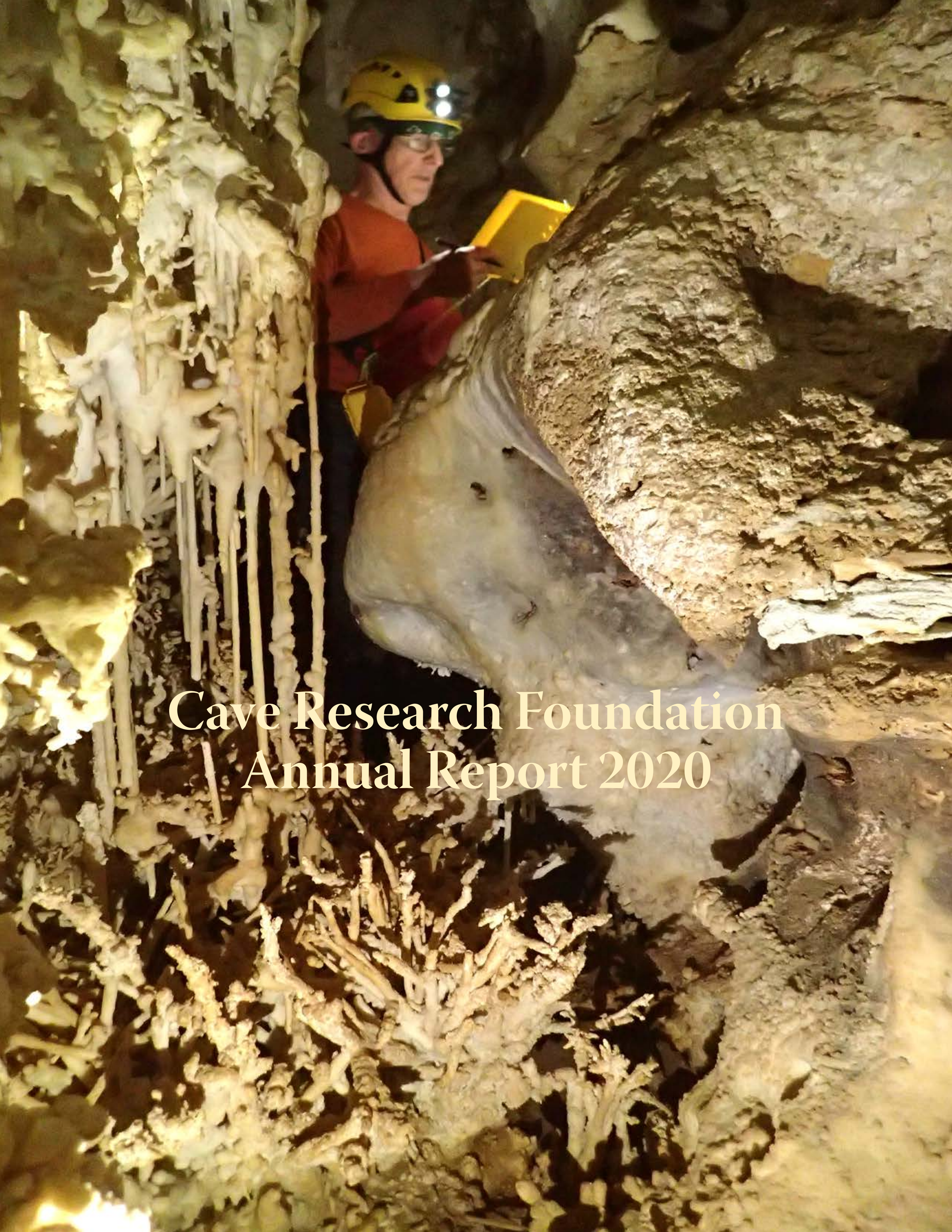

Cave Research Foundation Annual Report 2020

Cave Research Foundation
Annual Report 2020

The Cave Research Foundation was formed in 1957 under the laws of the Commonwealth of Kentucky. It is a private, non-profit organization dedicated to facilitating research, management, and interpretation of caves and karst resources, forming partnerships to study, protect, and preserve cave resources and karst areas, and promoting the long-term conservation of caves and karst ecosystems.

Cave Research Foundation 2020 Annual Report

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Back cover photos: *top*, appetizers after a day of work, Kings Canyon National Park. Photo by Fofo Gonzalez. *Bottom*, Jessie Bridges in Tumbling Creek Cave, Taney County, Missouri. Photo by Mark Jones.

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Contents

Operations Areas and Projects

Science

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2020

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Mammoth Cave National Park
Cumberland Gap National Historical Park
Cave Hollow–Arbogast Cave
TAG Region

Ozarks Operations Area

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Mark Twain National Forest
Ozark National Scenic Riverways
Missouri Department of Conservation
Missouri State Parks
Buffalo National River
Don R. Russell Preserve, Oklahoma

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Sequoia/Kings Canyon National Park

Northwest Operations Area

John Tinsley

Lava Beds National Monument
Craters of the Moon National Monument

Southwest Operations Area

Janice Tucker

Carlsbad Caverns National Park

Hamilton Valley Operation

Patricia Kambesis

Hamilton Valley Field Station

Cave Research Foundation Awards

The Cave Research Foundation awards Fellowship in the CRF to those CRF members who have made significant long-term contributions to the foundation. Individuals who have made significant contributions in a particular area are awarded Certificates of Merit. Both Fellowship and Merit awards are in appreciation of a member's efforts. The following people have received such recognition in 2020:

Fellows

Bob Lodge

Bob has been a quiet, steady, and reliable presence as an expedition leader at Mammoth Cave for many years. Beyond that, he has provided invaluable support to Cave Books, coordinating with Amazon and helping to ship books, plus other services. He also helps a great deal at Hamilton Valley by organizing the library in the archive building.

Derek Bristol

Although Derek has been active in multiple areas, he got his start with CRF at Mammoth Cave as a young whippersnapper in 1993. He has served on the board since 2012. In his own unique way, he has inspired and encouraged cavers across the country.

Derik Holtmann

Derik has been involved with the Ozarks Operation for nearly ten years. He has participated in numerous tough survey trips, while also spending much time on monitoring trips as well. He is best known for his incredible photographs which have graced several covers of the *CRF Newsletter* and provided much beautiful content for our annual reports.

Mark Brooks

Mark ("Fish") has been surveying with CRF members for decades. In recent years he returned to the fold and has become very active with CRF projects in Missouri and Arkansas. He is a tough, dedicated surveyor, and a budding cartographer. He is heading up the Onyx Cave (MO) resurvey and is one of the leaders of the Berome Moore survey project. He has also been involved with survey work at Mammoth Cave.

Greg Roemer

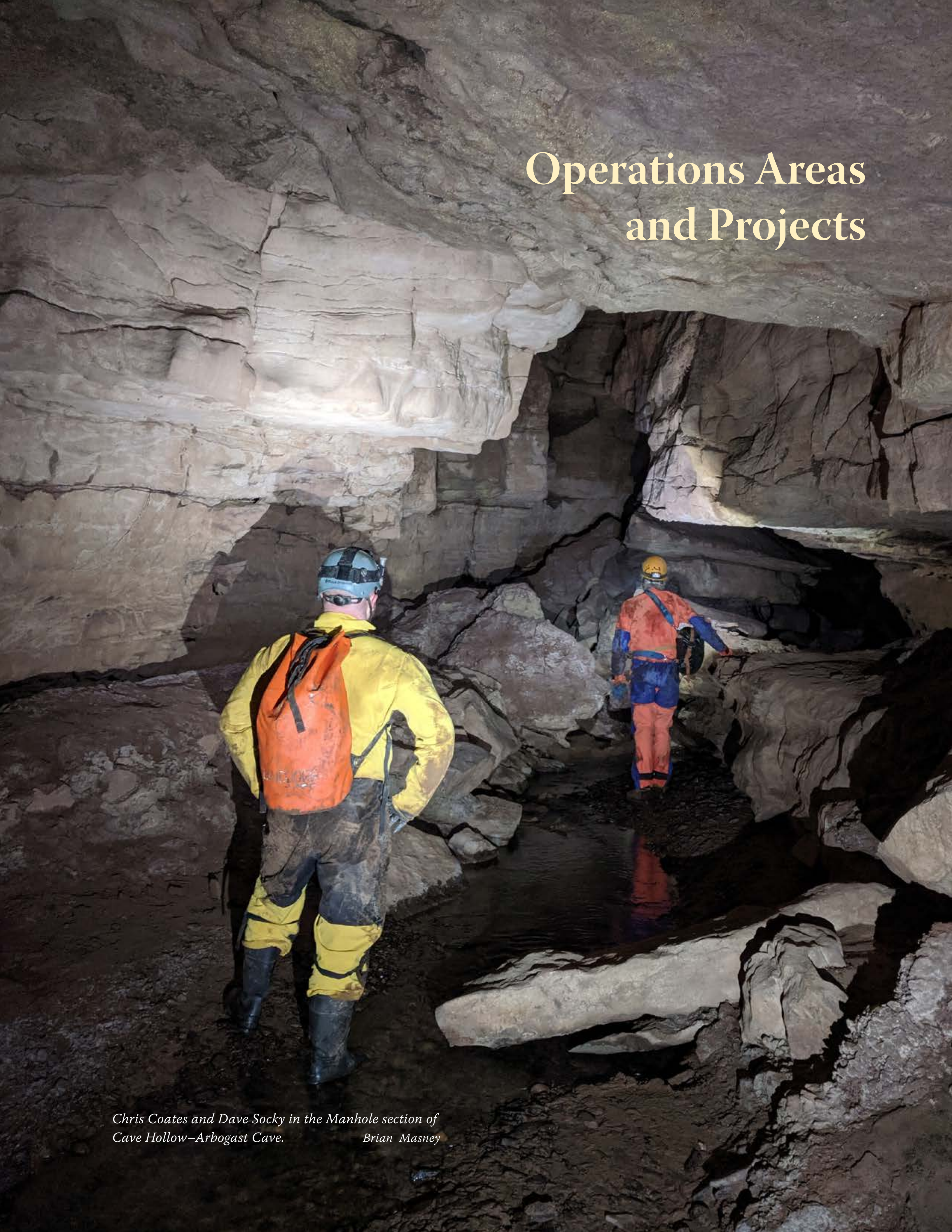
Since Greg joined the Sequoia/Kings Canyon National Park (SEKI)/Lilburn project in 2015, he has brought his unending enthusiasm to multiple expeditions as a member and an expedition leader. Greg reliably volunteers for the most grueling tasks with optimism and humor. He is an integral part of the team and has introduced and mentored many other youthful and excited members, expanding the overall project team capabilities.

Certificate of Merit

Aaron Bird and Rachel Bosch

Aaron Bird and Rachel Bosch organized the Kids Caving Expeditions at Mammoth Cave in 2018 and 2019. They dreamed up the idea, created a well-thought-out plan, and executed it creatively. It was an amazing success, enthusiastically received by the park and participants of all ages.

Operations Areas and Projects



Chris Coates and Dave Socky in the Manhole section of Cave Hollow–Arbogast Cave. *Brian Masney*

Eastern Operations: Mammoth Cave National Park 2019–20

Karen Willmes

Eastern Operations Manager

Overview and Highlights

The pandemic greatly affected our volunteer effort this year. We usually schedule 10 or more expeditions each year, with attendance ranging from a handful to over 50 participants. The March expedition took place just before everything shut down. We cancelled April altogether. By late May, we had a grasp on best practices for avoiding contagion, and we resumed expeditions cautiously and with limited participation of 20 or fewer per day. We required that everyone at our Hamilton Valley facility follow social distancing guidelines, such as wearing masks. Only family groups or people who traveled together could share a bunk room. The dining hall was set up to keep distance between people, and some people ate outside.

Unlike many volunteer efforts, however, we don't have to be at the park to contribute. Our cartographers continued to draw maps, for example. In fact, some of them may have gotten more done because they couldn't do anything else.

Despite the pandemic, we were able to hold nine expeditions. Participants traveled 208,574 miles to attend. CRF volunteers spent 11,943.71 hours on work that benefitted Mammoth Cave National Park. They spent an additional 1,179.11 for work indirectly applicable to the park, for a total of 13,122.82 volunteer hours. Not surprising given the restrictions, volunteer mileage was way down. But total volunteer hours were similar to previous years.

Between October 1, 2019 and September 30, 2020, 126 trips took place, supporting a variety of projects (some trips supported multiple projects):

- MCNP cartography—90
- Archaeology—2
- Biology—2
- Caves outside park (Biosphere Reserve)—12
- Geology—5
- Paleontology—5
- Roppel cartography—13
- Small cave inventory—24
- History—1
- Park requested support—17
- Hydrology—3
- Biomonitoring—4
- Conservation and restoration—1
- Signatures—2
- Technology—3
- Western Kentucky University classes—1
- Education—1

Park Support

One of the most exciting projects that used CRF's assistance was locating, photographing, and sampling shark remains and shark teeth. Five parties assisted with the effort. For example, a possible "fish or shark jaw" was noted in CRF's trip report database. We were able to get a photograph of it, and prominent paleontologist Dr. J. P. Hodnett was able to identify the fossil as an articulated skull of a Ctenacanth shark. The shark remains are notably diverse and well preserved. These significant discoveries are attracting major media as well as scientific attention.

In addition, CRF teams helped to install a data logger in Wilson Cave, recover a guide's Ranger hat from Crystal Lake, check major cave entrances for integrity and signs of tampering, photodocument a wooden artifact, and lay out tarps for collecting bat guano to see if COVID-19 or other viruses could be found.

Working on the Colossal Cave tour trail map, as was requested by the park, five teams continued the survey of the Pearly Pools Route, surveyed a fragment of trunk passage above the entrance, and sketched profiles and cross sections.

Science Support

Eastern Operations assisted several visiting scientists in addition to the shark research described above. Dr. Tom Byl sampled algae for a study of harmful algal bloom that is looking for evidence of cyanotoxins.

Leeanne Bledsoe retrieved charcoal dye receptors at Pike Spring, Horton Hollow Spring, Pohl Avenue, and Great Onyx Cave for Western Kentucky University's Great Onyx Basin Delineation Project.

For Rachel Bosch's dissertation research, parties measured erosion changes at micro-erosion monitoring stations near Roaring River, assessed hypothesized paleodrainage routes in Graham Springs Basin, and collected a modern sediment sample from the base of Cedar Sink.

Dr. Stan Sides took three teams to Crystal Cave to test cave radio transmitting antennas.

Cartography

Ninety trips supported cartography inside Mammoth Cave National Park, in caves large and small. Nine parties went to Colossal Cave. In addition to the trips supporting the tour trail map, two parties continued resurveying the complex Helictite/Belfry area. Another party improved passage floor detail along the route to Jones Shaft. Unfortunately, a party headed to the Bedquilt entrance found major obstacles: flooding had filled in the usual path to the gate. Another party investigated the entrance from the Colossal side and reached the gate, which was buried in mud. Reopening the route from either side will be difficult.

In Crystal Cave, a team replaced survey in Lost Paradise.

Two teams headed to Salts Cave. One team surveyed to tie known artifact and glyph locations to existing survey and found some additional glyphs. The second team went to East Salts to resurvey and attempted to relocate a climbing lead.

Using the Doyle Valley entrance, five teams went to Logsdon River to work on X-Loop and Big Rift. There are many leads in a complex multilevel maze of crawlways and canyons.

Forty-eight teams went to various parts of Mammoth Cave. After working in Napoleon's Dome, a party found a virgin lead in Wilson's Way and returned to survey it. Two teams headed to Janet's River to check the last remaining leads. The Albert's Dome map sheet is now finished.

In the New Discovery section, four teams closed a loop through Little Paradise and extended the survey line, surveyed a small maze underneath Big Avenue, and enhanced the sketch. One party finished the survey above Crevice Dome, also retrieving a carbide lamp that had been dropped down a pit in 1983. Three teams worked near the China Wall Passage, finding a mixture of resurvey and new survey. One party mopped up the remaining leads in North Gypsum Avenue. Four teams continued the resurvey of New Discovery West.

Three teams improved the two-mile loop between Miller Avenue and Bishop's Dome.

Eight teams worked on the route to Cathedral Dome and rigged Florence Williams Dome and Cathedral Dome. Another eight teams located known stations, tied in surveys, and resurveyed in Pilgrim Avenue, Martel Avenue, Cox Route, and Hell Hole.

Eight parties worked on updating the Frozen Niagara map between the New Entrance and College Heights.

The Ferguson Entrance is outside the park boundaries. No one from CRF has been in the cave since the 1980s. Aaron Bird talked to the landowner and gained access. So far, he has led three parties to leads near the entrance.

Twenty-four parties worked on small caves within the park. Compton Cave, Whittle Cave, Gully Cave #1, Gully Cave #2, Lost Water Cave, Morrison Crevice, Stone Quarry Cave, Triangle Pit, Mossy Root Cave, and Von Bretzel Pit were mapped. Three teams continued the survey of Brill Cave, ultimately finishing it. Surveying was begun at Deceptive Cave, South Cave Spring, and Logsdon Cave. A new cave was found on the way to July Cave. Another new cave was found on the way to Von Bretzel Pit. Attempts were made to find Tommy Denham Cave, Leaf Cave, and Rolling Rock Cave, but the caves were either not found or determined to not be enterable. Two parties mopped up leads in the Netherdomes, Not Kansas, and Northwest Territory in Wilson Cave. A photo and GPS coordinates were gotten for Hornet Hole, a new discovery in Wilson Cave Hollow, but efforts to survey it were stymied by excessive wetness.

Cartography Outside of Mammoth Cave National Park

Eastern Operations supported mapping efforts outside the park. During CRF expeditions, thirteen parties went to Roppel Cave. One party started surveying a lead called Old Mill Crawl, but they got too cold and were unable to continue even though the passage is still going. Teams resurveyed in Hobbit Trail and Walter Way. One team mopped up leads in Thanksgiving Maze. Another worked on Trifecta Dome. A virgin passage was found off Ursa Avenue and named Beginner's Luck. Four parties surveyed it. Two parties worked on leads in Lexington Avenue. Another surveyed Mojo Dome and resurveyed in Lower Elysian Way. A party rigged a climb in Metrolines Canyon.

History

In Mammoth Cave, one team examined names in Shelly Avenue to see if the name "Shelly" is a person's name, or indicate the passage has "shells" fossils leading to the name. Another party looked for signatures near Ultima Thule, in a small canyon which is on the Kaemper map, but didn't find any.

Education

The surface location of the collapsed Pike Chapman entrance was identified for NPS staff and for use by a Western Kentucky University Karst Field Studies course instructor.

Mammoth Cave National Park Small Caves Report

Bill Copeland

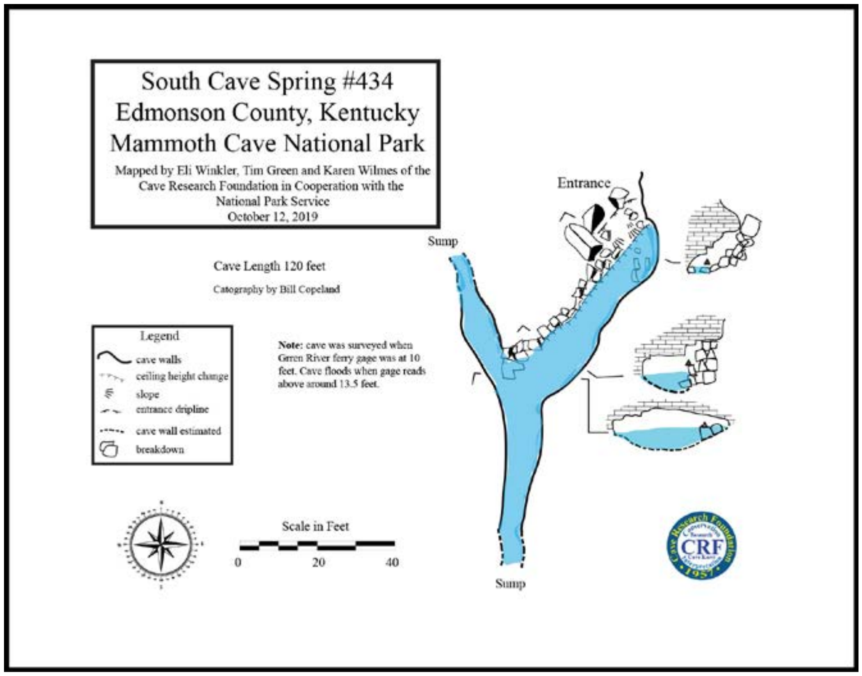
Despite the beginning of the COVID-19 pandemic, the Small Caves Project had another good year. It was the focus of 29 CRF trips, and we logged a total of 662.7 total person hours with a third of those coming from two camp trips to Wilson Cave. We finished six caves and worked on several more.

