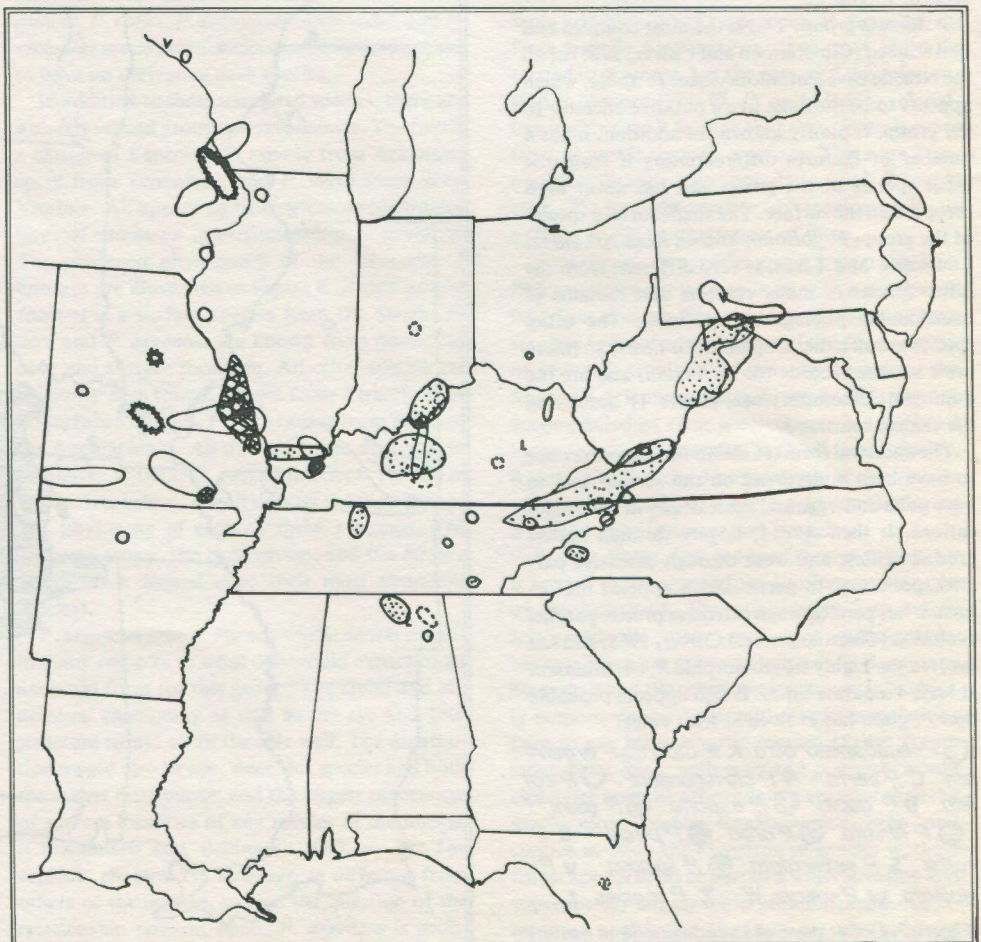


Table 1.
Cave Distributions of
Nearctic Cave Collembola.*

	Number of records from caves in different areas				
	Glaciated regions	Non-heartland, non-glaciated areas	Heartland areas	Collection west of Great Plains	
Entomobryidae					
Entomobryinae					
<i>Sinella</i>					
<i>agna</i>	4	0	0	15	0
<i>alata</i>	4	0	0	5	0
<i>avita</i>	2 ?	0	5	1	0
<i>barri</i>	3	2	6	13	0
<i>basidens</i>	5 ?	1	0	17	0
<i>caeca</i>	1	4	9	3	1
<i>cavernarum</i>	3	2	14	29	0
<i>curviseta</i>	1	0	0	2	0
<i>hoffmani</i>	4	1	0	35	0
<i>kekeleri</i>	4	0	0	22	0
miscellaneous	1-4	0	0	0	10
<i>Entomobrya</i>					
miscellaneous	1	4	4	2	24
<i>Orchesella</i>					
miscellaneous	1	2	1	1	1
<i>Lepidocyrtus</i>					
miscellaneous	1	3	2	2	1
<i>Willowsi</i>					
<i>Pseudosinella</i>					
<i>area</i>	2	0	5	6	1
<i>alba</i>	1	3	0	0	0
<i>argentea</i>	3	0	41	18	0
<i>certa</i>	4	0	0	2	0
<i>christianseni</i>	5	0	0	7	0
<i>collina</i>	2	0	2	12	0
<i>dubia</i>	3 ?	0	7	0	0
<i>españa</i>	4	0	4	0	0
<i>gisini</i>	5 ?	0	0	35	0
<i>hirsuta</i>	5	0	0	93	0
<i>nata</i>	2-3 ?	0	1	0	0
<i>octopunctata</i>	1	0	1	0	0
<i>orba</i>	4	0	0	16	0
<i>pecki</i>	4-5 ?	0	0	7	0
<i>rolfsi</i>	1	0	0	3	1
<i>sexoculata</i>	1	1	0	0	0
<i>spinosa</i>	4	0	0	39	0
<i>testa</i>	3 ?	0	0	1	0
<i>violenta</i>	1	6	2	2	161
<i>sp. w.</i>	4	0	0	1	0
<i>sp. z.</i>	4	0	0	3	0
Tomocerinae					
<i>Tomocerus</i>					
<i>bidentatus</i>	3	0	7	40	2 ?
<i>dubius</i>	2	0	3	9	1
<i>flavescens</i>	1	21	35	13	10
<i>lamelliferus</i>	1	0	3	2	1

*Based on localities in author's PICKER Computer locality program and thus not complete.