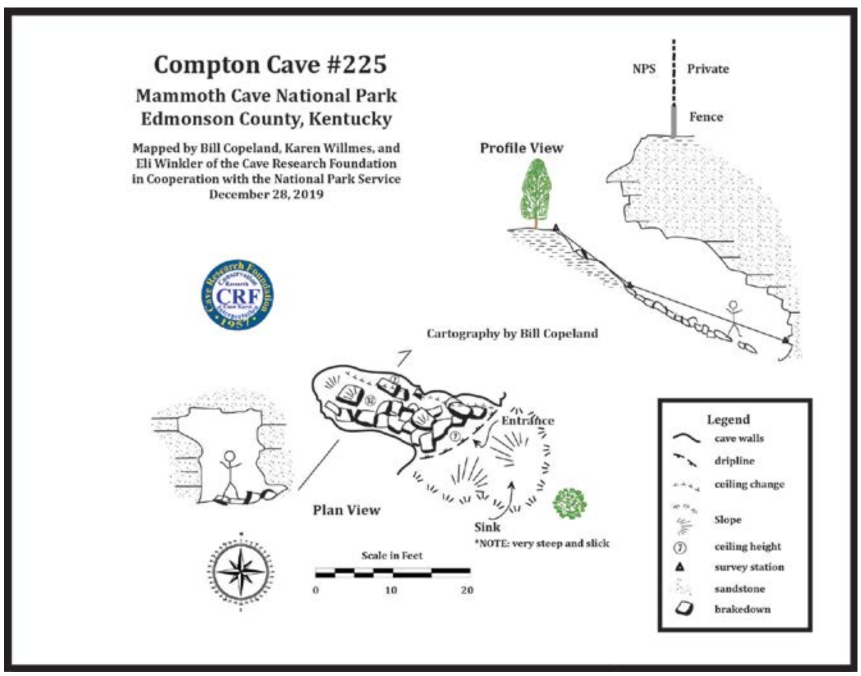
There were 5 ridge walking trips, 19 survey trips, 4 scientific trips, 1 photo, and 1 entrance stabilization trip.

Dave West may have found a new back entrance to Wilson Cave. Time will tell if the entrance to this sink cave will stabilize enough for cavers to safely enter.

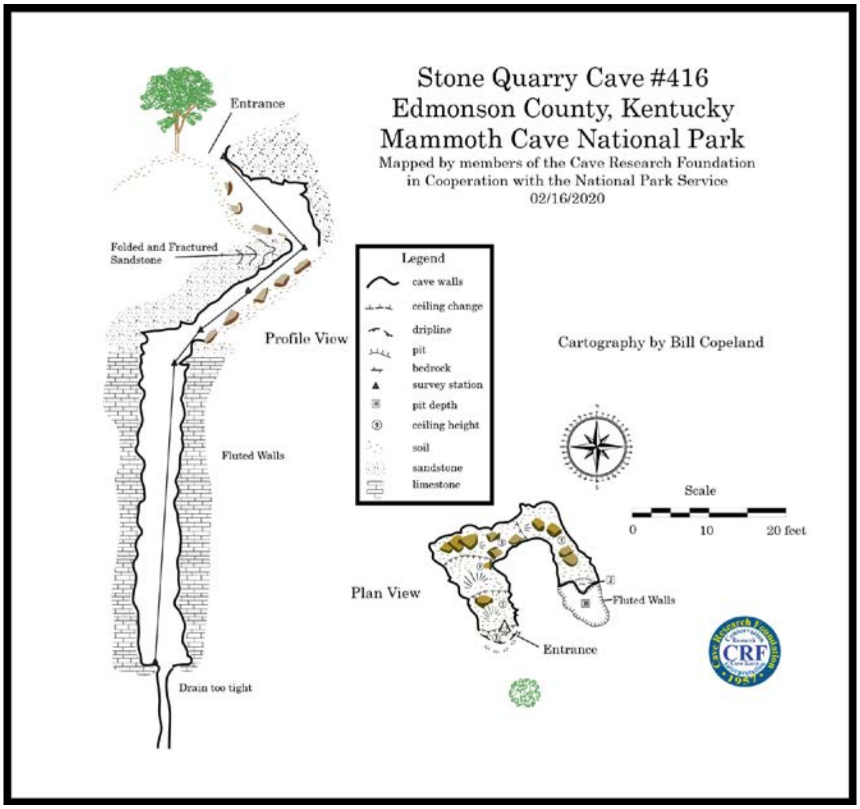
My focus this year was to begin ridge walking in Taylor Coates Hollow that reported to have at least three caves with entrances in the Girkin Limestone. The way there is tough walking with two large karst valleys and two tall ridges to climb that is just under two miles one way. I did find another two entrances in a karst window near Logsdon Cave.

Another focus was to begin surveying caves in the extreme southwest corner of the park south of Cedar Sink. We got one of these mapped and another one started that has a vertical aspect we didn't know about.

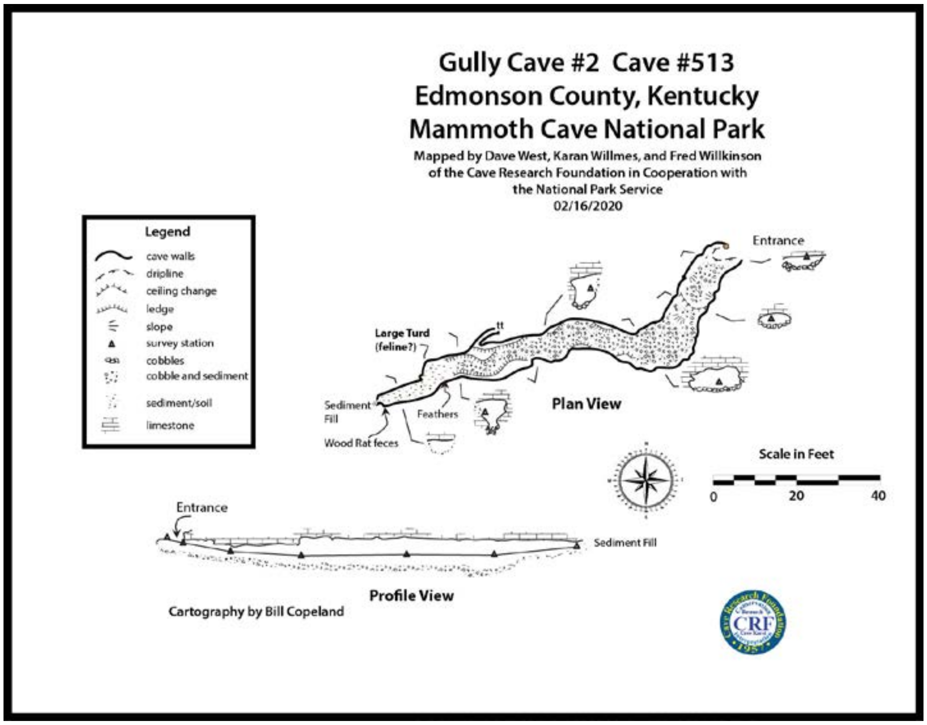


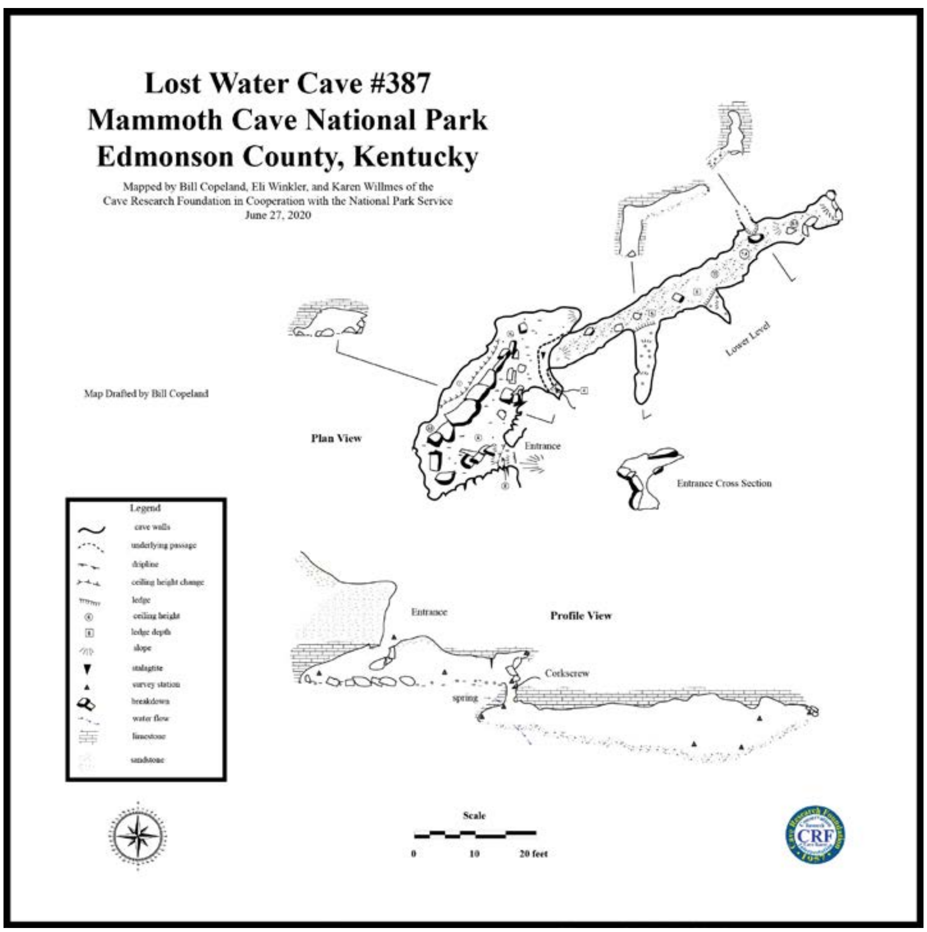


Cave bug in Stone Quarry Cave. *Elizabeth Winkler*



Stone Quarry pit looking up.
Brandon Van Dalsem


Gully Cave #2 Cave #513
Edmonson County, Kentucky
Mammoth Cave National Park
Mapped by Dave West, Karan Willmes, and Fred Willkinson
of the Cave Research Foundation in Cooperation with
the National Park Service
02/16/2020
Legend
cave walls
dripline
ceiling change
ledge
slope
survey station
cobbles
cobble and sediment
sediment/soil
limestone
Entrance
Large Turd
(feline?)
tt
Sediment
Fill
Feathers
Wood Rat feces
Plan View
Scale in Feet
0
20
40
Entrance
Sediment Fill
Profile View
Cartography by Bill Copeland
CRF


Lost Water Cave #387
Mammoth Cave National Park
Edmonson County, Kentucky
Mapped by Bill Copeland, Eli Winkler, and Karen Willmes of the
Cave Research Foundation in Cooperation with the National Park Service
June 27, 2020
Map Drafted by Bill Copeland
Plan View
Lower Level
Entrance
Entrance Cross Section
Legend
cave walls
underlying passage
dripline
ceiling height change
ledge
ceiling height
ledge depth
slope
stalagmite
survey station
breakdown
water flow
limestone
sandstone
Entrance
Profile View
Corkscrew
spring
Scale
0
10
20 feet
CRF

TAG Region

May 2020—October 2020

Hannah Lieffring

Historically, the Southeast has been a hotspot for cave exploration. Nearly 16,000 caves span across one of the most karst dense regions of the United States, TAG (Tennessee, Alabama, Georgia). The sheer number of caves alone is enough to draw in cavers from around the country, and even around the world. To this day, cavers flock to the region to get their own taste of TAG. From the Cumberland Plateau to the Gulf Coastal Plains, there are caves of all varieties.

Even so, it is not uncommon to assume that all discoveries have already been made. For those who continue walking the ridges and mapping new passages, they know this assumption to be false. In addition to searching for unknown caves, there are still hundreds of caves that have not been pushed to their full extent. As such, there are many incomplete maps or no map at all of the cave. Systematically, cavers in the Southeast have been gathering cave data for decades. By becoming a member of the Tennessee Cave Survey (TCS), Georgia Cave Survey (GCS), and/or Alabama Cave Survey (ACS) one can gain access to old reports, maps, locations, etc. The large number of grottoes in the Southeast also make it easy to get involved in different projects.

The most important organization in TAG is the Southeastern Cave Conservancy (SCCi). Founded in 1991, the SCCi is a nonprofit organization dedicated to protecting caves and karst across the Southeast. Over the years, the conservancy has acquired 33 preserves in 6 different states, and over 170 caves. Each preserve is unique in its own way, and many have tremendous scientific and historic value. The organization also encourages research, mapping, and exploration. Recently, the SCCi expressed interest in focusing more attention on biologic inventories and monitoring programs. In addition, several preserves and dozens of caves have yet to be mapped and others could benefit greatly from resurvey.

Gypsy Cave climb.

Hannah Lieffring and Jason Weyland. *Mark Jones*

A partnership between the Cave Research Foundation and the Southeastern Cave Conservancy is extremely beneficial to the conservation and management of caves and karst in this region. By harnessing strengths and abilities from both organizations, there is an opportunity to expand on new, innovative management methods. The mission statements of both groups are nearly identical and it all comes down to "The same three tasks recur across cultures and epochs; to shelter what is precious, to yield what is valuable, and to dispose of what is harmful."

The main focus of the Cave Research Foundation in TAG is to connect with organizations such as the Southeastern Cave Conservancy and state agencies. Currently, we have focused our efforts to project areas in Hamilton County, Tennessee; Jackson County, Alabama; and Dade County, Georgia. Most counties have multiple preserves and multiple caves, so it is likely that one county could take several years to complete. Over time, we hope to produce maps and collect data that will ultimately lead to the construction of cave-specific management plans.

Stephen's Gap Callahan Preserve

Southeastern Cave Conservancy (SCCi)
Bioinventory and Resurvey of Pipeside Pit

Statistics

- 6 trips total
- 11 different participants
- Visited 10 caves on the property

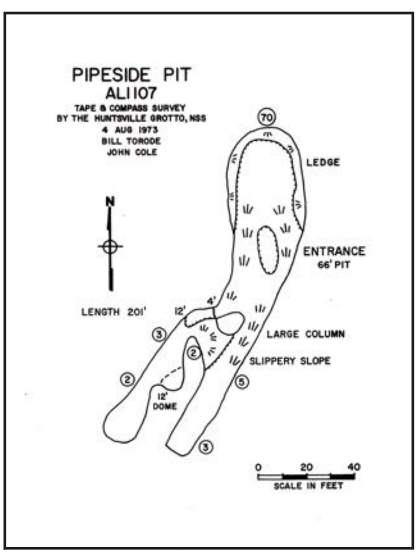
Completed Objectives

- Produced a new map of Pipeside Pit
- Conducted preliminary bio-inventory of all caves on preserve
  - ◊ Brandon's Blasted Burrow, Haley's Cave, Lost Cave, Nancy Callahan Cave, Nancy's Niche Cave, Nine-Foot Falls Cave, Waterfall Cave, Stephen's Ledge Cave, Pipeside Pit, Stephen's Gap Cave
- Investigated fossils/faunal remains in Pipeside Pit
  - ◊ *Cladodus bellifer*—an extinct cartilaginous shark, which have primitive teeth and easy to identify
  - ◊ *Helodus spp.*—an extinct hybodant shark from the paleozoic era, roughly 300 million years old

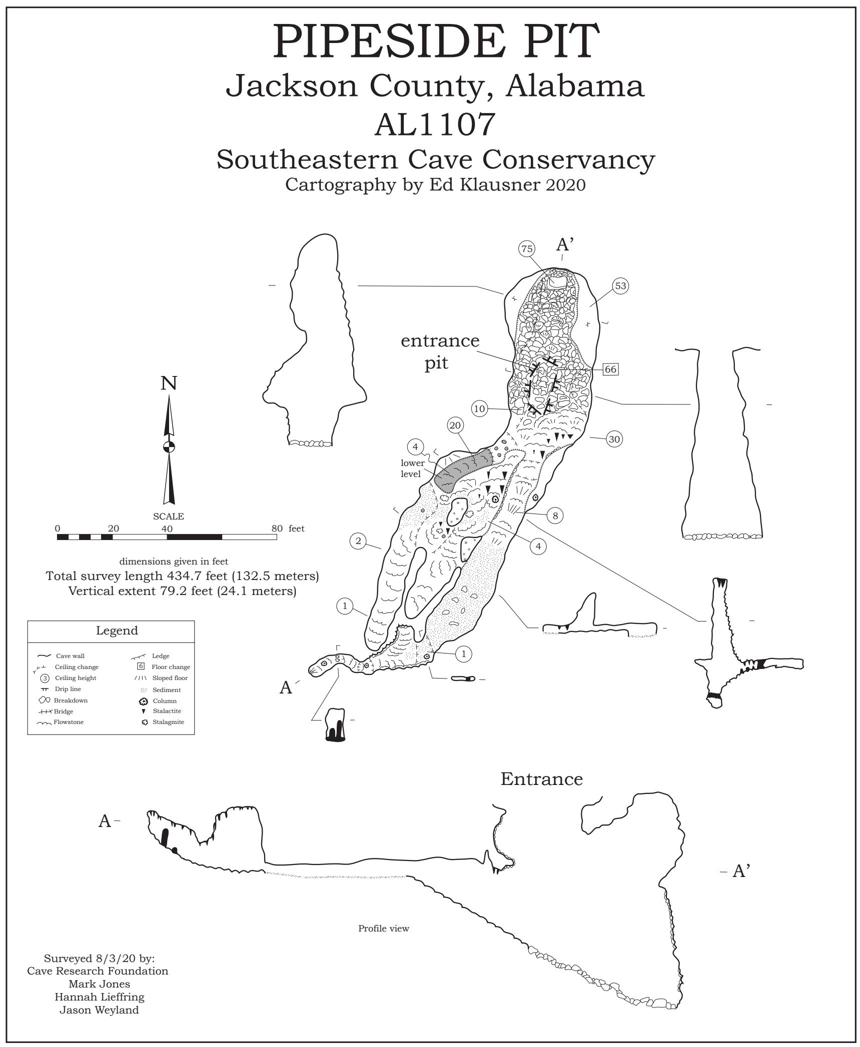
Pipeside Pit Summary

Located on the Stephen's Gap Callahan Preserve, Pipeside Pit is an open-air pit roughly 66 feet deep. The large opening allows for nutrients such as fallen leaves, branches, fruits, berries, and other debris to enter the cave. This provides habitat and food for the creatures living within. Due to the high nutrient intake, this cave is extremely biodiverse. Under each log, one can find healthy salamanders, and in every pool, a crayfish (or several). A few cave-adapted species (invertebrates) were noted in some of the pools. Guano was also present in the pools, which adds to the biomass and nutrient intake of the ecological communities. Several other monitoring trips were done in May and July. During one trip, the team focused on faunal remains (bones) and fossils (shark's teeth).

In August, Mark Jones, Jason Weyland, and I returned



1973 map.



Bradley in Pipeside Pit.

Levi Road Cave climb.

to Pipeside Pit to remap the cave. The original map was completed in 1973 by an excellent cartographer, Bill Torode. Our group wanted to add more detail to the map and create a profile view. The original length of the cave was 201 feet, which we did not believe was accurate. Our resurvey was able to add another 234 feet of length with a total length of 435 feet.

Levi Road Cave

Falling Waterfall State Natural Area
Initial Cave Survey and Bioinventory

Levi Cave Project Statistics

- 6 trips
  - ◊ Climb completed in June
    - Bolted, discovered, and mapped upper "balcony" passage
  - ◊ 2 survey trips in August
    - Roughly 800 feet of survey completed
  - ◊ 3 survey trips in September
- Current length: 2,671.4 feet

White worm in Levi Road Cave.

- Total depth: 107.6 feet
- Bioinventory and biomonitoring of cave
  - ◊ One white, cave-adapted worm was documented
  - ◊ Abundance of slimy salamanders, cave salamanders, and crickets

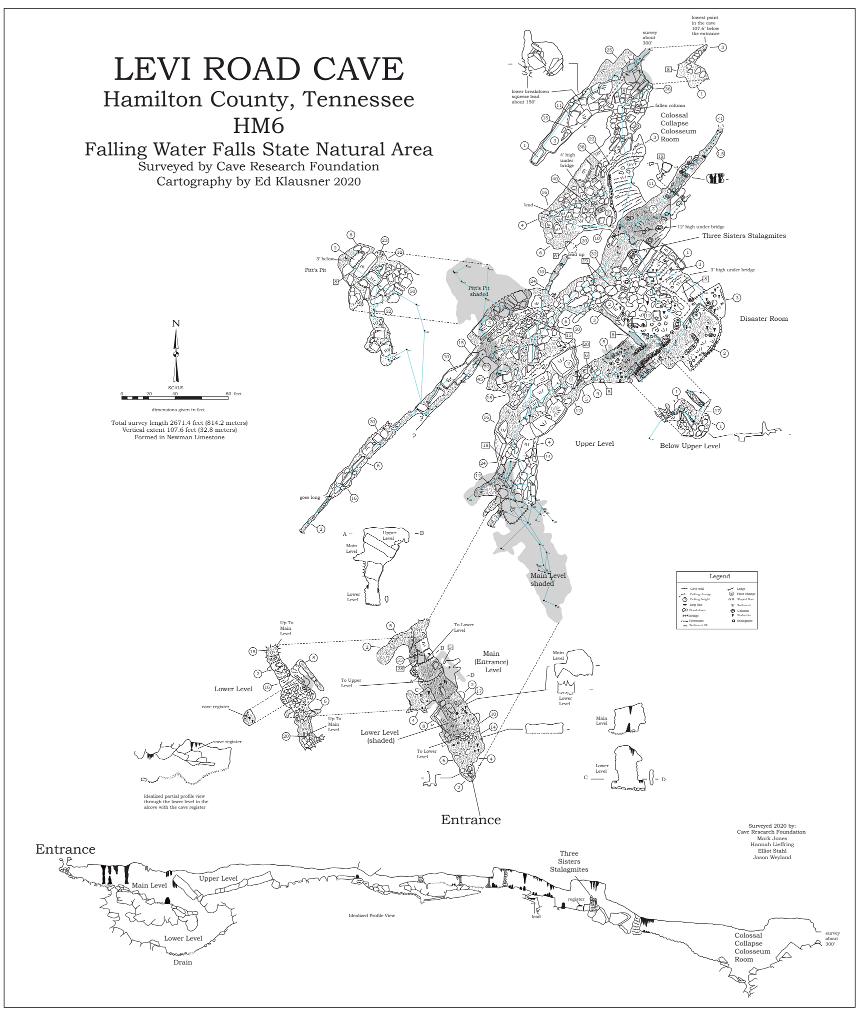
Mark Jones in Levi Road Cave.

Levi Road Cave Summary

Near the city of Red Bank, Tennessee, Levi Road Cave is located on the Falling Water Falls State Natural Area. A small group of cavers made dozens of trips to the cave between October 2019 and May 2020, mostly focusing on trash removal and biomonitoring. In August of 2020, the group began their official survey, but only after gaining a permit from the State Natural Area. The permit also allows restoration projects such as graffiti removal and formation repair. Although the cave map was submitted to the Tennessee Cave Survey (TCS) at 1000 feet long, the team was able to disprove the estimated length in just two trips. Nearly a half a mile of cave has been mapped with no end date in sight.

Gypsy Cave

Charles B Henson Johnson's Crook Preserve (SCCi)
Survey of New Passage and Resurvey

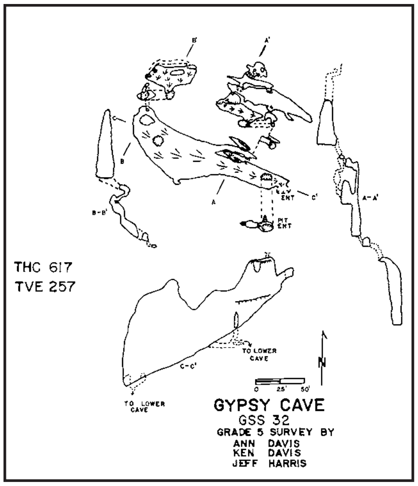


Gypsy Cave Project Statistics:

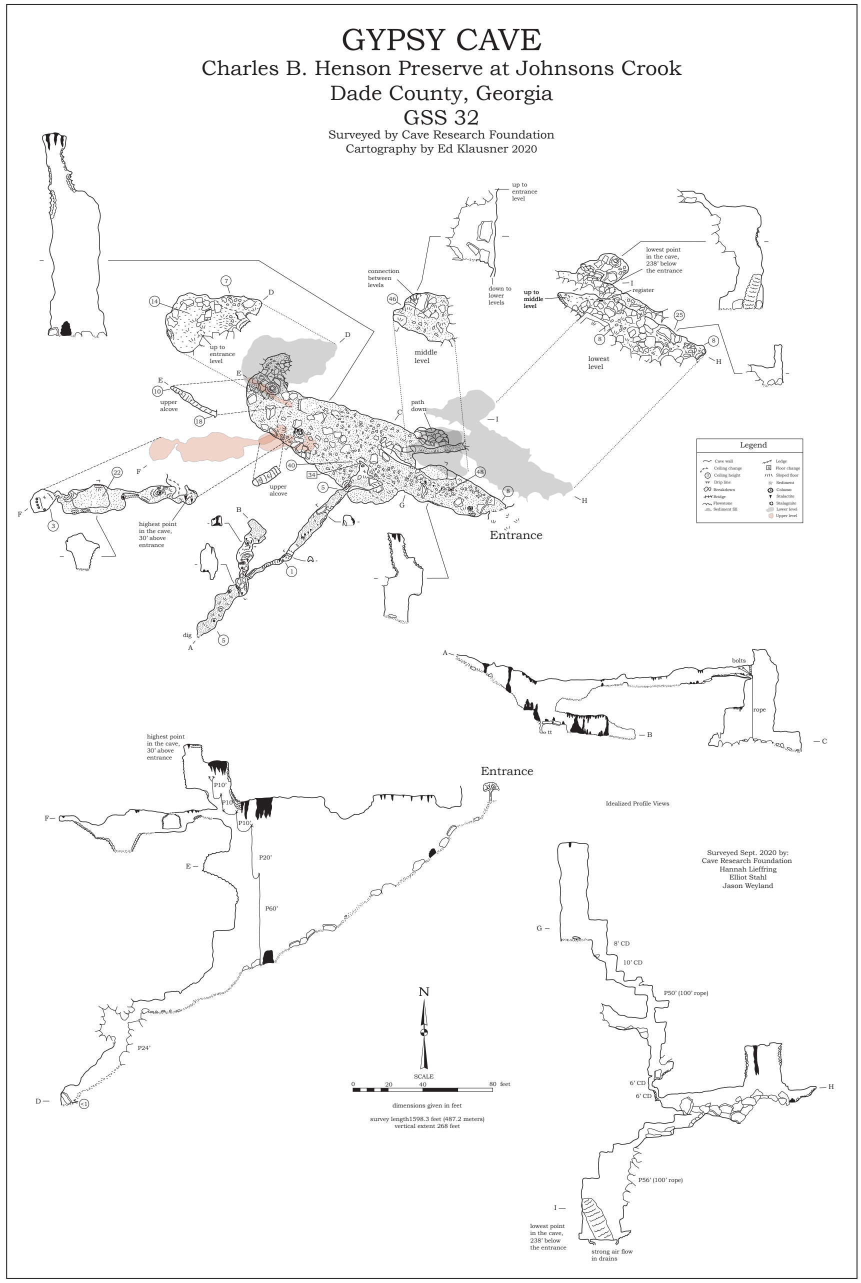
- 9 trips
  - ◊ 7 trips for bolting
  - ◊ 2 trips for survey
- Resurvey of cave
- Survey of newly discovered areas
  - ◊ Length of cave before survey: 617 feet
  - ◊ Length of resurvey: 1,598.3 feet
    - · Vertical extent: 268 feet

Gyspy Cave Summary

The Johnson's Crook (aka Charles B Henson Preserve) in Dade County, Georgia is one of the largest SCCi preserves. By Georgia Cave Survey standards, a "cave" must be at least 30 feet of length, depth, or total traversed (meaning a combination of length and depth). One of the Crook's more substantial caves is Gypsy Cave. Besides a few low leads in the floor, the cave is straightforward. That was, until Elliot Stahl and Jason Weyland began bolting. On several occasions, they were able to bolt up 40–140 feet from the entrance room to explore undiscovered upper levels. One level in particular extends nearly 200 feet to a beautiful formation room that ends in



Old map.



a dig. Other areas of the cave still have potential for ongoing passage, but will not be easy to reach.

Future Plans

The CRF TAG team will be involved in many other SCCi mapping, bio-inventory, and monitoring projects. Our next project will be mapping the newly acquired SCCi cave Balcony Sinks AKA Falling Cave. In that same cave, there will be the opportunity to explore undiscovered passage and document/research ancient bones. Ongoing research at Neversink Pit in Jackson County will continue to aid the Alabama Department of Natural Resources.

We also have plans to further pursue other State Natural Areas, State Parks, and (potentially) commercial caves. Although work with the SCCi is abundant, we are also interested in connecting with other cave-centric organizations to lend a hand where needed. Our ongoing Falling Water Falls State Natural Area project began because we saw a cave with no management plan. We hope to continue finding these small gems and find ways to protect and improve the caves.

Cave Hollow—Arbogast Cave Survey Project

Monongahela National Forest, West Virginia

Dave West

On October 5, 2019 Karen Willmes, Wayne Perkins, and I examined the sink in front of the Manhole Entrance to look for a reported new entrance. Nothing could be immediately entered there. We then entered the Arbogast entrance and surveyed 301.64 feet upstream in Serpentine Way.

We had 12 cavers participate in the November 2, 2019, expedition, so they split up into four teams. Chris Coates, David Smallwood, and Danielle Ellis went to continue the survey toward Lake Susan, while Bill Koerschner, Marissa Loftus, and Aaron Clair went to make the connection between the Pebblehenge Room and Morgantown Grotto Room. The last two teams went to the end of the E survey to continue down the Serpentine Way. They did a leapfrog survey until reaching Sowers Room. At this point, one team started surveying into the passage that heads back north east, paralleling the Serpentine Way. They soon reached a breakdown choke that some of the team could not fit through. Back at Sowers Room, they reconfigured the six cavers so that Bob Hoke, Kurt Waldron, and Gordon Birkhimer could head out, while Wayne Perkins, Brian Masney, and Dave Socky continued surveying down the large passage to the east. At 9:15 p.m., they headed out for the planned meeting time of 10 p.m. at the Arbogast Entrance. A total of 2,184.3 feet were surveyed.

Hunter Wodzenski and Karen Willmes in the Sowers Room. *Brian Masney*

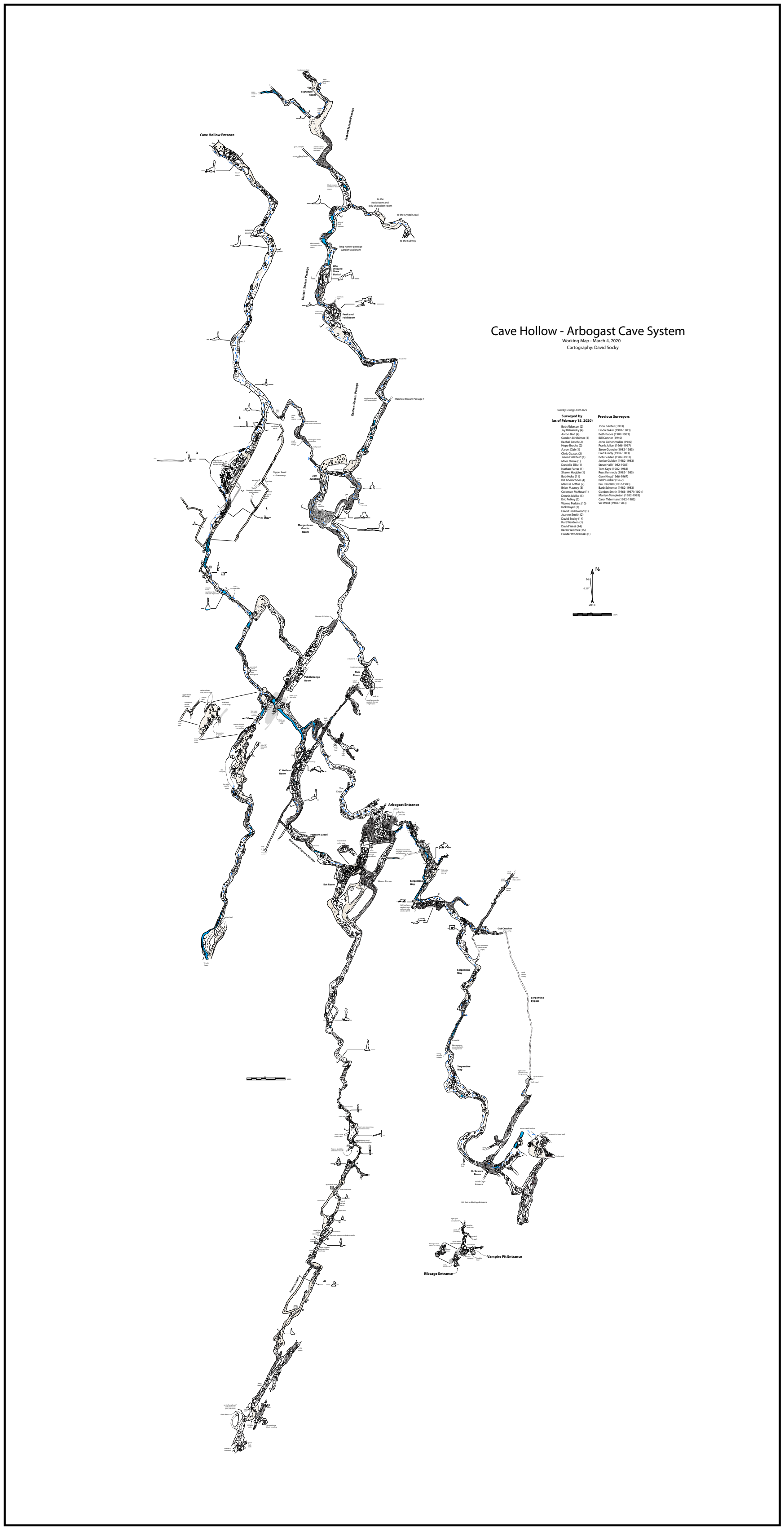
Cave Hollow Cave entrance in winter. *Brian Masney*

With six people attending the December 21, 2019, expedition, we split into two parties and agreed to meet back at the entrance at seven that evening. Brian Masney, Karen Willmes, and Hunter Wodzenski went up Serpentine Way to Sowers Room to continue the survey there. They got some photos and surveyed 260 feet of wet and muddy cave. They observed eight scattered tri-colored bats during their travels and returned to the entrance as planned. Bob Hoke, Dennis Melko, and I went downstream from the entrance to the Weiland Room and on to the Cave Hollow stream. We surveyed 150 feet of cut around crawl between the south end of the Pebblehenge Room and the Manhole stream passage junction. We searched the stream a short distance beyond the north end of the Pebblehenge Room and found two spring salamanders and a small black salamander, but still no blind salamanders.

The trip planned for January 4, 2020, was canceled due to snow.

On February 15, 2020, David Socky, Brian Masney, and Wayne Perkins went on the first February trip of the project. Because of the new snow on the Forest Service Road, they only drove halfway up the mountain, parking at the turnoff for the river campground and old river crossing spot. They hiked up the steep part of the Forest Road and entered the cave about 11:20 a.m. and proceeded directly to the Serpentine Way passage. Their goal was to survey the bypass to the main Serpentine Way and comes out in the Harry Sower Room. They did see some tri-colored bats near the start of the survey. They were unsuccessful in doing the full bypass because there are tight spots at both ends that none of them could even come close to fitting through. By the time they had surveyed both ends of the bypass, it was 5:30 p.m., too late to start anything new. They surveyed a total of 443 feet on a seven-hour trip.

The rest of the trips planned for the year were canceled due to COVID. It remains uncertain when the project will resume



Northwestern Operations Area: Lava Beds (LABE) and Craters of the Moon (CRMO)

John Tinsley

Manager, CRF Northwest Operations

For Lava Beds and Craters of the Moon, the year 2020 will go down in history as the field season that wasn't. With the March 2020 administrative shutdown of Lava Beds, including the research center, we found ourselves basically out of business. Hopefully there won't be too much more of this. Owing to COVID-19-wrought shutdowns, many national park units were closed for months, including Lava Beds. At LABE, we lost January and February field time to snowstorms and generally bad weather on those long weekends. Three expeditions projected to run for at least one week or more were canceled in April and May, plus the national expedition in October, and even the local cavers were not on site for the year.

During the shutdown, our principal investigators have worked to eliminate backlogs of mapping and inventory and are making preparations to hit the ground running whenever we are able to resume a full scope of operations at either LABE or CRMO, hopefully in 2021. The LABE research center opened for a non-CRF group in August, and opened again for four of our personnel in October. Dave West, Karen Willmes, Mark Jones, and Paul McMullen helped Pat Seiser complete monitoring work on the ice

Low oblique photograph looking nearly west towards Mt. Shasta, showing the forested arch of Medicine Lake Volcano in the middle ground and the western aspects of the 1000-year-old Glass Mountain obsidian flow in the right foreground.

Photography by J. C. Tinsley, with Captain M. J. Spiess commanding the flight.

levels and other ancillary administrative tasks, so Pat will hit most of her cave-related performance marks for the 2020. The CRF contingent also continued surveying in the Balcony flow lobe. A summary of individual projects follows, listed by Principal Investigator.

Jones: *Craters of the Moon National Monument and Preserve*: No trips taken in 2020.

Broeckel: *Caves of Modoc National Forest:* No trips taken in 2020.

Devereaux: *Ice Cave Monitoring*: Pat Seiser has taken this over, with assistance from CRF. This is one of the longer-lived data sets in LABE, going back to the late 1970s with Mike Sims and Don Denbo. CRF absorbed this ongoing monitoring study in 1989 when Janet Sowers organized the initial CRF effort at LABE.

Frantz: *Photomonitoring*: Bill and Peri have relocated to Vermont. This project is up for grabs. Contact Tinsley if interested in taking on this work that goes back to 1989.

House: *Caves of North and South Castle Flows*: He has refined some drafting and spent some time on improving the database.

Klausner: *Caves of Elmer's Trench, Caves of Central Lobe (Lower Cave Loop)*: Trip canceled due to COVID-19.

Tinsley: *Caves of the Valentine Flow; Basalt of Mammoth Crater Studies*: Tinsley has been picking away at drafting caves surveyed during 2019 from the basalt of Valentine Cave and is processing samples of basalt of Mammoth Crater from Sentinel and Post Office caves for chemical analysis by Julie Donnelly-Nolan of the U.S. Geological Survey. No trips this year on the ground at LABE. Tinsley also has assisted organizers of the 2021 NSS Convention (Weed, California) with aspects of that guidebook. He assisted Liz Wolff with preparation of a self-guided geomorphology field trip from McCloud to Medicine Lake volcano (July) and assisted with the previewing of Bill Hirt's geology field trip to the Mt. Shasta area (October). He also was privileged to conduct an aerial reconnaissance of Shasta/Medicine Lake Volcano/Lava Beds via light fixed-wing aircraft (October) under the command of joint venture member Mike Spiess.

Wolff: *Cartography of Cave Loop Caves*: No trips to LABE this year. Liz has been spending much time preparing for the Convention caving trips, by locating entrances, organizing trip leaders, and so forth. This convention would not be nearly the success it will be absent Liz and the Shasta Area Grotto. Incidentally, this is another outstanding example of how CRF personnel wear multiple hats with the NSS and local grottoes and get things done.

West: *Balcony Boulevard Caves:* Led late October 2020 expedition to Lava Beds with Karen Willmes, Paul McMullen, and Mark Jones. See separate report.

Deer grazing in burn area outside the Research Center.
Dave West

Karen Willmes next to Heppe Pit with Upper Heppe Bridge entrance.
Dave West

October 2020 Lava Beds (LABE) Report

Dave West

Due to COVID-19 and a fire that burned seventy percent of the monument, Natural Resources had fallen behind on their Monitoring and Mapping Program and requested that a small group come out to assist them in getting caught up. Only four people would be allowed to stay in the Research Center (RC) to comply with COVID guidelines.

Karen Willmes and I flew out from Baltimore while Mark Jones and Paul McMullen drove to the Monument from their homes. Mark arrived early and starting October 12, spent four days exchanging monitors and placing signs in various caves throughout the Monument. Paul arrived on the afternoon of October 16, so he and Mark proceeded to map Overpass Cave. Karen and I arrived in the evening of October 17 in time to prepare dinner for the group.