†This genus is such a common laboratory inhabitant that any cave records must be viewed with great suspicion.

Table 1 (continued).

	Number of records from caves in different areas				
	Glaciated regions	Non-heartland, non-glaciated areas	Heartland areas	Collection west of Great Plains	
<i>missus</i>	4	0	9	0	0
<i>vulgaris</i>	1	2	0	0	1
miscellaneous	1-4	0	0	0	14
Oncopodurinae					
<i>Oncopodura</i>					
<i>hoffi</i>	3-4 ?	0	3	0	0
<i>iowae</i>	2	10	16	0	0
miscellaneous	2-4	0	0	0	12
Isotomidae					
Isotominae					
<i>Isotoma</i>					
<i>notabilis</i>	2	6	6	4	0
miscellaneous	1	7	11	3	6
<i>Folsomia</i>					
<i>candida</i>	2	16	31	17	8
<i>stella</i>	3 ?	8	0	0	1
miscellaneous	1	6	5	3	2
misc. Isotomidae	1	2	1	1	1
Hypogastruridae					
Neanurinae					
<i>Neanura</i>					
miscellaneous	1	2	1	2	0
misc. Neanurinae	1 ?	2	1	2	0
Hypogastrurinae					
<i>Hypogastrura</i>					
<i>denticulata</i>	3 ?	6	8	6	0
<i>lucifuga</i>	4	0	0	2	0
miscellaneous	1	5	13	7	2
<i>Schaefferia</i>					
<i>alabamensis</i>	4	0	0	3	0
<i>christianseni</i>	4	0	0	1	0
Onychiuridae					
Onychiurinae					
<i>Onychiurus</i>					
<i>gelus</i>	4 ?	5	0	0	2
<i>reluctus</i> and <i>casus</i>	2	15	12	7	0
<i>reus</i> , <i>obesus</i> , and <i>paro</i>	3 ?	6	0	2	0
miscellaneous	1	11	12	12	5
Tullberginae					
<i>Tullbergia</i>					
<i>neelus</i>	Omitted due to untrustworthy records				
Sminthuridae					
Katianninae					
<i>Arrhopalites</i>					
<i>altus</i>	4	0	0	3	0
<i>benitus</i>	1	1	0	3	0
<i>clarus</i>	5 ?	0	30	5	0
<i>dubius</i>	2	4	0	0	0
<i>hirtus</i>	2 ?	9	1	3	2
<i>pygmaeus</i>	2	8	72	30	5
<i>whitesidei</i>	1	2	4	4	3
<i>Dicyrtoma</i>					
miscellaneous	1	0	2	5	2
misc. Sminthuridae	1	1	1	1	

monly intergrades with *A. pygmaeus*. The only other known collections are from a cluster of caves in the eastern heartland, where it appears to displace *A. pygmaeus* entirely (Fig. 9). The best explanation for this peculiar distribution is parallel speciation of the form at least twice (eastern and western populations) from a common *pygmaeus*-like ancestor. The slightly troglomorphic *A. hirtus* is known from surface collections in Oregon, California, and Quebec and from cave localities, mostly in Iowa and Wisconsin (Fig. 9). This would appear to be a case of a formerly widespread species surviving in the east in scattered cave refugia.

The last 2 species are both apparent troglobites of a very limited distribution. The moderately troglomorphic *A. bimus*, related to *A. benitus*, is found in 1 county of Indiana, while the highly troglomorphic *A. altus*, related to the epigeic *A. amarus*, is limited to 2 counties of Kentucky (Fig. 9). Both appear to be the results of single successful adaptations to cave life and subsequent evolutionary change.

In summary, the genus *Arrhopalites* shows a considerable array of patterns of cave distribution similar to, but less extensive than, those seen in the Entomobryinae.

Genus Onychiurus

The majority of cavernicolous Collembola of the family Onychiuridae belong to the genus *Onychiurus*. Four species are currently known only from caves: *O. eous*, *paro*, *gelus*, and *obesus*. The first two are known only from single cave collections. The third, *O. gelus*, is an interesting apparent glacial relict. Its closest surface relatives are found in Norway. The species has been found in a glacière ("ice cave") in Iowa, 2 Wisconsin caves, and a cave in Washington. A related species is found in a sub-alpine Polish cave (Stach, 1954). The fourth species, *O. obesus*, is found in a number of Iowa and Wisconsin caves.

The most widespread and abundant cave species, *O. reluctus*, is rarely found on the surface, but shows no clear pattern of cave occupation, except that it is relatively rarer in caves of the heartland than elsewhere (Fig. 10) (Table 1). The same is not true of all other species of *Onychiurus*. These are all forms which are more common (usually much more common) in surface than in cave habitats. All of these probably represent opportunistic troglophiles.

Thus, the genus *Onychiurus*, while common in United States caves, appears to consist largely of opportunistic cave invaders and is not strikingly more successful outside the heartland than in.

Genus Tullbergia

This ubiquitous endogeic genus is poorly represented from Nearctic caves. This almost certainly is primarily a result of the minute size of the animals, requiring special techniques for extraction (berlese funnel or flotation). Evidence for this is the fact that three-fourths of the known Nearctic cave collections of this genus were made by the author or his students. One species, *T. hades*, is presently known only from caves in Wabasha

County, Minnesota and Jackson County, Iowa. All six of the other species known from eastern Nearctic caves are clearly opportunistic cave forms, found more commonly on the surface.

HYPOGASTRURIDAE

This family is very poorly represented in Nearctic caves. The subfamily Neanurinae is remarkably scarce. A single population presently identified as *Anurida granaria* occurs in caves of Edmonson County, Kentucky. Further study may show this to be a separate, troglotic species. In addition to this, 1 epigeic species of *Paranura* and 3 epigeic species of *Neanura* are occasionally opportunistic cave invaders.

The great majority of cave records of this family belong to the subfamily Hypogastrurinae and to the related genera *Hypogastrura* and *Schaefferia*. There are 3 apparently troglotic species (Fig. 11), each very limited in distribution. In addition, the widespread *H. (Ceratoophysella) denticulata* and *H. pecki* appear to have made local successful cave adaptations. Many of these are slightly troglomorphic, differentiated from surface forms of the species, and may be in the process of evolving distinct cave species.

It is interesting to note that *H. (C.) denticulata* and *H. pecki* occur more commonly outside the heartland, whereas the only troglotic species of *Hypogastrura*, *H. lucifuga*, and both species of the troglomorphic genus *Schaefferia* occur only in

marginal heartland. *Hypogastrura (H.) antra* is (so far) known only from heartland caves. In spite of its apparently troglotic distribution, it shows no troglomorphy and will probably turn up in surface collections, later.

In addition to these species, there are 4 additional surface species which are opportunistic cave forms (Fig. 11) (Table 1).

Thus, it appears that, unlike the situation in Japan, Mexico, and Europe, hypogastrurids are poorly represented in United States and Canadian caves. The occurrence of many apparently nascent troglotic forms points to the possibility that they are increasing their occupancy of cave systems.