Karen Willmes holding tape for a shot on the Goliath profile. *Dave West*

The Monument also requested a map of Trapper Cave as both Overpass Cave and Trapper Cave are monitored by the Monument and better maps were needed. We surveyed Trapper Cave, and Mark provided Ed Klausner with photos of the Overpass and Trapper Cave notes. Ed had a draft ready the following day.

Pat Seiser had provided a list of caves that needed maps for either monitoring or for anticipated research. High on the list were the Heppe Caves and Goliath Cave. This visit also provided us an opportunity to map Black Ice Cave and Just Right Cave, which are protected for cultural reasons.

On Monday the 19th we headed out to map Heppe Ice Cave, which was almost but not quite completely lacking any ice. Paul found a minuscule patch hiding well down in the breakdown by peering through rocks on the floor. The current map of the Heppe Caves was from the 1970s and focused on volcanic features, leaving out other details in the style of the time. It turns out that the scale on the map was incorrect as well. At some point, the map was reduced by fifty percent, but the scale remained the same, making the caves appear to be half their actual size. We finished the survey of the Ice Cave, but it became clear that surveying all of the Heppe Caves would take more time than we had initially thought.

On Tuesday, October 20, Paul, Mark, and I ventured out to Goliath Cave and began the survey of it. The back of the cave is an unstable scree slope. Paul and Mark rigged an etrier and a hand line and were able to complete the survey while I stayed at the top of the slope to minimize any resulting rockfall. The high lead at the back of the cave remains unsurveyed. An undercut wall of congregate seems to remain in place, providing no safe place to ascend. We ran out of time before finishing a lower level near the front.

We returned to Goliath the following day. Paul and Mark went into the cave to mop up a few things while Karen and I ran a surface survey for a profile view on the map. It was necessary to continue the profile survey into the large pit collapse upflow before arriving at a point above the back of the cave. When Mark and Paul reappeared, we proceeded to the Heppe Caves and mapped Heppe Grotto. While it is true that one can see the back wall of Heppe Grotto from the surface, that wall is eighty feet away, twice what is needed to qualify as a cave in the monument.

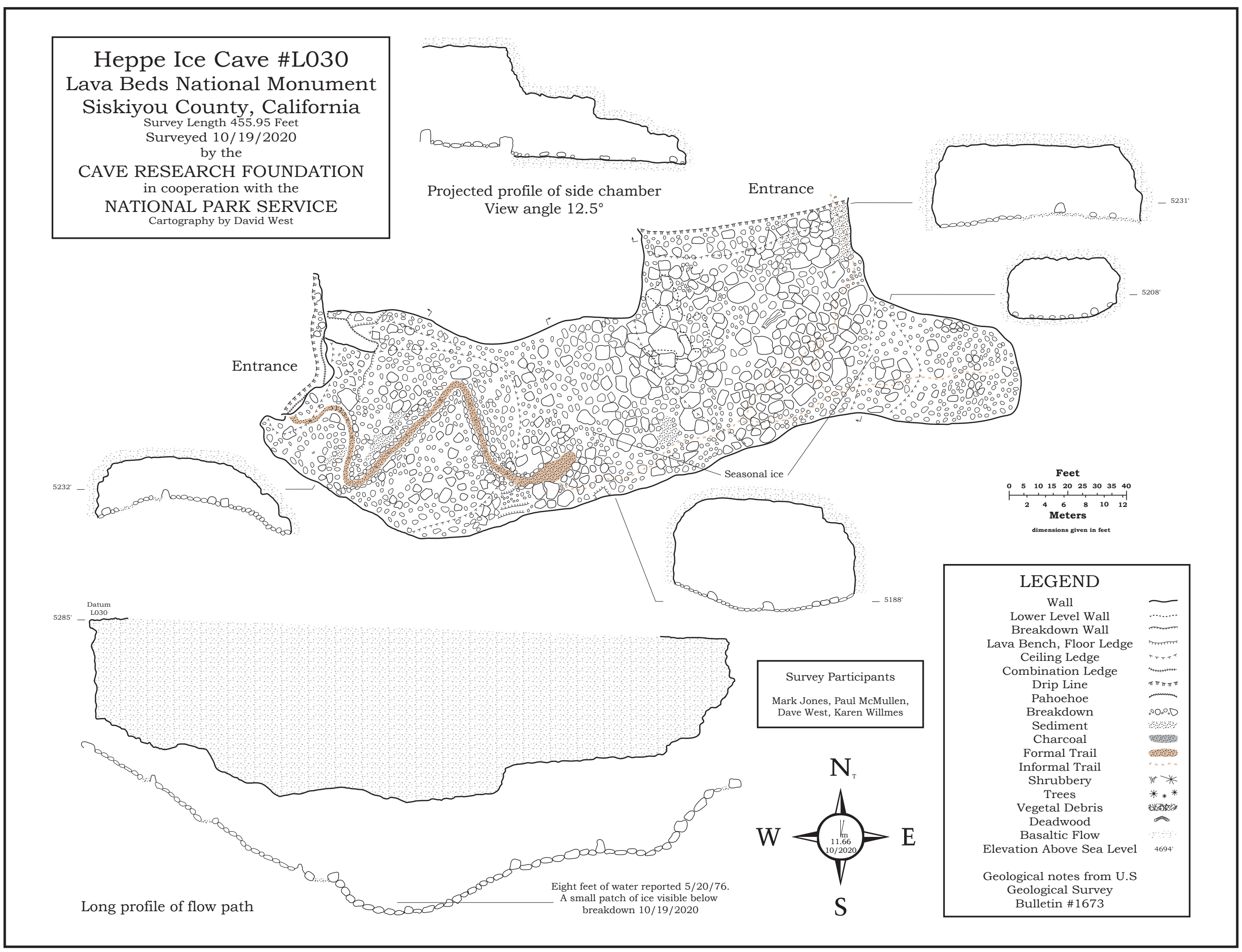
Mark Jones makes his way across the collapse to Goliath Cave. *Dave West*

Karen and I in a similar manner before returning to his office. We found Black Ice Cave to be almost completely lacking in ice. An area reported to be 25 feet by 5 feet was completely devoid of ice. A patch of ice in a pit off to the side of the main chamber had been reported to be 4 feet by 15 feet. It had been reduced to about 3 feet by 10 feet. While Paul and Mark were able to complete the survey of Just Right Cave, Karen and I had time for only a few shots before it was time to return to the Research Center (RC).

On Friday, Mark and Paul went to Himmel Cave to swap out monitors.

On Thursday the 22nd, Chris Combel from Cultural Resources joined us. We proceeded to Just Right Cave, where he showed Mark and Paul the resources needing extra care. Leaving the two of them to map that cave, the other three of us went on out to Black Ice Cave, where Chris advised They then walked the northeast burned area of the Balcony Flow, finding a few holes that will be checked when we survey the caves in that area.

On Saturday we all went to Black Ice Cave in an effort to finish it. A number of shots were taken that avoided



stepping on the charcoal of interest in the cave. While I worked on the sketch for these shots, Mark and Paul went upflow to a lead Paul had found on a previous visit and surveyed what is now called Two Drop Inn Cave. With the ice gone, what had been noted on an earlier sketch as a lower level was now sort of accessible. And Karen found a room not noted previously that had been completely blocked by ice. Out of time for the day, we returned to the RC.

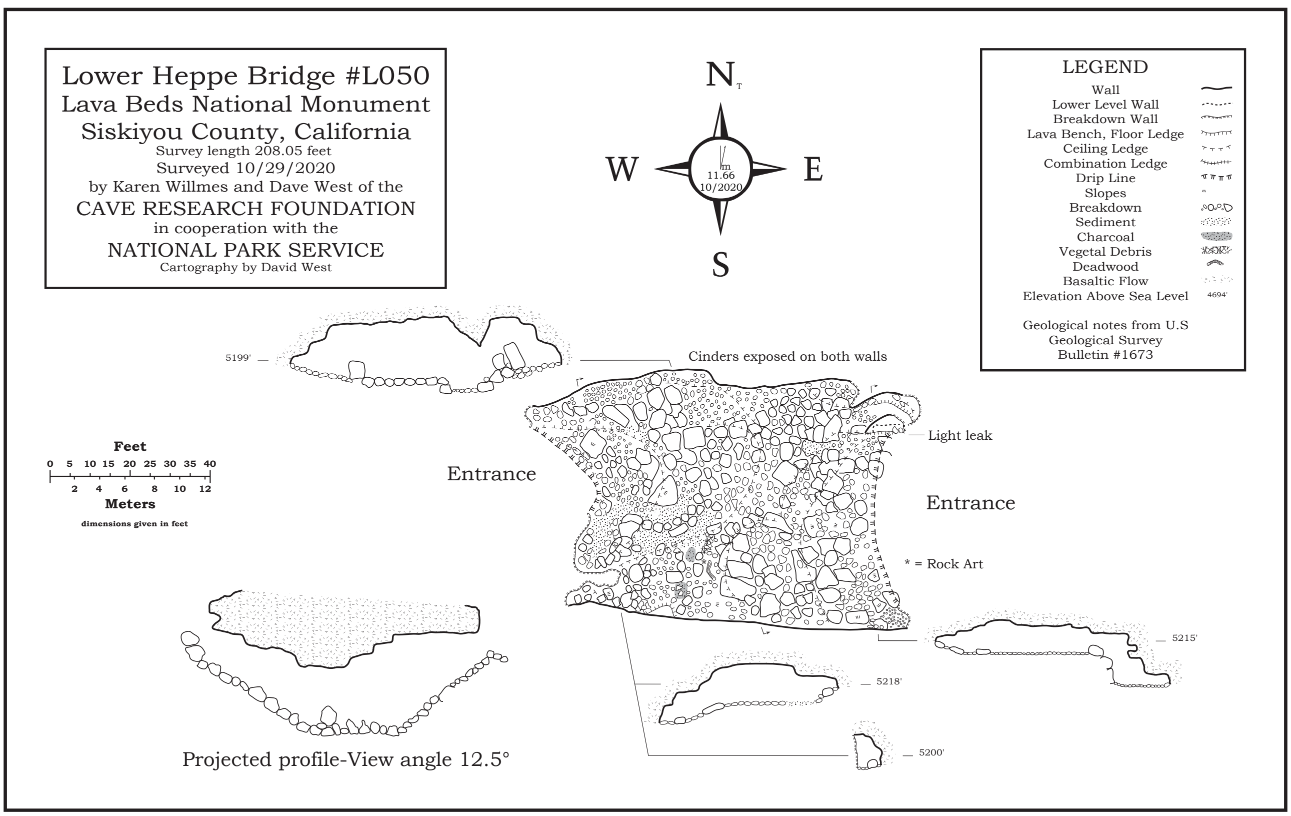
On Sunday the 25th, we began the survey of Upper Heppe Bridge. We were joined by a Monument volunteer, Dave Donner and his son Sasja. Upon reaching the halfway point in the cave, we found the cave was acting as a venturi of very cold air. I found it necessary to go outside and warm up before I could finish up sketching the last shot of the day.

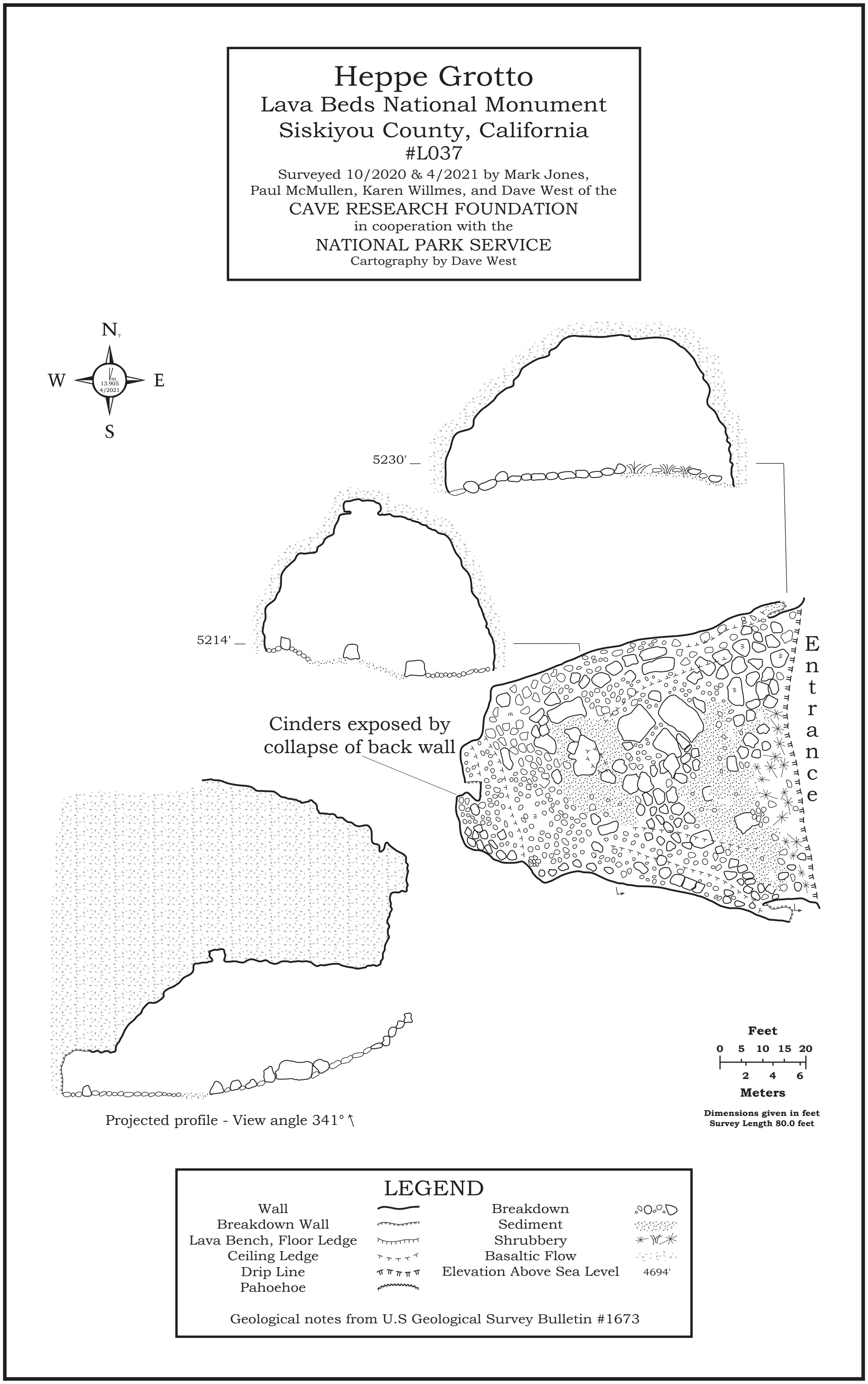
Mark and Cal-Dave (as Mark differentiated the two Daves) went out the Lyon Trail to swap out monitors in caves there on Monday. Karen and I went back to Black Ice Cave and got details of the lower area as well as surveying the room she had found. The room was about forty feet long and had some nice black lavasicles, but absolutely no charcoal or other evidence of any previous human visitation. A very old woodrat midden contained some bones, which were photographed for reference.

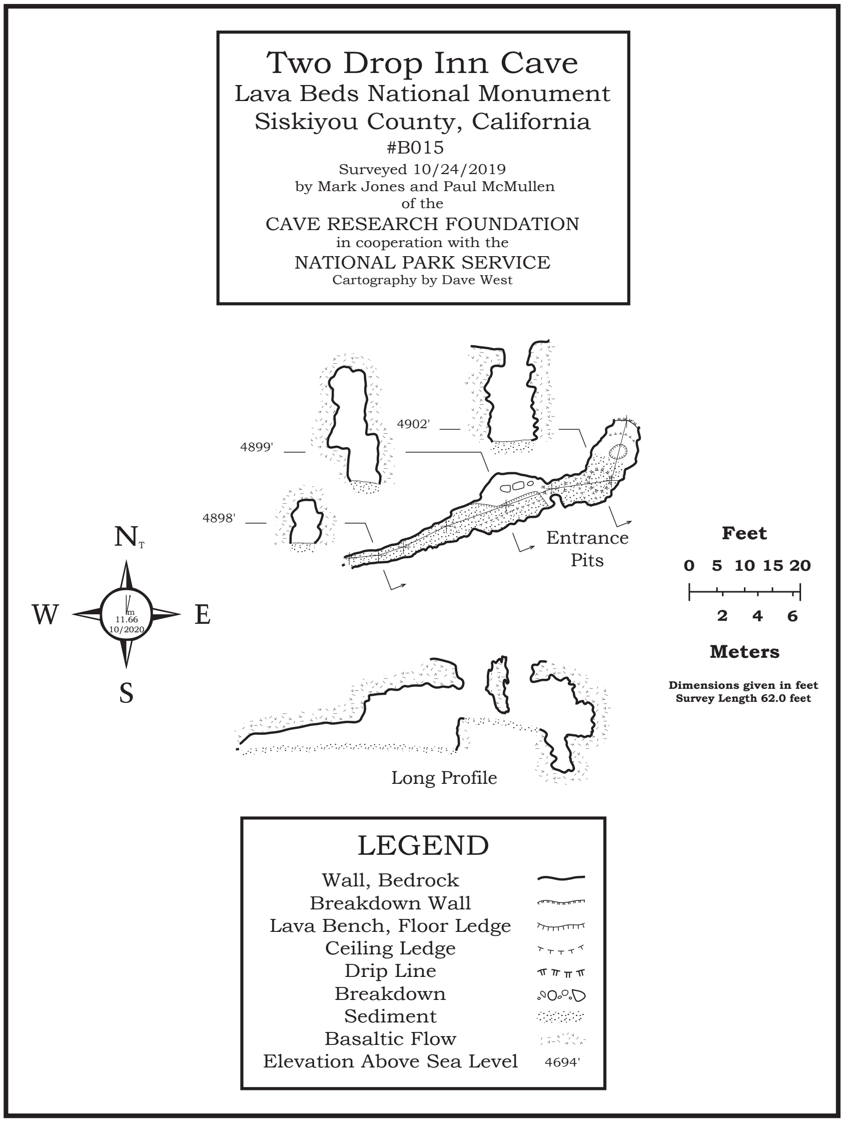
On Tuesday the 27th we all joined Pat Seiser for a trip to Cox Cave for ice monitoring. Much of the ice was covered by as yet unfrozen water, so photogrammetry was

Karen Willmes in the newly discovered chamber in Black Ice Cave. *Dave West*

employed. Karen and I left the group to return to the Heppe Caves. We first did a surface survey of the trail over Heppe Ice Cave and Heppe Chimney. We then returned to Upper




Heppe Grotto
Lava Beds National Monument
Siskiyou County, California
#L037
Surveyed 10/2020 & 4/2021 by Mark Jones,
Paul McMullen, Karen Willmes, and Dave West of the
CAVE RESEARCH FOUNDATION
in cooperation with the
NATIONAL PARK SERVICE
Cartography by Dave West
N
W
E
S
5230'
5214'
Cinders exposed by
collapse of back wall
Entrance
Projected profile - View angle 341°
Feet
0 5 10 15 20
2 4 6
Meters
Dimensions given in feet
Survey Length 80.0 feet
LEGEND
Wall
Breakdown Wall
Lava Bench, Floor Ledge
Ceiling Ledge
Drip Line
Pahoehoe
Breakdown
Sediment
Shrubbery
Basaltic Flow
Elevation Above Sea Level
4694'
Geological notes from U.S Geological Survey Bulletin #1673



Heppe Bridge in an effort to complete it. Our return time came up before I finished sketching the 96-foot shot Karen had set, and we would have to return yet again. After finishing the ice monitoring with Pat, Mark, and Cal-Dave went out to Incline Cave in the South Castle flow to swap out monitors.

Wednesday was to be another day of ice monitoring in Skull Cave. Pat and one of her co-workers assisted her with the task. Karen and I returned to the Heppe Caves to increase the possibility of finishing them. We first continued the surface survey down to the Heppe Ice Cave entrance, but we were not able to locate the tie station. Returning to Upper Heppe Bridge, we did finish it, and also surveyed the trench between it and Lower Heppe Bridge.

With the foreboding weather forecast of more snow, Mark decided to head home. Karen and I went out armed with notes of all things Heppe and first tied our surface survey to the Ice Cave survey. We then went to the Lower Heppe Bridge. We observed more charcoal in it, and also observed some "cave art" on the ceiling above it. We finished the survey of this cave and returned to the RC.