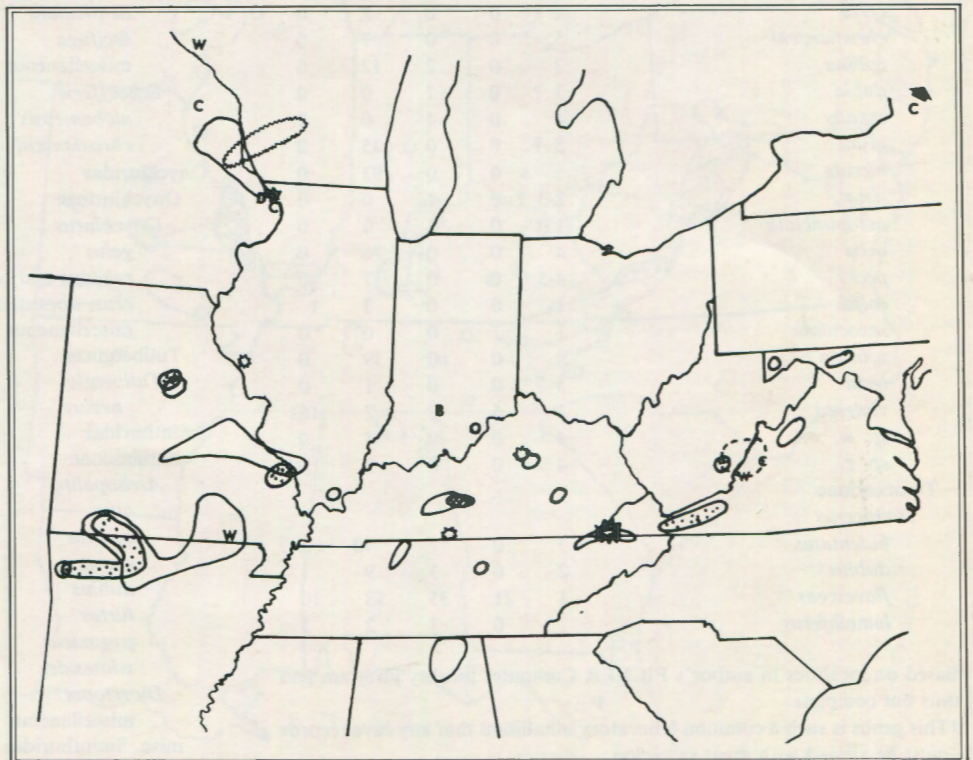
ISOTOMIDAE

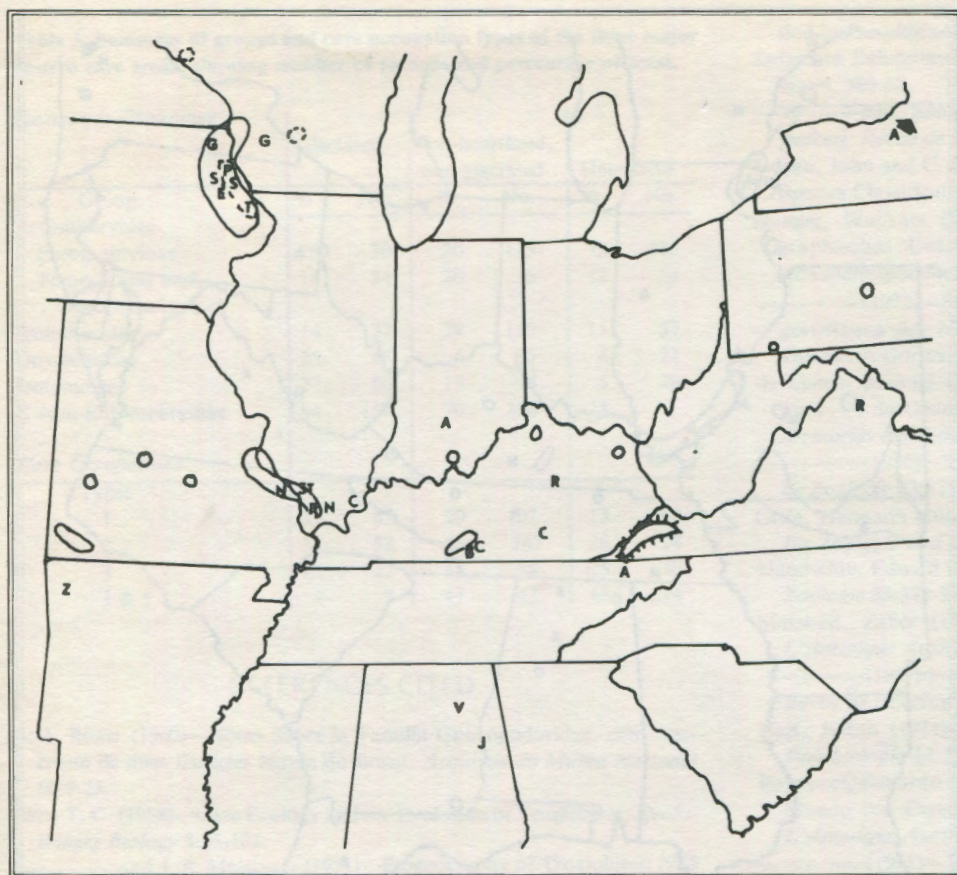
This family is very poorly represented in caves. The genera *Isotoma* and *Proisotoma* are represented in a number of cave collections, but almost all of these are clearly epigeic forms. Species, such as *Isotoma nixonii*, that are recorded only from caves but are not at all troglomorphic, probably represent undescribed surface species or relict Arctic forms. All such forms are known from single collections.

The genus *Folsomia* contains the only widespread cave forms in the family. *Folsomia stella* (Fig. 12) is a widespread surface form which appears to have successfully invaded the caves of Iowa and Wisconsin. The single collection from

Figure 9. Collections of *Arrhopalites* in eastern caves; conventions as in previous figures.

● *Arrhopalites altus*. ○ *A. pygmaeus*. B *A. bimus*. ○ *A. benitus*. C *A. caecus*. ● *A. clarus*. D *A. dubius*. * *A. hirtus*. W *A. whitesidei*.



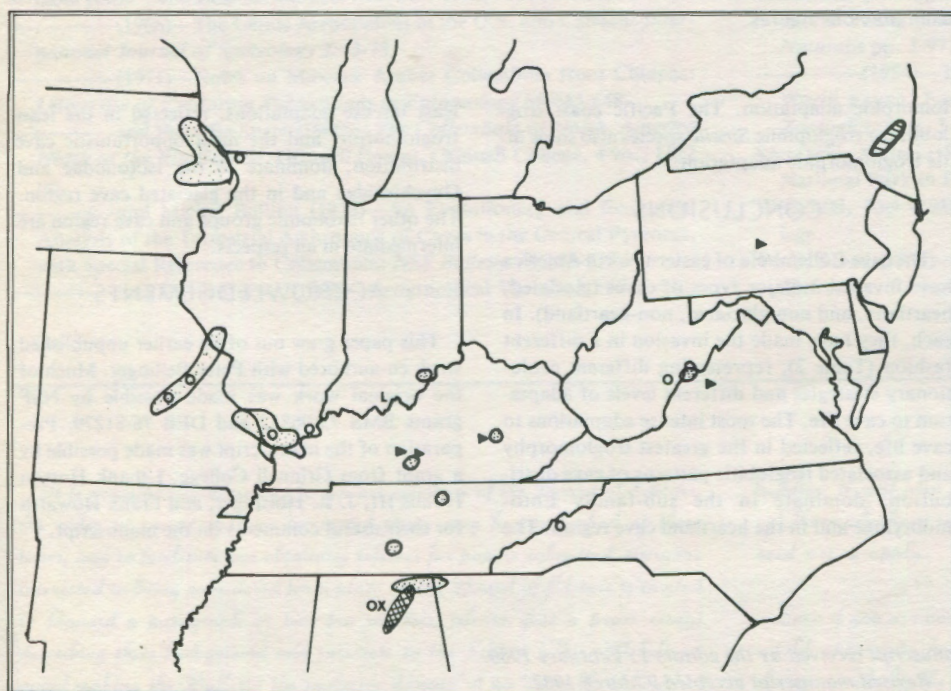


A *Onychiurus armatus*. B *O. bimus*. G *O. gelus*. J *O. janus*. O *O. obesus*. V *O. paro*. P *O. parvicornus*. Z *O. pseudofimentarius*. O *O. ramosus*. O *O. reluctus*. R *O. reus*. T *O. sibiricus*. S *O. similis*. ST *O. subtentius*. E *O. eous*

Figure 10. (left) Collections of *Onychiurus* in eastern caves.

Figure 11. (below) Collections of the family Hypogastruridae in eastern caves; conventions as in previous figures.

● *Schaefferia alabamensis*. X *S. christianseni*. ⊙ *Hypogastrura denticulata*. L *H. lucifuga*. ⊗ *H. pecki*. ○ *H. miscellaneous species*. △ *Neanurinae miscellaneous genera*.



Oklahoma may represent the first record of another such invasion. A scattering of other *Folsomia* species appears to represent the same kind of opportunistic cave invasion seen in the epigeic species of *Isotoma* and *Proisotoma*. The majority of cave records in this genus are *Folsomia candida* (Fig. 12). This largely parthenogenetic species is a common inhabitant of greenhouses and is a rare, but widespread, soil inhabitant. It is a common opportunistic cavernicole all over the Holarctic region.

In summary, cave Isotomidae are exclusively opportunistic cavernicoles. *Folsomia stella*, a possible exception, may have made only 2 successful local cave adaptations.

NEELIDAE

These minute forms are subject to many of the same effects seen in *Tullbergia*. Thus, they are undoubtedly vastly under-represented in present cave collections. All known species are endogeic forms which are almost certainly opportunistic cavernicoles. Their distribution, due to the faulty records, is too fragmentary to comment on.

MISCELLANEOUS GENERA

In addition to the forms mentioned above, there are a number of other genera of epigeic Collembola which have been found once or twice in caves (Table 1). These are probably surface strays (trogloxenes) in many cases and do not represent genuine cave occupations. They give no significant information about cave distribution.

GENERAL DISCUSSION

Overall, the patterns of collembolan cave occupation appear to be of 5 basic types (Table 2). The first type includes the great majority of species found in caves and represents the simplest level of cave life. These forms are generally *r*-selected species and are the most common surface forms of their genus, with opportunistic cave invasions. In most of the genera, there is a single species which is the common one in this category.

The second category is only weakly differentiated from the first. The primary difference is that, unlike those in the first group, these species are more common in cave than in surface habitats. It is interesting to note that in two of these cases where there is no dominant species in category 1, there is one very dominant species in category 2.

Category 3 includes a number of species which are only assumed to be troglomorphic, *i.e.*, they are non-troglomorphic forms with a few scattered cave collections or one known cave locality.

Categories 4 and 5 are sometimes difficult to

Table 2. Patterns of cave occupation in Major Genera (figures = number of species in each category).