Our original plan had not included caving on our last day at the monument, but I wanted to get a profile and sketch of the central collapse at the Heppe Caves. We had a short survey that I had not sketched connecting the three entrances along the unimproved trail. We recovered the stations and I got left wall readings. My original plan for the day included a similar survey along the other wall before running the profile down the middle. Observing that that area of the pit remained in shadow, I elected to skip that and get a series of splay shots with the disto to nail down the wall as we did the profile down the middle. I then sketched in the various slopes, trees, and shrubbery, along with the rocks larger than four feet square before returning to the RC for lunch, packing, cleaning, and departing.

We plan to return in late April when we will get a proper survey of Heppe Chimney and then return to the Balcony Flow to continue the survey of it.

Ozarks Operation Activities 2020

Scott House

Ozarks Operations Manager

Primary Funded Projects

Please note: since we regularly report on activities, see the CRF Newsletter *for more details on field work. Ozarks Operation has fielded 250 trips over the past 12 months.*

Ozark National Scenic Riverways

CRF Ozarks works with the Ozark National Scenic Riverways, National Park Service (NPS) under a cooperative cave management agreement. This agreement expired at the end of FY2019. The agreement was renewed for an additional five years; it will expire in 2025. Despite the pandemic, many trips (80+ field trips) were taken as volunteers went out in very small groups (2–3). More caves were monitored this year than ever before. Scott House is project director.

Buffalo National River

CRF work at Buffalo National River (NPS) is facilitated through a cooperative cave management, survey, and bat monitoring agreement. This agreement expired at the end of FY2019 but was renewed for another five years. Fewer trips (26 total) were taken to Buffalo NR as the Arkansas Fish and Wildlife Office felt that it was important to constrain visits to caves with bats. Kayla Sapkota is project director and has a separate report.

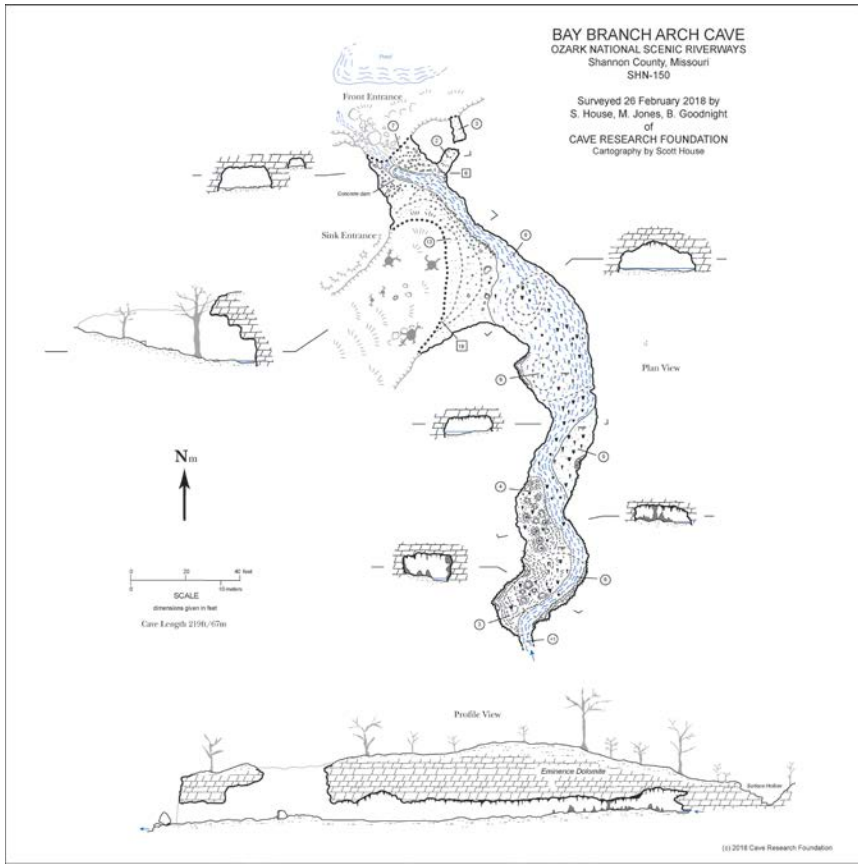
Looking out of the entrance of Tater Cave, Ozark National Scenic Riverways. *Tyler Skaggs.*

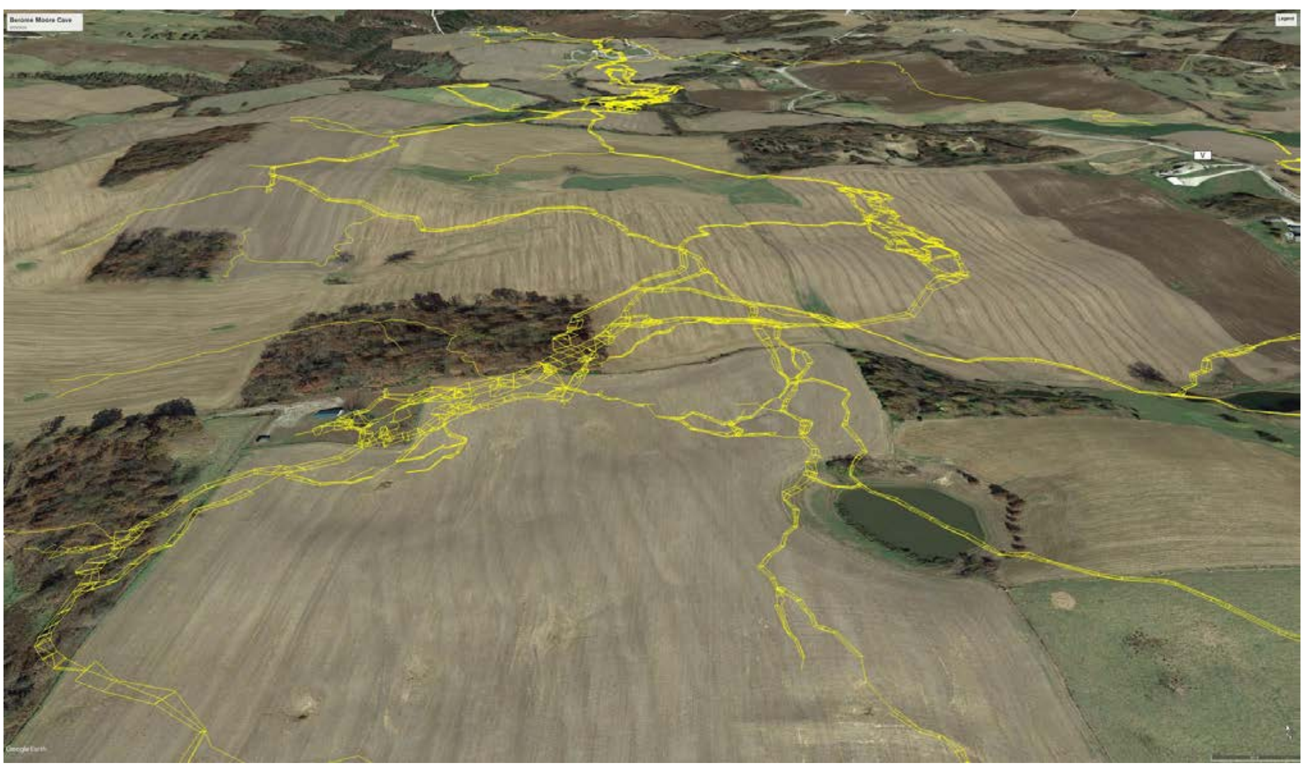
Mark Twain National Forest

CRF work on Mark Twain National Forest (U.S. Forest Service) is performed through a pair of cooperative agreements covering inventory, survey, monitoring, and gating. We have had two separate funded cooperative agreements, expiring on different dates. Our old general agreement will officially expire at the end of June 2021, but its funds have been drained. A new agreement was signed and is good through 2025. Nearly 70 trips were taken over the past year. Project directors include several people. Funding was obtained for continuing the Roaring River Spring tracing project headed by Ben Miller and Bob Lerch.

U.S. Fish and Wildlife Service

A new project to establish biological census protocols was undertaken at the Moore Cave System in Perry County. Mick Sutton is heading this up and five trips have been taken. The primary goal is to census the endangered grotto sculpin; secondarily the





A view of the Moore Cave System winding its way under a pastoral landscape. Graphic by Chad McCain.

project will assess the overall cave life web in this large and important system. The Service also supported several trips to known gray bat caves to assess the need for cave gates. Volunteer-wise, CRF helped the Arkansas field office with assessing Ozark big-eared bat habitats.

Unfunded Projects

Ozark Underground Laboratory (OUL)

Nine trips have been taken to continue the mapping and restoration of Tumbling Creek Cave, Taney County, Missouri. This project is being supported by the OUL in the form of free housing and other support (evening reminisces by Tom Aley count for a lot). Dan Lamping is doing the cartography while the restoration is headed up by Jon Beard.

Pioneer Forest (L-A-D Foundation)

This project is being done as part of our mission with a friendly landowner. Some trips are taken in cooperation with Meramec Valley Grotto. Cartography and inventory are the main goals.

Three Forks Cave Project

Mark Jones leads this project to map caves in a defined area in Oklahoma. Ed Klausner is doing primary cartography. Mark Jones has a separate report.

Missouri State Parks

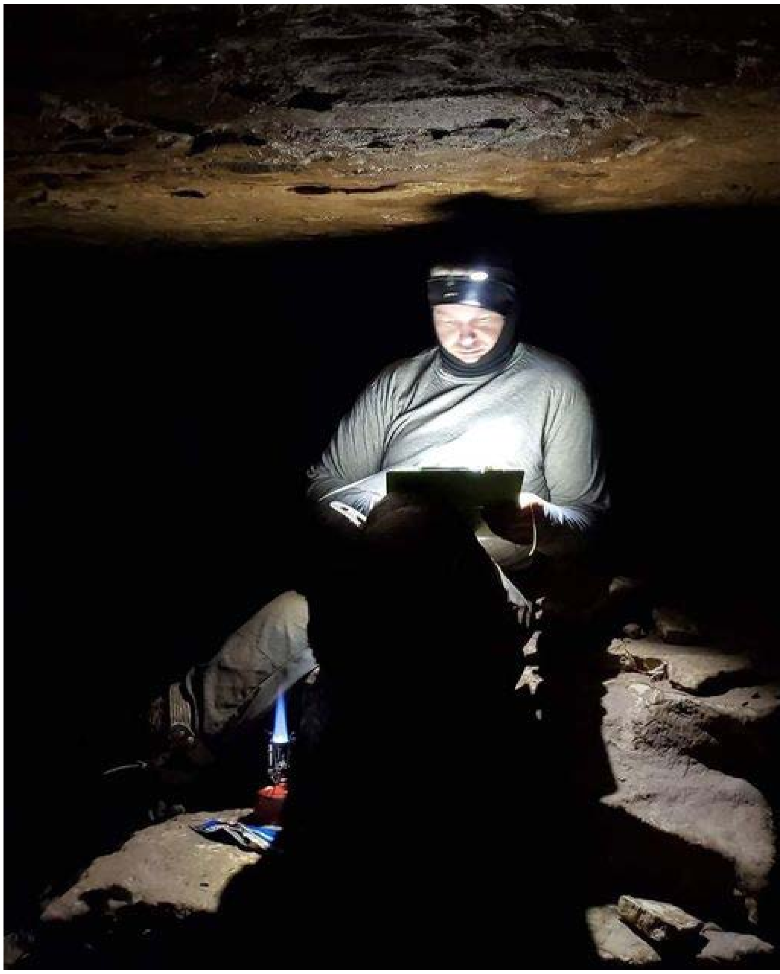
Work on Missouri State Parks (Missouri Department of Natural Resources) is done through a series of letters of authorization. Trips continue on a mostly informal basis, responding to agency requests. Ken Grush and Jeff Crews are the primary contacts.

Missouri Department of Conservation

CRF work on lands administered by the Missouri Department of Conservation is done through a series of special use permits and grants. Ten trips have been taken for gating, inventory, and survey purposes. A new cave gate project is in the planning stages. Dan Lamping serves as the primary contact.

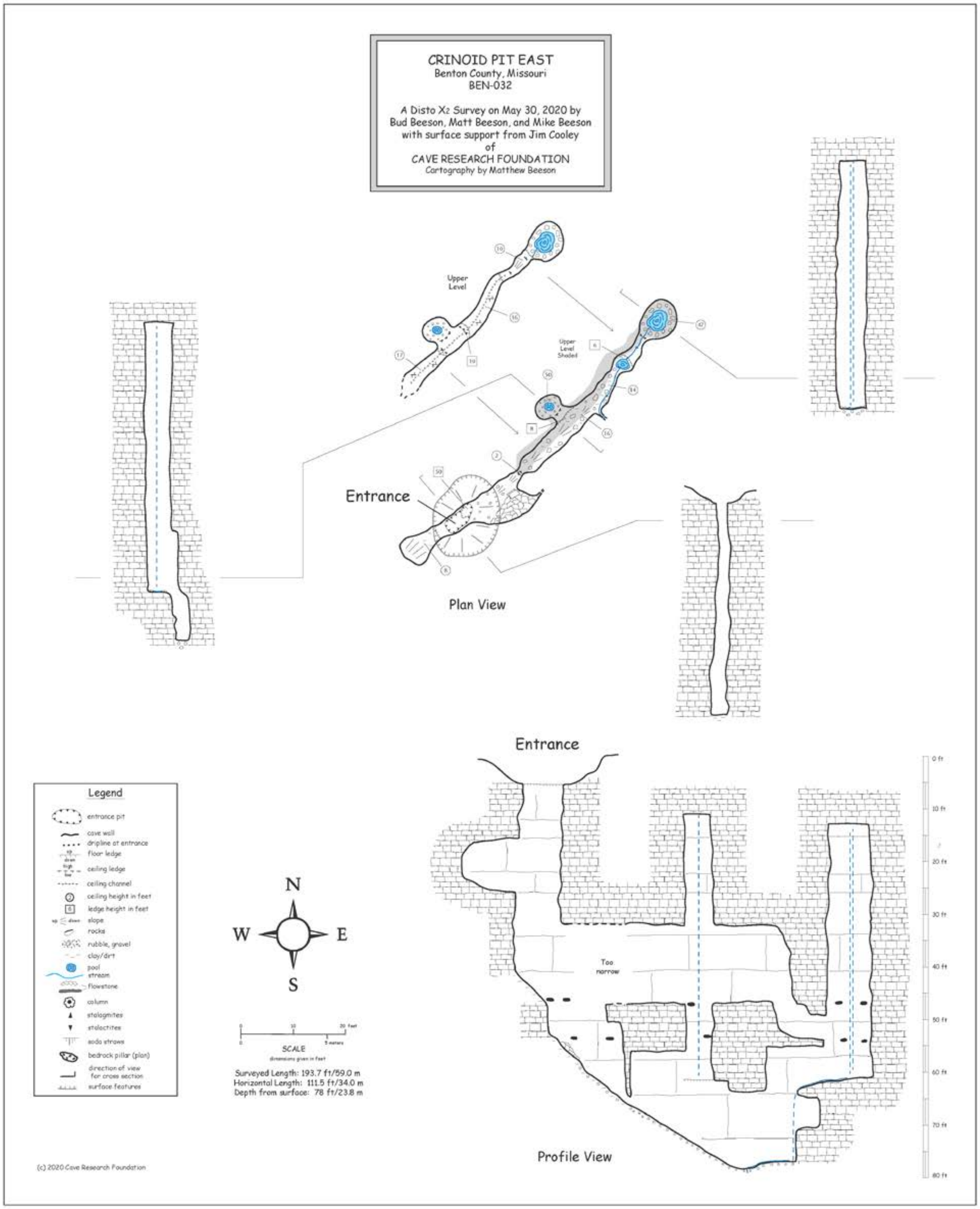
City of Perryville

Work in and around the City of Perryville, Missouri, is facilitated through a cooperative agreement between the city and the Missouri Speleological Survey. Seed funding is provided by CRF. Survey is ongoing in Crevice Cave, the longest cave in the state, headed by Alex Litsch. A new series of signs is being created to explain karst features to the public.



Brian Biggs sketches in Moore Cave. *Mark Brooks*

A populated Otter Den in Welch Spring Cave, Ozark National Scenic Riverways. *Mark Jones*


CRINOID PIT EAST
Benton County, Missouri
BEN-032
A Disto X2 Survey on May 30, 2020 by
Bud Beeson, Matt Beeson, and Mike Beeson
with surface support from Jim Cooley
of
CAVE RESEARCH FOUNDATION
Cartography by Matthew Beeson
Upper Level
Upper Level Shaded
Entrance
Plan View
Entrance
Too narrow
Profile View
0 ft
10 ft
20 ft
30 ft
40 ft
50 ft
60 ft
70 ft
80 ft
Legend
entrance pit
cave wall
dripline at entrance
floor ledge
ceiling ledge
ceiling channel
ceiling height in feet
ledge height in feet
slope
rocks
rubble, gravel
clay/dirt
pool
stream
flowstone
column
stalagmites
stalactites
soda straws
bedrock pillar (plan)
direction of view for cross section
surface features
N
W
E
S
SCALE
dimensions given in feet
Surveyed Length: 193.7 ft/59.0 m
Horizontal Length: 111.5 ft/34.0 m
Depth from surface: 78 ft/23.8 m
(c) 2020 Cave Research Foundation

Arkansas Natural Heritage Commission

Several trips were taken to support cave work on lands owned by the Commission. See a separate report from Kayla Sapkota.

Army Corps of Engineers

A nascent project was investigated in the Bull Shoals project. This was to involve a cave gating but the cave was deemed less than critical.

Missouri Caves and Karst Conservancy

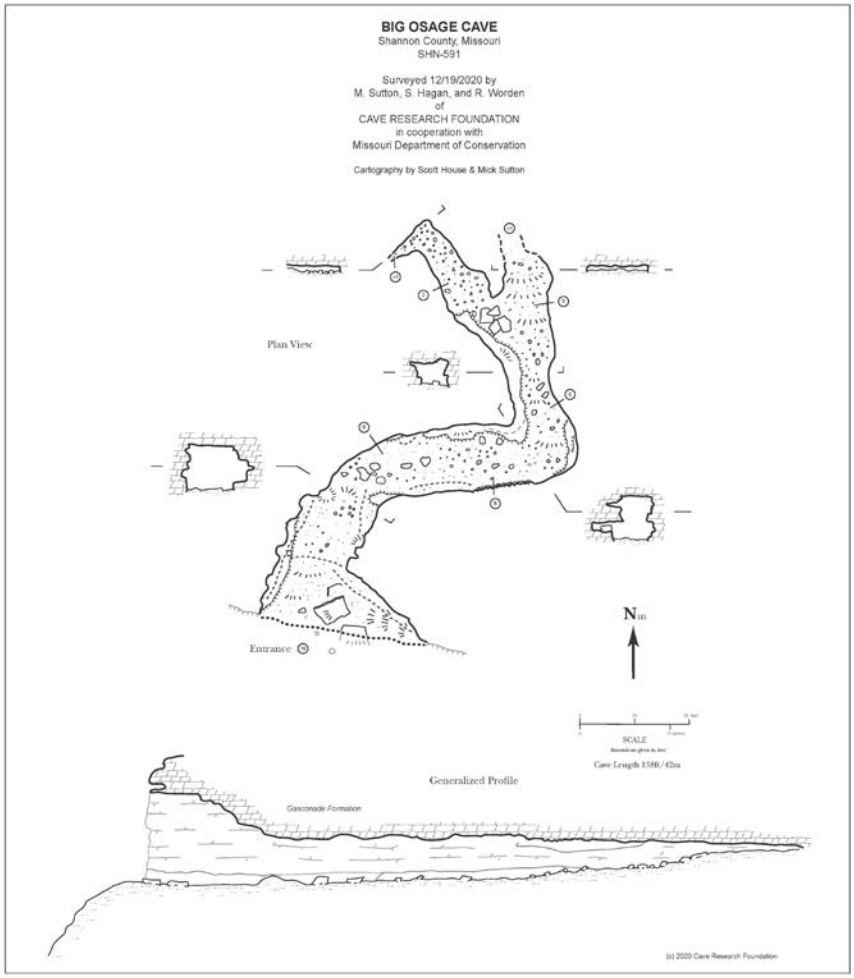
We continue to support the mapping of the Moore Cave System in Perry County, Missouri, under the leadership of Chad McCain. Current surveyed length exceeds 23 miles.

Missouri Speleological Survey (MSS)

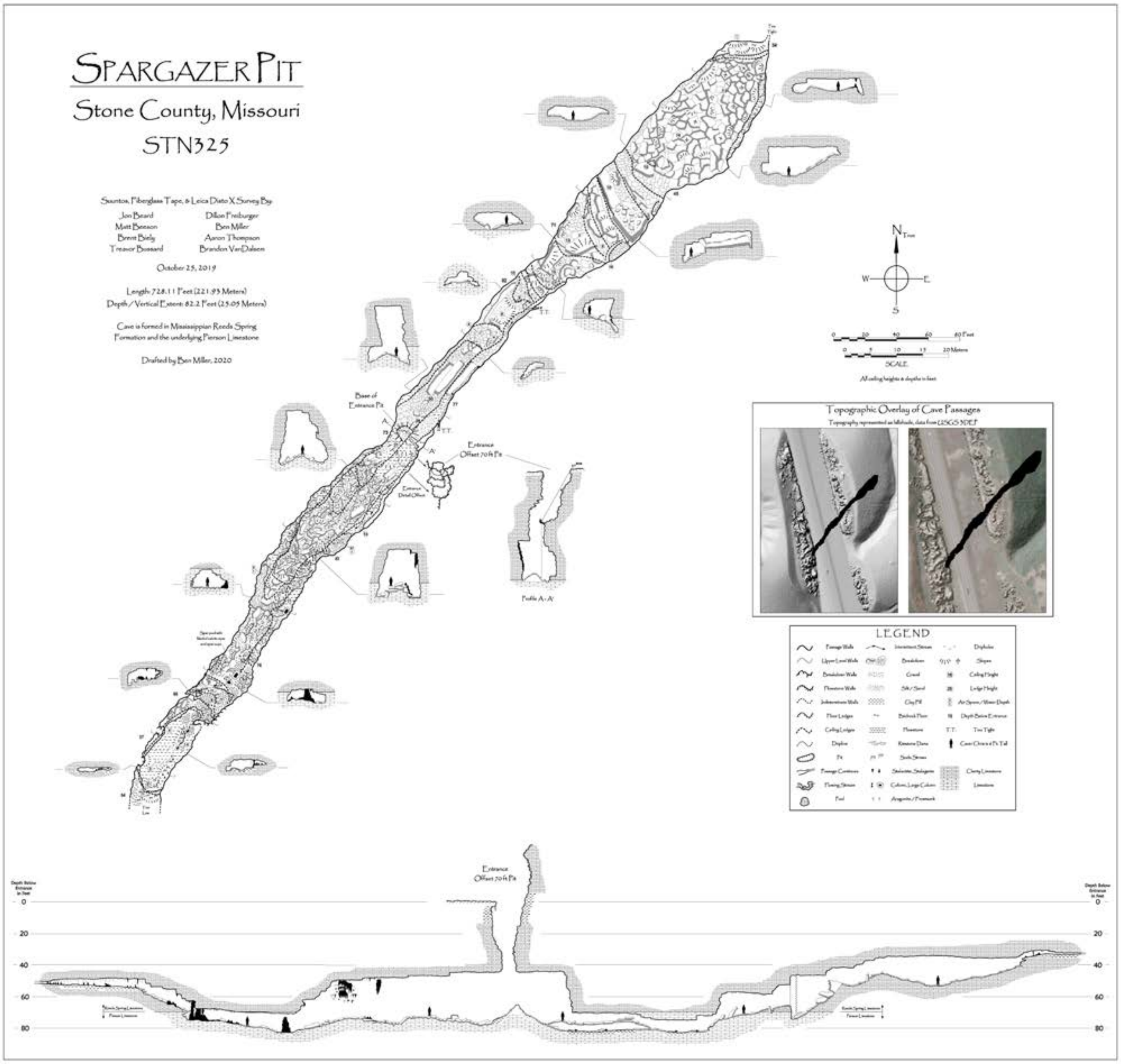
We continue to guide the development of the Missouri Cave Database and share all information gained with the MSS. The five members of the cave files committee are all CRF members. Three CRF members serve as president, vice-president, and treasurer.

Other Private Lands

Numerous trips were taken to non-agency lands including a private ranch in Arkansas; a former show cave in Missouri; interested landowners; small Perry County, Missouri, holdings; private lands bordering Forest Service properties; gray bat caves; and others.



Right: ***Jessie Bridges in Tumbling Creek Cave, Taney County, Missouri.***
Mark Jones


SPARGAZER PIT
Stone County, Missouri
STN325
Suuntos, Fiberglass Tape, & Leica Disto X Survey By:
Jon Beard
Dillon Freiburger
Matt Beeson
Ben Miller
Brent Biely
Aaron Thompson
Treavor Bossard
Brandon VanDalsen
October 25, 2019
Length: 728.11 Feet (221.93 Meters)
Depth / Vertical Extent: 82.2 Feet (25.05 Meters)
Cave is formed in Mississippian Reeds Spring
Formation and the underlying Pierson Limestone
Drafted by Ben Miller, 2020
Base of Entrance Pit
Entrance Offset 70 ft Pit
Profile A - A'
SCALE
Topographic Overlay of Cave Passages
LEGEND
Entrance Offset 70 ft Pit

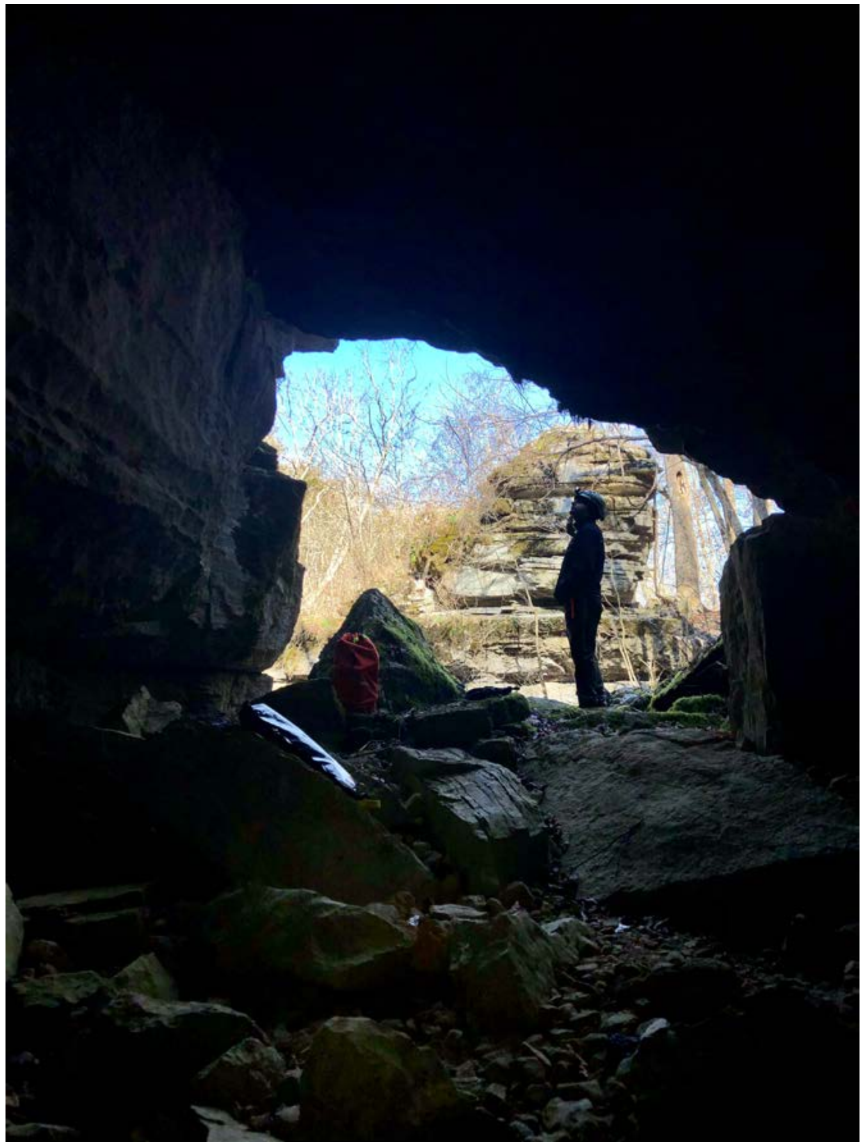
Ozark Operations: Arkansas Projects

Kayla Sapkota

Buffalo National River

As in our other projects, in-field cave-related work on the Buffalo National River stalled during the COVID-19 pandemic, though data and cartography work at home continued. Use of the Steel Creek Research Center was suspended starting in March 2020 with limited occupancy allowed for the remainder of the year. Likewise, use of the Toney Bend Research Center was suspended due to COVID-19 restrictions. Field work was paused from April 2020 through the year's end.

In the first quarter of 2020, field work focused on winter bat surveys, small caves mapping, and the continued resurvey of Fluted Maze Cave. Small caves mapping and inventory focused on sites in the Lower District of the Park, including Maumee, Dillard's Ferry, and Buffalo Point. Roughly 2,400 feet of caves were mapped, and 35 caves were monitored.



Pradeep Sapkota stands in the entrance of a cave at the Hell Creek Natural Area.

Kayla Sapkota

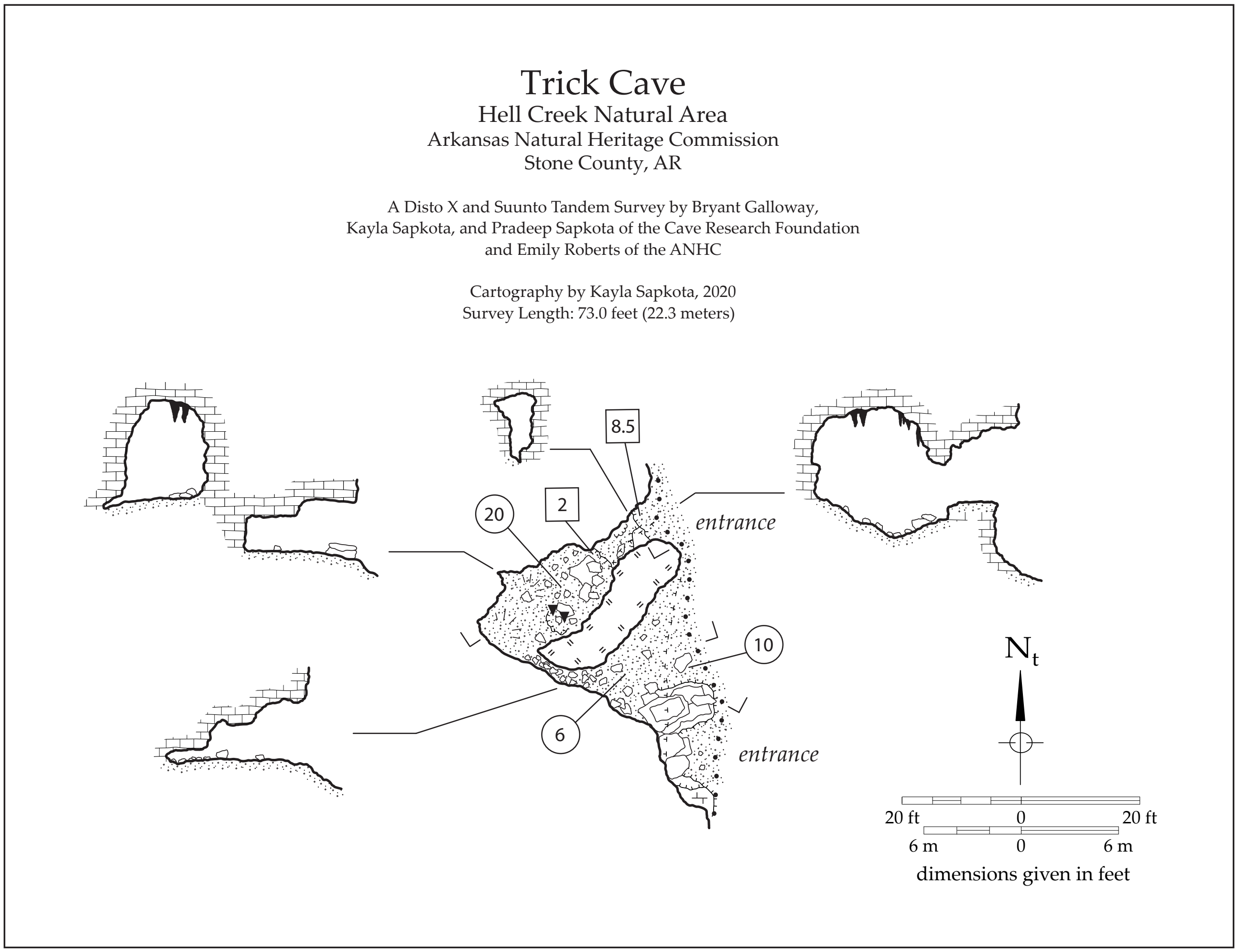
Arkansas Natural Heritage Commission (ANHC)

Despite COVID-19 pandemic restrictions, we were able to accomplish quite a bit of work on several natural areas in the state. Small teams made a trip to finish mapping Column and Pit Cave in the Devil's Eyebrow Natural Area and ridgewalked looking for others. This area is one of the larger ANHC holdings. On one of the trips, we hauled out old tires and wiring that were deposited near a cave.

Teams documented features in the remote Slippery Hollow Natural Area over the course of a few trips and mapped five caves. This area was of particular interest, as Ozark big-eared bats (an endangered species) are commonly found in the area. Teams included permitted individuals and did not disturb previously known Ozark big-eared bat caves.

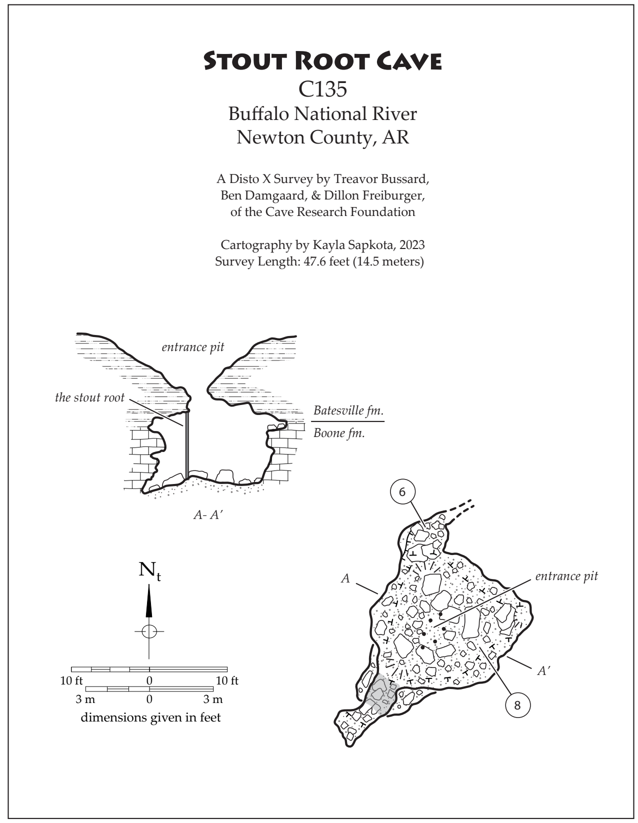
Teams made a handful of trips to the Devil's Knob Natural Area, mapping around 400 feet in three caves there, one of which was a complex vertical cave, though not lengthy.

In total, CRF mapped over 1,360 feet for the Arkansas Natural Heritage Commission across three natural areas.



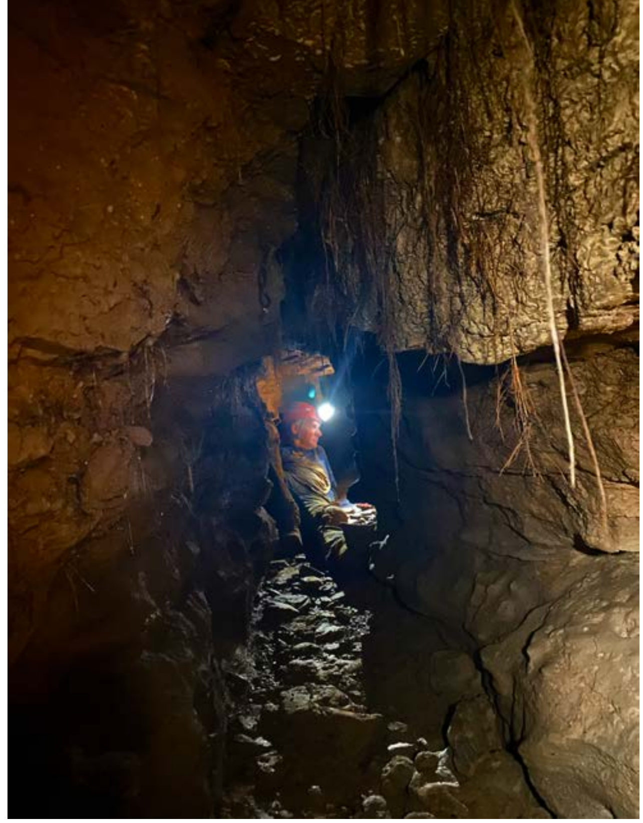
Trick Cave
Hell Creek Natural Area
Arkansas Natural Heritage Commission
Stone County, AR
A Disto X and Suunto Tandem Survey by Bryant Galloway,
Kayla Sapkota, and Pradeep Sapkota of the Cave Research Foundation
and Emily Roberts of the ANHC
Cartography by Kayla Sapkota, 2020
Survey Length: 73.0 feet (22.3 meters)
8.5
2
20
entrance
10
6
entrance
Nt
20 ft
0
20 ft
6 m
0
6 m
dimensions given in feet

Jenn Ellis shoots stations in Fluted Maze Cave. Mark Brooks



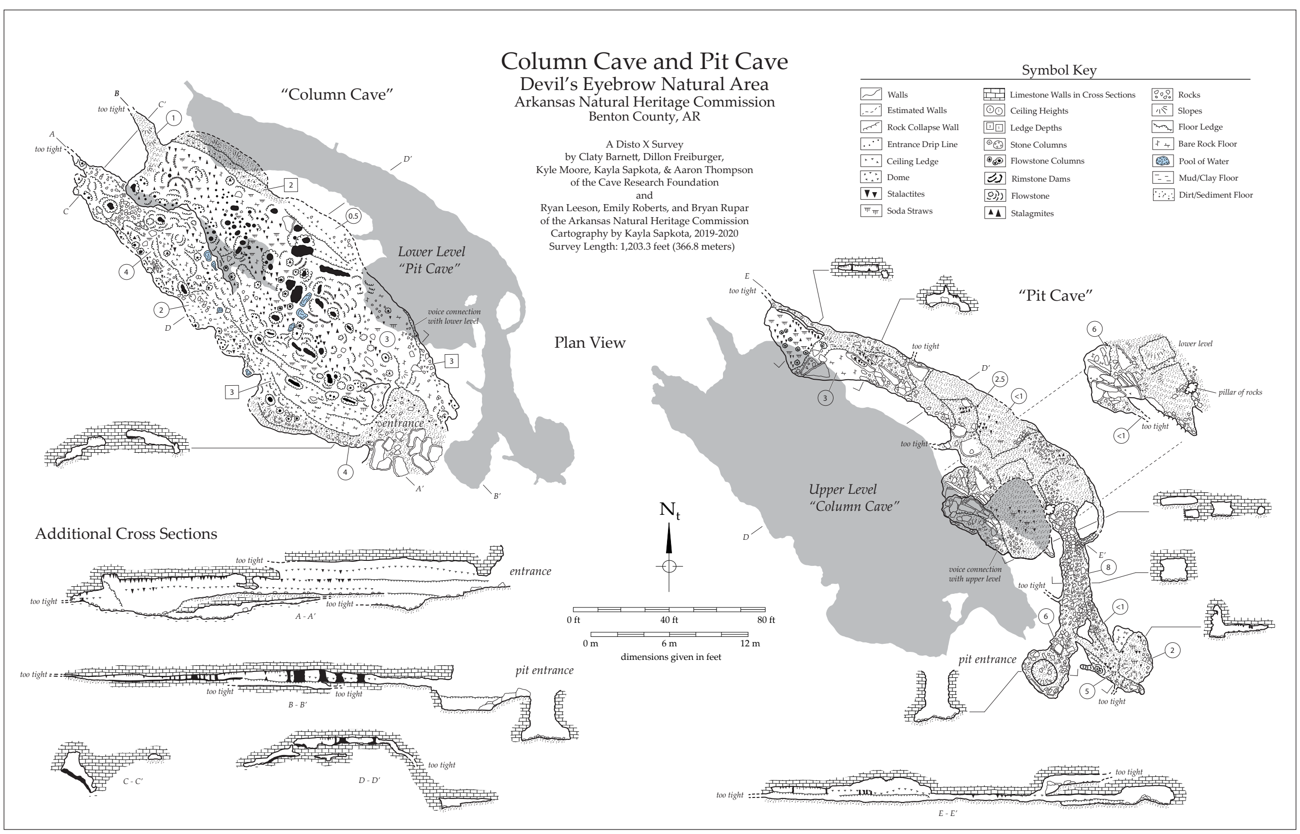
Krista Bartel in Fluted Maze Cave. Mark Brooks

Kayla Sapkota and Destany Lytle in Fluted Maze Cave. Mark Brooks



Mark Brooks in Fluted Maze Cave. *Destany Lytle*

Left: ***Claty Barnett pushes a lead in Column and Pit Cave.*** *Aaron Thompson*



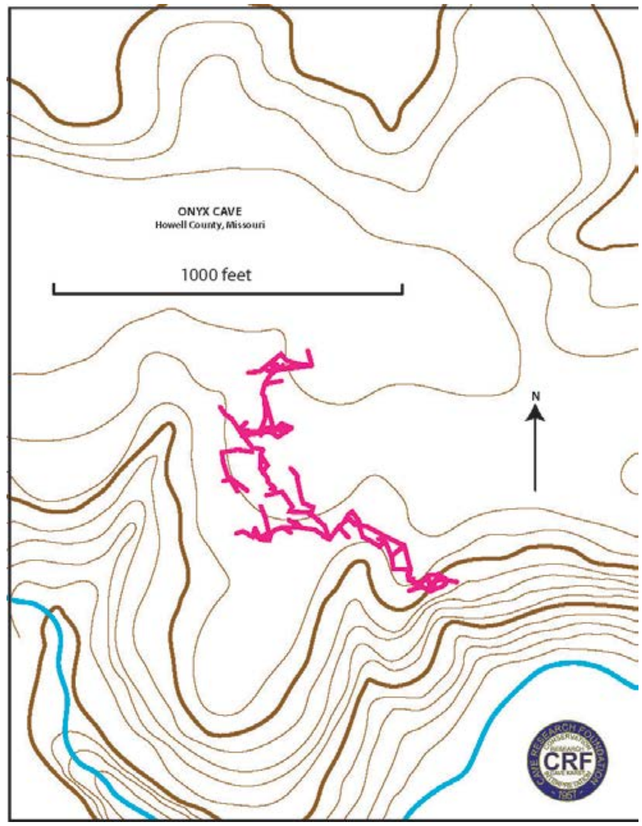
Onyx Cave Survey Project

Howell County, Missouri

Scott House and Mark Brooks

Onyx Cave, Howell County, Missouri is a spectacular and interesting cave on private property. Years ago, Mark Brooks and others began mapping it. That effort was never formally published, and Brooks decided to update and redo the map with more modern methodologies. Over the past few years, he and a small group of helpers have mapped over 3,700 feet of well-decorated cave. This is a high upland cave, relatively rare in the southern Missouri Ozarks, developed in the Ordovician Roubidoux formation. The cave is home to a number of species, including one of the few caves in the county that harbor the grotto salamander.