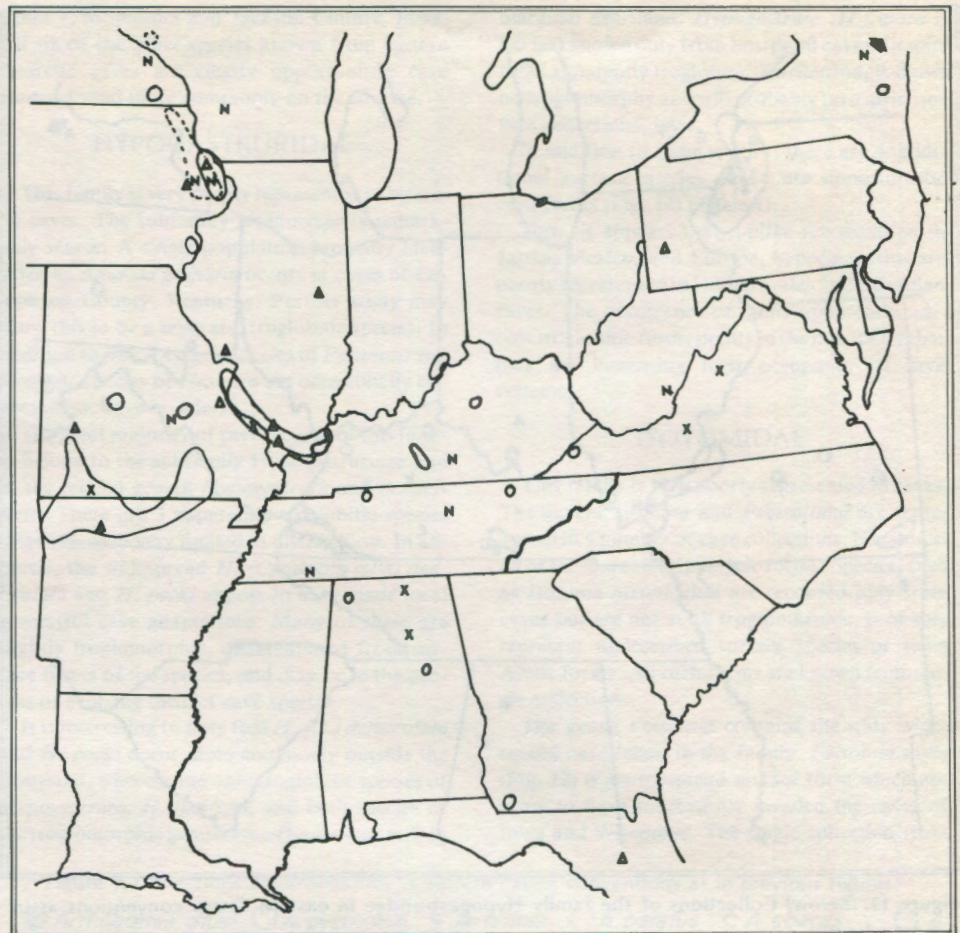
Category	1	2	3	4	5
Description					
	Epigeic forms with opportunistic cave occupation	Troglophilic forms with opportunistic cave occupation	Troglophilic, non-troglobitic apparent troglobites with scattered successful cave invasions	Troglobitic troglobites with single cave invasions	Troglobitic troglobites with parallel speciation
Genus					
<i>Sinella</i>	2	1*	2*	4	1
<i>Pseudosinella</i>	4	2*	4*	7*	4*
<i>Tomocerus</i>	3	1	1	1	0
<i>Oncopodura</i>	0	0	1*	1*	0
<i>Isotoma</i>	6	1	0	0	0
<i>Proisotoma</i>	6	0	0	0	0
<i>Folsomia</i>	5	1	1	0	0
<i>Neanura</i>	4	0	0	0	0
<i>Hypogastrura</i>	7	0*	2*	1	0
<i>Onychiurus</i>	11	2	4	1*	0
<i>Tullbergia</i>	6	1*	1*	1*	1*
<i>Arrhopalites</i>	3	1	1*	1*	1*
<i>Neelus</i>					

*These categories include some species of doubtful placement.

distinguish, as remarked earlier. Patterns 1 to 4(5) clearly represent a gradient both in troglomorphy and in the degree of cave limitation.

It is noteworthy that the types of cave distribution are not equally represented in the 3 major cave regions (Table 3). Category 1 is the dominant type in glaciated caves, category 2 in non-heartland, non-glaciated caves, and categories 4 and 5 in heartland caves. Category 3 species distributions have approximately the same percentages in all cave regions.

In a similar and related fashion, the different taxa are not uniformly distributed (tables 1 and 3). There is a steady increase in the role of the Entomobryinae and a decrease in the Onychiuridae and Isotomidae as one moves from glaciated to non-heartland unglaciated to heartland caves. The other groups are most important in non-heartland, non-glaciated caves and least important in heartland caves. These last two are the only families to show a great deal of troglomorphy outside the heartland. They also are the only groups to show high troglomorphy in western caves. In contrast, the one species of Entomobryinae (*Pseudosinella violenta*) which has extensively invaded southwestern caves shows very little trog-



○ *Folsomia candida*. ○ *F. stella*. X *F.* miscellaneous species. N *Isotoma notabilis*. △ *Isotoma* and *Proisotoma* miscellaneous species.

Figure 12. Collections of the family Isotomidae in eastern caves. *Folsomia candida* and *F. stella* lumped as in previous figures.

lomorphous adaptation. The Pacific coast troglobitic or troglophilic *Sinella* species also show little troglomorphy adaptation.

CONCLUSIONS

The cave Collembola of eastern North America have invaded 3 major types of caves (glaciated, heartland, and non-glaciated, non-heartland). In each, they have made the invasion in a different fashion (Table 2), representing different evolutionary strategies and different levels of adaptation to cave life. The most intense adaptations to cave life, reflected in the greatest troglomorphy and associated troglobitic patterns of cave distribution, dominate in the sub-family Entomobryinae and in the heartland cave region. The

least intense adaptations, reflected in the least troglomorphy and the most opportunistic cave distribution, dominate in the Isotomidae and Onychiuridae and in the glaciated cave region. The other taxonomic groups and cave region are intermediate in all respects.