The project continues with Mark doing data reduction and cartography.



Onyx Cave overlay map.

Room in Onyx Cave. *Mark Brooks*

Don R. Russell Cave Preserve

Adair County, Oklahoma

Mark Jones

On the first day of the 2020 expedition to the Don R. Russell Cave Preserve, Ed Klausner, Elizabeth Miller, Daniel Smith, and I started up Gittin Down Mountain to Linda Bearpaw Cave. While Ed drew a cross section through a bear bed, Elizabeth and Daniel checked the remaining leads in the area. None of the remaining leads led to more cave. The group then went to a different entrance and got two more cross sections in the Canyon Connection.

Turning our attention to the western section of the cave, Ed drew three more cross sections before we dropped down to the First Guano Room. Measurements were taken and revealed that quite a maternity colony is present during the summer. Last January we'd surveyed this area, and now, a year later, the guano was so thick that our tracks were erased. Climbing up to a ceiling crawl, we dropped back down to the Second Guano Room. Again, the guano was so thick that our footprints were no longer visible. Ed got four more cross sections in this area to close the book on Linda Bearpaw Cave with over 3,000 feet inventoried and surveyed.

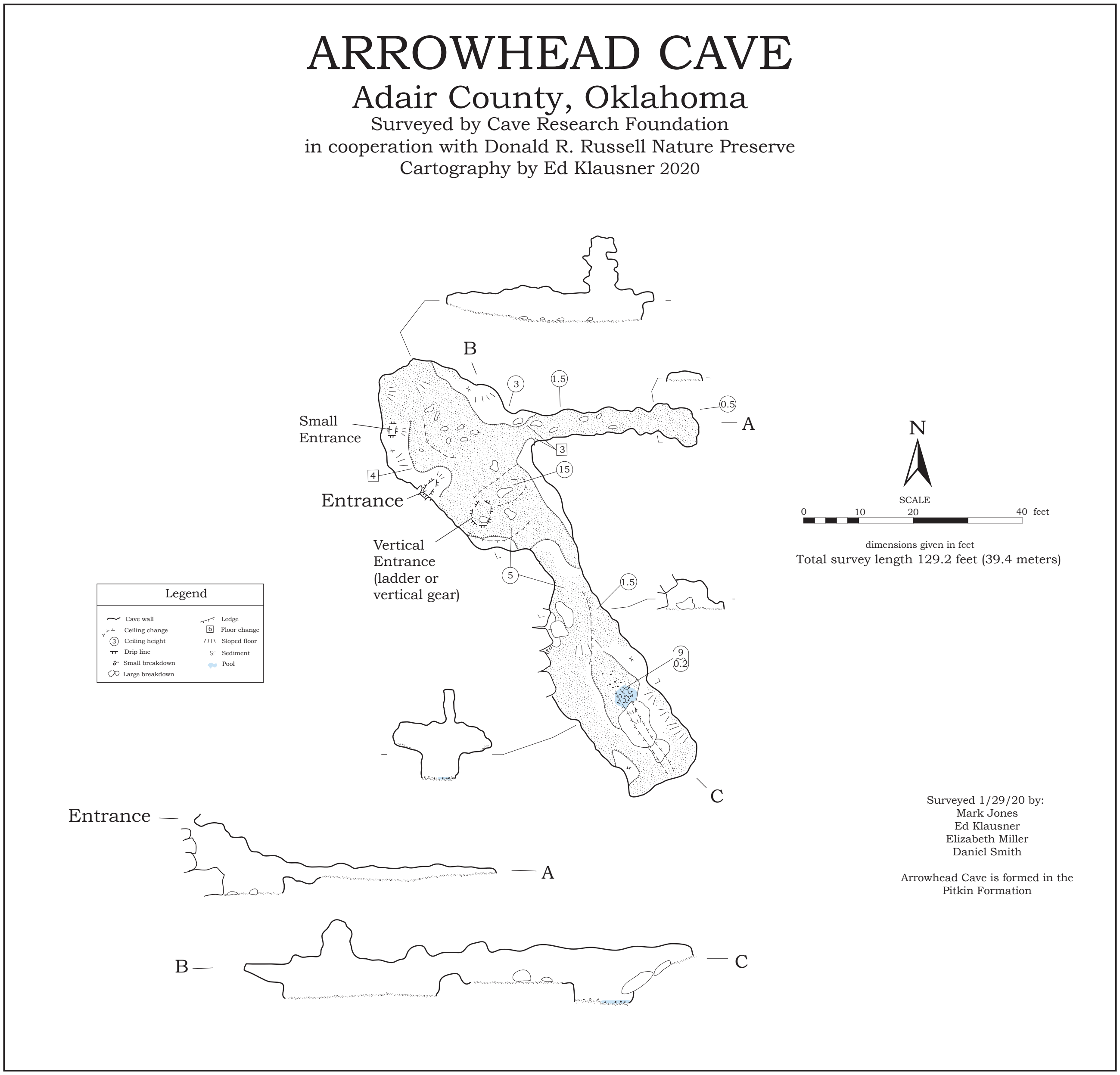
Mark Jones entering Arrowhead Cave. *Ed Klausner*

While Dennis Novicky and Rhett Finley tackled leads in the Bearcrawl Entrance of Three Forks Cave, Ed Klausner, Elizabeth Miller, Daniel Smith, and I focused our attention on the smaller caves in the preserve. The first cave on our schedule was Arrowhead Cave. Nearly 130 feet was documented in Arrowhead Cave.

Down the bluff from Arrowhead Cave, we found the rocky crawl entrance into Crevice Cave. After fifteen feet, the floor sharply dropped creating a canyon that meandered sixty feet before narrowing down to less than six inches. Water dripped from the ceiling pestered us during the entire survey, but we still racked up 67 feet.

On January 29, 2020, Rhete Finley and I entered Bear Crawl Cave. Within one hundred feet from the cave entrance in our second bellycrawl, I found bear tracks in the mud floor that had been recently formed by two bears; apparently made by a female bear and cub as one of the imprints was much smaller than its counterpart.

Upon reaching the Axle Grease passage, we found that the duck under was mostly full of water, forcing us to



retreat to the B-13 survey station and begin our survey heading to the left passage.

A majority of this unexplored passage was belly crawling, making it difficult for 6'5" Rhete to traverse the precarious passage which required me to move some clay for him to reach our final survey shot at D-5. The D-5 station has five routes. All the passages are lower than 1 ½-foot high, with the water passage having a 1½-foot deep, 10-inch wide water trough meandering throughout. We were only able to survey 54 feet, before equipment failure and Rhete's lengthy stature.

The following day, Clayton Russell, Ed Klausner, and I set off to Gittin Down Mountain Cave to conduct the annual Ozark big-eared bat survey per the management plan. A count is made in the winter during hibernation by members of the management committee. In addition, we begin surveying the uninhabited branch.

We descended thirty feet to a large room of sandstone breakdown. Weaving between the rocks along the wall we climbed down another fifteen feet to a cold sink in a sixteen-foot diameter room. To reduce disturbing the bats we took photographs of the small clusters and exited the area. When reviewing the pictures an estimated 250 Ozark big-eared bats (*Corynorhinus townsendii ingens*) were counted which is comparable to years past.

On the last day of surveying caves on Gittin Down

Mark Jones and Dennis Novicky in Three Forks. *Nicole Ridlin*

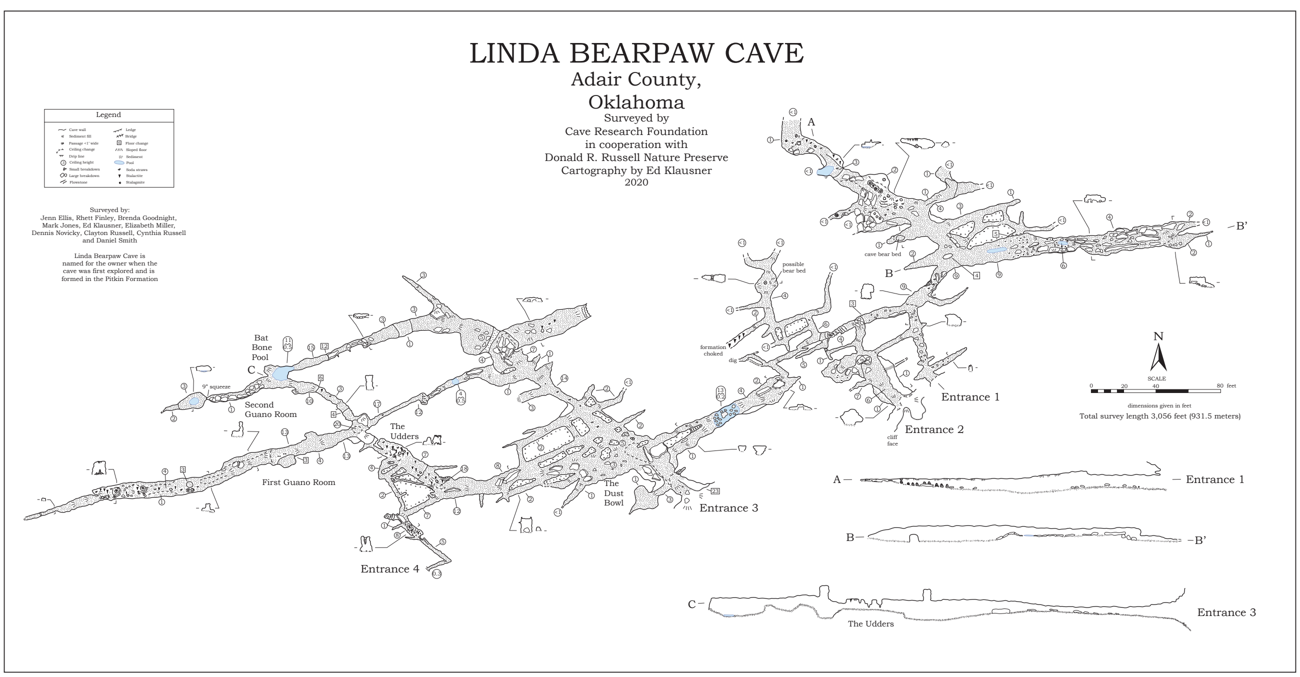
Mountain (January 31, 2020), Kirsten Alvey-Mudd, Trevor Bussard, Dennis Novicky, Nicole Ridlen, Brandon Van Dalsem, and I hiked up to the Washtub Entrance of Three Forks Cave to mop up leads in the Elephant Room area. Just inside the canyon passage we discovered several pipistrelles or tri-colored bats (*Perimyotis subflavus*) and counted 21 before reaching the Muddy Maze.

After slithering through the Muddy Maze, Dennis and Trevor began surveying a ceiling level crawlway while the rest of us started toward the Elephant Room. The first lead

Ed Klausner in Linda Bearpaw Cave. *Mark Jones*

was a comfortable crawl that terminated after fifty feet. The second lead had a similar length that was less inviting but with more decorations. Before addressing the third lead we stopped to see the impressive Bear Claw Scratch Room where the walls were etched with claw marks. Our last lead was less than inviting, but Brandon squirmed through to close a loop.

Meanwhile the other team finished with their first lead with seventy feet and began their next lead. We both got around sixty feet. All know leads east of the Guad are now checked, and our attention can be focused beyond the Octopus Room and between the Bear Crawl Entrance and the Cactus Formation.



Sequoia and Kings Canyon National Parks (SEKI) including Redwood Creek, Lilburn Cave, and Mineral King

Jennifer Hopper and Fofo Gonzalez

Operations Managers

General Observations

In early 2020, we sadly lost Annie Esperanza (Branch Chief—Physical Sciences, Air Resources Specialist) who had undergone a heart transplant in the Fall of 2019, but never fully recovered from it. She was a strong advocate for the CRF efforts in the park, and she will be sorely missed. Erik Meyer is her replacement, Acting Branch Chief and Ecologist, Physical Sciences Branch. We have established a very positive relationship with him.

Two primary projects are in their fourth year: 1) Paleoclimate study (Barbara Wortham, PI), using stalagmites to determine likely precipitation and temperature variation over the last 20,000 years. 2) Cave inventory project (Carol Vesely, PI), developed in Lilburn Cave, but we expect to carry over the project to multiple caves in the SEKI area to give access and provide data for many years.

Due to COVID-19, (as of October 23, 2020), caves within SEKI are closed to research until further notice. Park reopening phase is 3B, and cave research will be evaluated

Phones, even in the wilderness. Cavers relaxing after a work day. *Fofo Gonzalez*

Jen Hopper at Lilburn Cave. *Fofo Gonzalez*

on a case-by-case basis for the risk to humans and wildlife.

An extended 2019 winter season severely affected our ability to execute trips into the canyon. 13 trips were scheduled, but the presence of snow dictated that the first trip of the year was in early June. From that point on, all scheduled trips except for one were completed, for a total of 7 trips for the year.

Rain levels remained adequate through the year, which allowed us to focus on research activities, as opposed to water collection and purification duties (in 2016 this caused a major impact in our activities).

The personnel that participated in the shortened season was almost on par with 2018, even with roughly half the trips of the previous year, so interest remained high. We had 13 new joint venturers join the project.

Due to the extended winter impact, the volunteer hours donated to the park decreased from 5,380 (202 person-days) to 2,490 volunteer hours (122 person-days). However, when we were in the canyon, we were extremely active, with a 40% increase in volunteer hours per trip when compared to 2018 (in part the average was increased because some of the trips executed were longer weekends, like 4th of July, Labor Day, and Veterans Day).

The exploration project in Lilburn Cave is ongoing, and a brave team expanded the cave length by 336 hard-earned feet, for a total cave length of 22.23 miles.

Cave Management

We continue to abide by strict qualification guidelines for cavers entering Lilburn. In the past, some people with no caving experience or who had not been vetted by other Lilburn regulars went on Lilburn trips. This qualification procedure has the ultimate goal of preventing any major incidents due to the possibility of an inexperienced caver being injured. The expedition leader is responsible for choosing whether or not to test JVs in vertical skills on site before entering the cave.

We maintain online platforms including an email distribution group, social media, and Google Drive for expeditious data sharing with key park personnel and JVs. Investigators and trip reports, as well as other data collected, are uploaded after expeditions. This assures the continuity and data preservation with leadership changes.

In order to promote a welcoming, safe, and inclusive environment for everyone involved with the CRF, we have adopted the Geological Society of America Code of Ethics to set expectations in a way that is easy to understand and well-defined. This code includes language about alcohol use and expectations that everyone will stay in control of themselves when drinking. It also prohibits sexual harassment of any form and encourages discussions with trip leaders about any concerns that may violate the code of ethics. We have the code available online and at the cabin so everyone can take time to become familiar with it.

Cave Data Management

The Chief Cartographer, Jed Mosenfelder, updated the cave atlas with the latest survey information as of 2018, for a total of 91 quads. The data was made available on Google Drive, with a backup on Dropbox and multiple personal computers, as well as with the park.

We maintain a laptop at the fieldhouse which enables trip report preparation, sharing, and storage.

Hydrology and Geochemistry: Paleoclimate Project (Barbara Wortham, PhD candidate)

Understanding the future of our climate depends on building records of how our climate has changed in the past. Records of paleoclimate can be built from stalagmite archives found in cave environments.

A stalagmite sample was analyzed for U-Th to date its formation. In addition, thin sections of the stalagmite pieces have been analyzed for trace elements. This analysis may show how El Niño Southern Oscillation impacts the southern Sierra Nevada. In addition, the stalagmite was tested as a possible record of past fire activity. Thin sections were used for oxygen and carbon isotope analysis, to determine variability in precipitation and vegetation.

Ongoing monitoring of the cave environment includes cave water pH, and stable isotopes, pCO_2, temperature, and humidity. This data is collected during trips to Lilburn. The goal of this monitoring work is to understand how 1) the surface water that is likely primarily derived from snowmelt is influencing the dripwater in Lilburn, and 2) how temperature and precipitation variability impact dripwater, physically and chemically. From this we can better interpret our results from the Lilburn stalagmite.

Babs Wortham and Nora Soto, collecting water at The Glacier formation for the hydrology and paleoclimate study, Lilburn Cave. *Fofo Gonzalez*

Babs and her team collected over 100 dripwater samples in 2019. Findings include geochemical changes in dripwater occurring approximately one month after a precipitation event. Human visitation to the cave increases CO_2 levels for 24–26 hours.

The research permit for this project has been extended through 2022 (normally permits are given on a yearly basis). Permit will be valid based on no changes in methodology or research location(s), submission of spatial information on study sites, and annual submission of the Investigators Annual Report (IAR).

The PI for this project will be finishing her PhD this year and may need to change her research focus and location. However, university colleagues plan to continue paleoclimate research in the cave.

Cartography Project (Jed Mosenfelder)

The total length of passages surveyed in 2019 was 336 feet. Total cave length as of January 2020 is 22.23 miles, putting Lilburn at #30 in the list of long caves in the US.

A possible objective in the cartography project is to expand the group of individuals working on the cave map. In years with a large amount of survey data to process, having a single person responsible for all updates on the cave map proved inefficient due to the magnitude of the responsibility and the limited time that is normally available for any single person to work on it. In recent years this has not been an issue.

Permit issued is valid 2019–2021 and will be renewed thereafter.

Cave Inventory (Carol Vesely and Roger Mortimer)

Working under the cartography permit, we continue to develop a cave inventory collection system using an app based on an Android operating system for portability and ease of deployment. Ongoing beta testing and data collection are in process. The focus is making the software nimble, self-explanatory, and logical as possible. As of 2019, 19 JVs have been trained in cave inventory. As more JVs become familiar with the system, we expect the rate of inventory to increase.

Each summer and fall expedition supported 1–2 cave inventory teams. Over 140 stations have been inventoried to date. Approximately 52 hours were spent underground performing inventory work, and an additional 24 hours were spent on data management and app development.