ACKNOWLEDGEMENTS

This paper grew out of an earlier unpublished work co-authored with Peter Bellinger. Much of the original work was made possible by NSF grants BMS 73-06852 and DEB 76-81279. Preparation of the manuscript was made possible by a grant from Grinnell College. I thank Horton Hobbs III, J. R. Holsinger, and Frank Howarth for their useful comments on the manuscript.

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Revised manuscript accepted 9 March 1982.

Table 3. Summary of groups and cave occupation types of the three major eastern cave areas, showing number of records and percentage of total.

Taxonomic Groupings	Glaciated		Non-heartland, non-glaciated		Heartland	
	%	No.	%	No.	%	No.
Entomobryidae						
Entomobryinae	16	30	30	115	72	385
Tomocerinae and Oncopodurinae	18	34	20	76	12	64
Sminthuridae	14	27	29	110	11	57
Onychiuridae	25	47	6	24	4	21
Isotomidae	27	50	15	56	5	29
Σ Non-Entomobryinae	84	158	70	266	28	
Cave Occupations						
Types						
1	49	83	29	107	13	60
2	34	57	45	167	26	124
3	13	22	15	58	15	70
4 & 5	4	7	11	43	46	214

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buddies; it will also help induct beginning scholars into the system.

Those who have submitted their names previously are still on record and need not re-apply.

Even if you are unable to participate in the operation of the Bulletin, we would appreciate having your suggestions and criticisms. Many of the changes made by the present staff were suggested to us by readers.

ORIGIN OF BLACK DEPOSITS IN CAVES

Discussion

Donald G. Davis

Route 1 Box 93-A, Parachute, Colorado 81635

Carol Hill (*NSS Bulletin* 44:16-17, January 1982) is, in my opinion, correct in identifying the black coating in Black Cave, New Mexico, as forest-fire soot. It clearly originated in a short-term event, because the coating terminates abruptly along a former rubble floor level just inside the cave entrance. However, a flood that filled the cave is not the only medium that could have introduced soot to the cave and is far from being the most probable means in this case.

Black Cave is an old phreatic cave, unrelated to any surface watercourse, and is situated near the top of a ridge. The cave has too little surface drainage catchment area to cause significant flooding, and it probably has not been water-filled within the 2,000- to 10,000-year range estimated by Hill for the black coating. Nor does the cave contain clastic inwash suggestive of flooding.

When floodwater bearing forest-fire debris invades a cave, conspicuous bits of charcoal often persist in the cave sediment, as in mud fill in Fort Stanton Cave, New Mexico, where charcoal is associated with Pleistocene horse bones in the Valentine Passage. No such charcoal has been found in Black Cave.

Black Cave does, however, have substantial airflow. Thus, the soot coating probably settled, not out of floodwater, but out of the cave air when the cave was inhaling smoke-filled air during a forest fire. The Black Cave carbon is all fine-grained and could easily have been airborne. Because smoke from fires of torches and lamps readily blackens cave surfaces via the cave air, it should be expected that the large-scale smoke production of a forest fire would do the same if the smoke were drawn into a cave.

Reply

Carol A. Hill

Route 5 Box 5444A, Albuquerque, New Mexico 87123

The evidence for a flooding versus a soot origin for the black deposits of Black Cave, Guadalupe Mountains, New Mexico is the following:

(1) The Second Parallel Passage is flooded now and has reached levels at least 6 ft higher in recent times (Jerry Trout, personal communication). It is not hard to imagine the cave being flooded to even higher levels. There is black material suspended in the water of the Second Parallel Passage.

(2) The black deposits occur mainly on the cave floor and *not* on the ceilings or walls, as one would expect from smoke-derived soot. Black material in floor pockets often exceeds 10 cm in depth.

(3) Slumping of clastic floor fills near the cave entrance after deposition of the black material can be most easily explained by carbonaceous materials settling out of suspension followed by slumping of clastic deposits as water drained from the cave.

KARST DENUDATION RATES FOR SELECTED SPRING BASINS IN WEST VIRGINIA

Discussion

Mark Stock

East Side Station Box 3471, Bartlesville, Oklahoma 74005

In the article "Karst Denudation Rates for Selected Spring Basins in West Virginia" (*NSS Bulletin*, 44:6-10, January 1982), Albert Ogden has failed to balance the units in his formulae.

(1) From context, Q in equation (1) should have units of cubic feet or cubic meters. If the units are ft^3/sec or m^3/sec , the period of interest should be presumed to be one second.

(2) In Equation (2), the value of C is correct, but it must have units of $(\text{liters} \times \text{grams})/(\text{ft}^3 \times \text{mg})$.

(3) In Equation (3), if D has the given units, then C is a constant to convert seconds to thousands of years (i.e., $C \approx 3.16 \times 10^{10} \text{sec}/1000 \text{yr}$).

(4) The supposedly interchangeable units of the vertical axis of Figure 13 are not equivalent.

Reply

Albert E. Ogden

Edwards Aquifer Research and Data Center
Southwest Texas State University, San Marcos, Texas 78666

Thanks a lot.

Timbiteni: The Cave of the Beer Pots



Locating caves on the jumble of cliff faces was almost impossible until teams started using walkie-talkies to guide search parties to the cave mouth they were seeking.

When we first saw the cave from across a deep ravine, I had serious doubts. I had climbed to so many only to find their surface areas no bigger than the floor of an average-sized elevator, swept clean of any deposits, that I feared this would just be one more. From where we were first standing, this new cave looked the same, too small and without sufficient floor deposits. When we finally arrived at the cave, however, it was much larger than it had looked through binoculars. In fact, it is one of the largest caves we have found in Swaziland, measuring over 20 meters wide at the mouth and going back into the rock over 30 meters. It is about the same size as Border Cave.

This cave is now classified as S-131/80, not the most romantic or provocative name. The local chief, describing it to the team, called it "Timbiteni," which means "the place of the beer-pots." The cave was hardly a brewery. Rather, the name comes from its geology. The erosion of the frothy lava has left the roof covered with deep spherical cavities—the bubble holes in

the lava—and these resemble Swazi beer-pots. Hence the name.

We hope that the cave will have a dense array of archaeological debris beneath modern surface that will include artifacts of Middle Stone Age date. Certain indications are favorable. In one corner is a tool-manufacturing area with piles of Middle Stone Age debris. This means that Middle Stone Age people were here at Timbiteni, as we had hoped. Stone tools and debris can also be found in the ground around the outside of the cave, scattered in the bushes. It is exactly like the material from Border Cave that I have seen. Timbiteni lies in the same rainfall region as Border Cave, and bone preservation is very good in these conditions, as other sites in the Lubombo Mountains have proved. Several other caves we have examined are stuffed with faunal remains, so there is a very good chance that this will hold true for Timbiteni. If that's the case, then there is a chance that we shall also find hominids at this site.

Overall, the site is very much like Border Cave:

the location is the same, the raw material is the same, the tools are the same, and the size is the same. My feeling is that this will be the long-sought analogue for Border Cave. But, of course, unlike Border Cave, Timbiteni is virginal, with all its secrets still intact. What of the hominid remains? The speculation and our expectations run high. If we do find them, Timbiteni would then be, for a long time, one of the most exciting discoveries in this part of the world—the archaeological "gravy train" *par excellence*. This summer we shall see.

Usutu Gorge, Swaziland

Search for the earliest *homo sapiens sapiens* remains in the just discovered "Cave of the Beer Pots" with **Dr. David Price Williams**, archaeologist from the University of London. Jun 28-Jul 11, Jul 12-25, Jul 26-Aug 8, Aug 9-22, 1982 (\$1235) *Spaces available: 8 per team.*

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James R. Reddell

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Edited by James R. Reddell

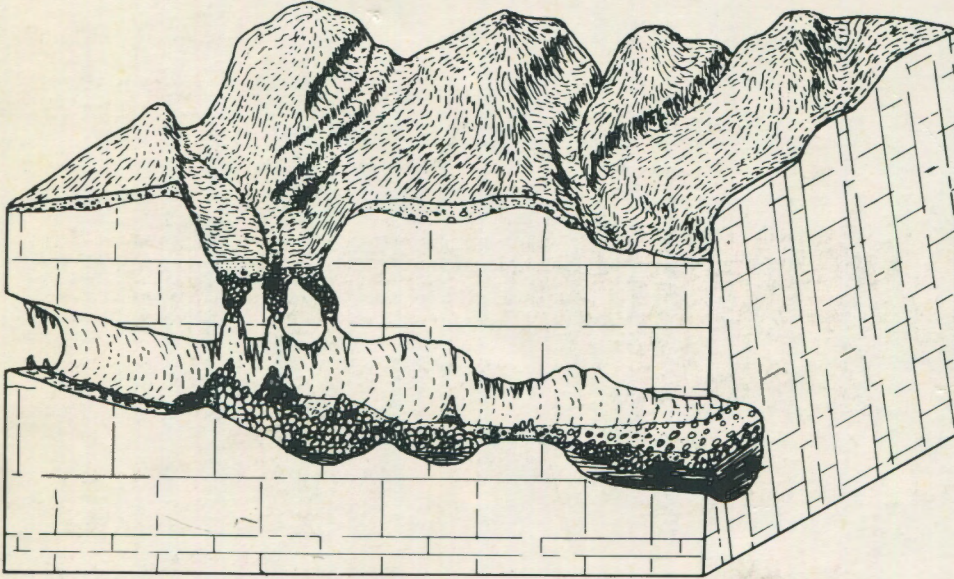
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