We have assembled three full sets of cave inventory kits, which consist of a tablet in a rugged, shockproof, and waterproof protective case, a pencil and paper cave inventory backup system, and a custom zippered carrying bag.

In the future, we would like Carol and Roger to expand the cave inventory to other areas of the national park. Given that cave inventory is a topic that has attracted the attention of multiple national parks, we could even help other

Carol Vesely, Nora Soto, and EC Moe on a cave inventory trip in Lilburn Cave. *Fofo Gonzalez*

parks set up their own cave inventory initiatives, thanks to the ease of implementation of the Android-based app.

Other Projects

Structural Geology and Lilburn Cave (Marek Cichanski)

This project evaluates the role of structural deformation on the karst and its surrounding non-carbonate rocks. In 2017, Cichanski performed geologic mapping in the cave and created six geology quads, which are stored on a shared online platform. In 2018, Marek was not able to attend any trips due to a combination of work and health issues. Marek has requested a merge of his Structural Geology project into the Cartography project. He plans to add photos to the digital inventory help section of the app to assist JVs in the recognition of geologic features. He also would like JVs to be able to measure strike and dip using a tablet.

Sedimentology of the Redwood Canyon Karst (John Tinsley)

Data compilation for Big Spring hydrology is underway, and acquisition of recent data logger information is desired so the story may be shared. Detailed descriptions of collected sediments are in process, with dating revisions needed.

Passage Restoration at Lilburn Cave (Bill Frantz)

We had more water in the canyon in 2018 than 2017, and some areas in the cave were washed completely clean of sediment that had been in place for years. In October 2019, Bill and Peri moved to New Hampshire, so we will be seeking assistance to continue this project as needed.

In 2019, Amanda Mortimer performed some restoration work. String has been chosen to replace flagging, with color designations depending on the route or marker type.

Certain fixed aids may be replaced as needed.

Mineral King Caves (Marcia Rasmussen)

The higher elevation areas in the Mineral King section of Sequoia National Park are home to several small caves and karst features. They are accessible only for a few months every year, and this project requires strong hikers, doing ridge walking at elevation.

The park requested our assistance in a project by the California Water Resources division, to move the meteorological station from Farewell Gap to the White Chief area. The plan was to help the NPS by ridgewalking the area to look for cave resources, to prevent damage to those sensitive environments. We were recently informed that the weather station will not be moved, so there is no need to do this evaluation.

Maps of White Chief Cave and the Area of Thousand Entrances: Multiple marble pockets are yet to be explored in the vicinity of White Chief Cave and Area of Thousand Entrances, therefore this project will likely extend for multiple years. The focus of this project area will likely shift to cave inventory for the near future.

Ursa Minor (Joel Despain)

This project focuses on geomorphology research in the cave (sediments, bedrock features, and water samples), as well as on continuing the cartographic study of the cave by pushing leads in the upper levels.

A climbing lead is still pending, and although there were no trips during 2019, this is still considered an ongoing active project, with alternating work trips and restoration trips to preserve the pristine nature of the cave.

Hurricane Crawl Survey (Carol Vesely)

Hurricane Crawl, a pristine and delicate marble cave, was first explored about 30 years ago. Sections of the survey are not up to standard, and there are still promising leads to be surveyed. However, Carol Vesely's energies are currently devoted to testing the developing inventory software, and training JVs on its use. In the future, Carol will work with Joel Despain to submit a research proposal to continue surveying Hurricane Crawl.

Slide Creek/Eleven Range Overlook (David Angel)

Joel Despain proposed this area for a CRF project several years ago. The access is difficult and requires ropes to descend into the canyon. Once there, the terrain is difficult to move through with poison oak and uneven ground without trails. Although some caves have been located in the area in past years, the few recent attempts to relocate the caves were not successful and GPS data for the known caves and karst features was determined to be inaccurate. David was able to recruit a person familiar with the terrain and the cave locations, but due to COVID-19 they were not able to go. Once the base data of the known features has been established, further trips will be planned.

Other Possible Projects

Unsurveyed Caves

The park has notified us of approximately four caves in a road construction area. One to two may be significant, and we have discussed possible future survey trips.

Monitoring of Stage at Big Spring (Jennifer Hopper)

We are continuing field tests of the data loggers and Bluetooth data collection systems (after a few issues), since we are using equipment designed and created specifically for this project. This proposal has undergone a park-mandated tribal/historic review and has not yet been approved. This project would support the Hydrology and Geochemistry project. The data loggers will be retrieved in the next opportunity, and we will be able to download the first batch of data.

Map showing Karst Features of Redwood Canyon (John Tinsley).

Ebb-And-Flow Potentiated Air Flow Changes at Lilburn (Howard Hurtt)

Per the park's suggestion, we have purchased instrumentation with a smaller footprint than the original prototype. This research will support the Hydrology and Geochemistry project.

Educational and Cooperative Efforts

Every two years there is a celebration of research and fire management called "50 Years of Research" at Sequoia National Park. In 2018, Babs Wortham, Joel Despain, and John Tinsley presented research updates and history of the Lilburn project and supported a touch table. Research posters are on display at the visitor center.

For now, due to COVID-19, in-person sessions and events are on hold.

John Tinsley has organized brown bag lunch sessions at the park.

Future projects may include educational posters regarding karst areas and the importance of caves and the surrounding flora and fauna.

Plans for the Future

We continue to work with park representatives, inviting park employees to participate as JVs on the project.

We have expanded our scope to other areas in SEKI besides Lilburn Cave and Mineral King. There are several areas in the park that have not been a focus of research, and several caves other than Lilburn have potential for projects, including possible unexplored leads. The expansion of the Cave Inventory project will allow for one avenue of research outside the traditional areas of focus.

The relocation of the outhouse will be a primary objective once the research projects are restarted.

2020 Southwest Region Report

Janice Tucker

Operations Manager

This year we have had very limited project caving completed by CRF in the Southwest Region due to COVID-19. The governor of New Mexico has set fairly strict guidelines regarding limitation of group size and the need for visitors to the state to quarantine for 14 days upon their arrival. With the limited housing available at Carlsbad Caverns, meeting these guidelines with out of state participants has been a challenge.

Three CRF expeditions occurred. William Tucker led a restoration weekend, Dave West and Dwight Livingston each led exploration/cartography expeditions.

Ed Klausner and Fred Wilkinson. *Paul McMullen*

William Tucker Restoration Weekend, February 15–16, 2020

Project entailed cleaning a pool basin in the Big Room near Rail number 522.

The volunteers included Jimmie Worrell, Mary Ann Bradshaw, Kelly Holladay, Barbe Barker, Frank Everitt, Ed Knetsch, Tracey Knetsch, Tammy Tucker, and William Tucker. The effort was led by William Tucker. Work had been done at this site on two previous trips.

The primary effort was in fine cleaning of the pool basin. The project was not completed, but they hope to complete it on future trips.

This was an unusual volunteer group with all members having extensive experience working on restoration at Carlsbad Caverns. On their exit from the cave Saturday night, they walked past Longfellow's Bathtub, an area that was beautifully restored many years ago. Unfortunately, they noted that the paint on the bridge was flaking. Obviously, remediation of this may be necessary. William completed a proposal with recommendations for how to address this issue.

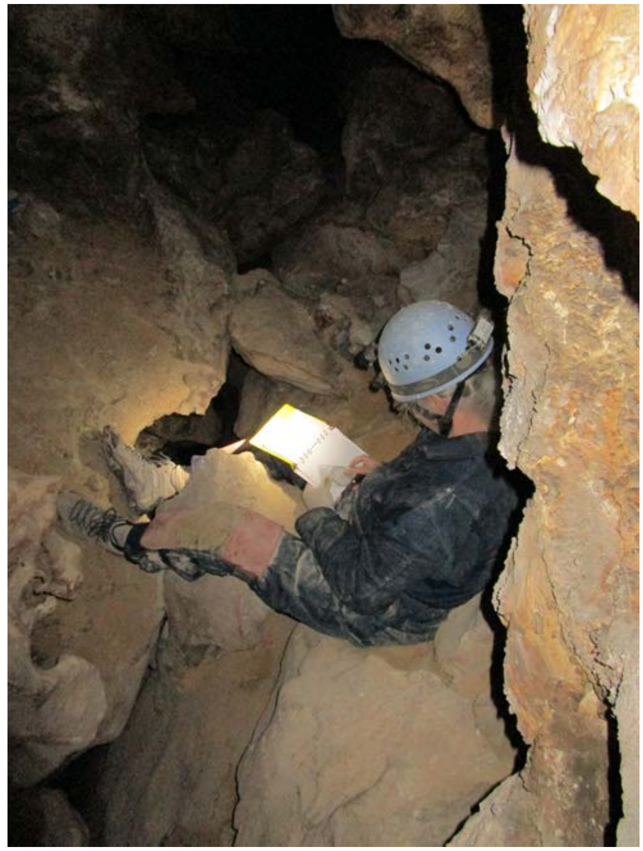
Nine volunteers worked for a total of 139.5 hours on this project.

Dave West and Dwight Livingston have separate reports.

February 2020 Music Room Expedition

Carlsbad Caverns National Park

Dave West



Dave West sketching in Carlsbad Cavern. *Jeanette Muller*

Participants were Dave West, Karen Willmes, Ed Klausner, Elizabeth Miller, Chris Beck, Jeannette Muller, Mark Jones, Paul McMullen, and Fred Wilkinson.

We had a number of objectives as follows:

1. Get a profile of the tourist trail below Windowlands and survey the last remaining leads there.
2. Continue survey in Osteoporotic Boneyard.
3. Survey mid-level leads, some bounded by breakdown under a massive boulder.
4. Resurvey down from MA15 to MA20, investigate side leads along the way.
5. Investigate leads in Paul Burger's MA419–440 survey.
6. Resurvey MA48–53. When Ed attempted to add detail to the survey from MA48–53, he strongly suggested it be resurveyed. Leads were ignored. May or may not start that this expedition.

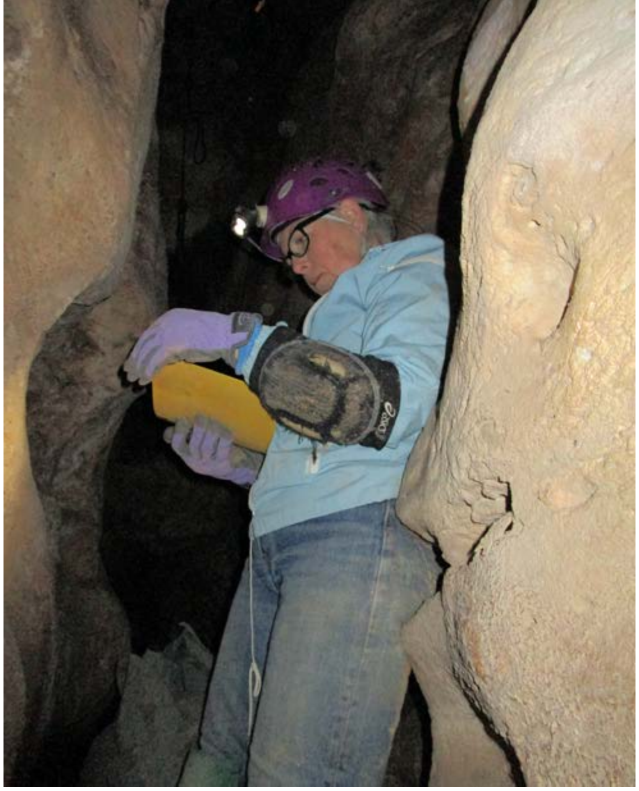
On February 24 we began with a meeting with Ellen Trautner from the NPS for general orientation and to obtain survey paper and other necessary materials. I had requested she have a look at the MA301 pit the previous year, and she provided me with copies of the notes. Chris and Jeanette were fighting off colds. Ed, Paul, Mark, and Fred resumed work on the Osteoporotic Boneyard that was begun last year. Karen, Elizabeth, and I obtained additional detail for two profiles. We also attempted the lead at MA356. Billed as "walking passage" it was anything but. I am sure there is a floor somewhere below the narrow canyon. None of our party were comfortable pursuing it, and we will do so when we can send a team fully capable of traversing it. Ed's party turned in 97.7 feet of new survey and 192.1 feet of resurvey while ours turned in 116.92 feet of redundant survey.

On the 25th Ed, Elizabeth, Paul, and Fred continued in Osteoporotic Boneyard and Karen, Mark, Chris, and I began surveying mid level passages in the Music Room boneyard. This day Ed accomplished 139.2 feet of new survey and 29.1 feet of resurvey. We accomplished 264.94 feet of new survey. Poor Jeanette remained at the apartment fighting her cold.

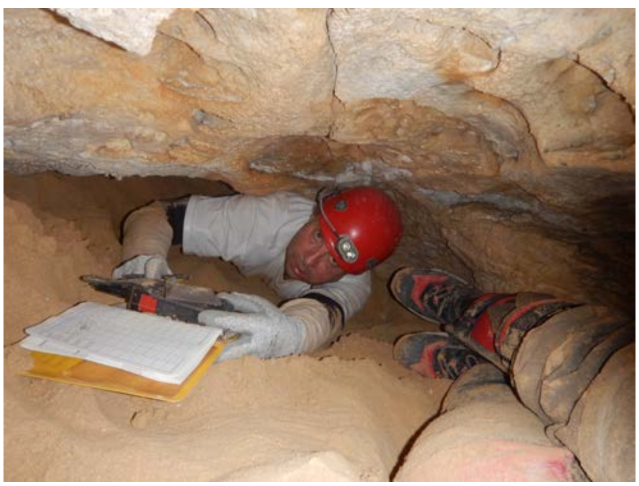
February 26 saw Ed, Karen, Paul, and Mark knock off a lead at MA72 before finishing up the survey in Osteoporotic Boneyard and obtaining the profile from MA44 to MA46. Meanwhile Chris, Fred, and I finished up the mid-level surveys. Ed's team had 165.1 feet of new survey and we had 208.5 feet of new survey and 34.8 feet of redundant survey. Elizabeth was suffering from a sore shoulder while Jeanette continued fighting her cold.

On February 27 Karen opted to stay in the apartment and read her book. Frustrated at being sick during what may be her only opportunity to go caving for a while, a medicated Jeanette joined Fred, Elizabeth, and me as all of those caving headed to MA419–MA440 survey to investigate the 17 or so leads there. Ed, Mark, Paul, and Chris would also look at resurveying from MA16–MA20. My party returned with 172.7 feet of new survey and 7.4 feet of redundant survey while Ed's party had 132.4 feet of new survey and 9.6 feet of resurvey. Ed put off the resurvey of MA16–20, wishing to have 8-1/2×11 paper and a clipboard to finish it.

February 28, the penultimate day of the month this year, was to be our last day of caving. Elizabeth's shoulder had resumed acting up, and she elected to not go caving. Karen and I needed a short day, so we could start packing to leave early the following day for a flight out of El Paso. Jeanette was determined to cave for another day, and Paul joined us as well. Ed, Fred, Mark, and Chris returned to the



Elizabeth Miller doing inventory. *Jeanette Muller*



Mark Jones in Carlsbad Cavern. *Paul McMullen*

MA16–20 resurvey. My party examined the area where the Guadalupe Trail and the Music Room Boneyard converge and determined it would need more work than we could devote to it this day. They took a couple shots in an effort to improve a loop thought to have problems. Ed's party returned with 313.3 feet of new survey and 69.5 feet of resurvey.

We are much closer to being finished that I expected. The lead at MA355 remains. We have three pits to drop, one at MA432, one at MA46, and one at MA19C. Other side leads remain at MA432, MA436, three at MA438, and one at MA448. The pit at MA46 will give access to Ellen's MA301 series, where there are seven leads reported. And there are three un-surveyed leads in the MA-G confluence area as well as the need to better represent the beginning of the Guadalupe Trail. We might finish up next expedition.

Bottom line: 1,969.46 feet of survey was accomplished. Of this 1,493.84 feet was new survey, 300.3 feet was resurvey, and 175.32 feet was redundant survey.

Fred Wilkinson in Boneyard at Carlsbad Cavern. *Paul McMullen*

Paul McMullen in Carlsbad Cavern. *Mark Jones*

Mystery Room Report

Carlsbad Caverns National Park

Dwight Livingston with contributions by Mark Minton

In our 2019 report, we described our visit to Mabels Room, where we identified a utility line hanging above a drop down to the Mystery Room. At the 2019 NSS Convention, during the Fellows Reception, I described this utility line to Rod Horrocks, Cave Specialist at Carlsbad National Park, and explained how this might give access to two leads above the big Mystery Room passage, possibly reaching a couple of nearby ceiling windows that we had plotted last year, which in places measured 120 feet off the floor. Rod thought we ought to pursue it. Also attending were Yvonne Droms, Bob Alderson, and Mark Minton, who also thought these were interesting leads and wanted to join the expedition. That was the start. Later Nathan Canaris and Abigail Mack signed on for the last couple of days, and we got more help from rangers Ellen Trautner and Aria Mildice.

In addition to those ceiling leads, our expedition proposal included survey cleanup, a wall climb on the north wall (in case the ceiling leads didn't get us there), and a high ceiling lead farther west, which had measured to 220 feet, a goal added in case we ran out of things to do.

Our expedition had Quarters 56 to ourselves for most of the week, so we spread out among the three bedrooms and their 14 bunks. We found the caving supplies that Ellen left for us as promised. There was a box of links, bolts, and hangers for rigging, a new belay rope, hundred-foot lengths of rope, and stacks of looseleaf survey forms, including title sheets, expedition report sheets, data sheets, grid sheets, inventory sheets, lead list sheets, and rope log sheets—all

Mark Minton rappels down Mabels drop. *Yvonne Droms*

The big northwest lead looks very promising. *Bob Alderson*

of which with a week's work we would convert into a pack of data the size of a medium-length paperback novel.

After a brief orientation with Ellen and some gearing up, we dropped off the Big Room tourist trail down to Lower Cave and the Yellow Brick Road boneyard climb and steep traverse lines up to Mabels Room. We stopped where the trail ended at a window down to the Mystery Room 50 feet below. Bob belayed out to retrieve the utility line and we pulled a 9mm line up and over the jug handle 25 feet

Dwight Livingston traverses the ledge beyond the bridge. *Yvonne Droms*

as the passage northwest. I knew CFM was not in the current DAT files for Lower Cave or Mystery Room.

We needed more rope, and new policies at the park required us to exit the visitors center by 5:00 p.m. every day. We rigged the drop down from Mabels Room with 11mm rope, off the nose of a bedrock projection. The lower rig became "Mabels drop." Mabels drop is spectacular, falling as it does alongside the big ghostly columns that frame the high section of the Mystery Room, where everything has been smoothed and rounded white by atmospheric corrosion. We all walked over to H14D to see the north wall bolting lead, then headed out via the King's Palace.

On the way back to quarters we stopped to ask ranger Erin Lynch for more rope. She provided 135-foot and 75-foot lines, two rope pads, and helped us to start a longer piece of 11mm soaking for use later. She suggested we all look in the park files for a CFM survey. With her help we found a mention of a May 1993 trip with a CFM survey, then found a short report than indicated about 70 feet for CFM1A thru C, but there was no survey data and not much description.

The following day, we started on the big lead that headed northwest. As became the pattern much of the week, Bob and Mark rigged while Yvonne and I surveyed. First, though, we needed to calibrate the DistoXs. We did that in Mabels Room, picking random targets roughly orthographic from a convenient center point. I am now completely sold on in-cave calibration, as compared to using a small calibration course on the surface. I think the long shots are more precise, the dark is helpful, and there was no chance of any hidden metal nearby.

That done, we surveyed up to the doughnut then out along the traverse line Bob and Mark left in their wake. The passage sloped down then continued horizontally, steeply tilted to the left. Columns and other flowstone features abounded, providing natural anchors and interesting sights, with calcite coatings, and antler and other sorts of helictites. What started as a closed passage soon became an open loft. Holes on the left side were succeeded by a continuous open drop overlooking the Mystery Room floor. At a high

overhead. I climbed up, then pulled a rope end up for an extra wrap around the anchor. To exit the little pocket at the top, you could either slide through a hole or haul yourself onto a shoulder-high shelf. I took the hole then stood up to look around. I saw continuing passage to the northwest and figured we were in business.

Everyone came up for a look. No one liked the tight route so we switched to hauling ourselves out of the pocket directly. The shelf had room for all. We found a station, CFM1C, on yellow flagging wrapped around a column near the rigging and later saw a similar yellow flagging around a stalagmite on the other side of the pit, in front of a flowstone slope going roughly south—a potential lead. The approach to it around the lip looked reasonable if on belay, insane if not. The lead was curious but not as compelling

Bob Alderson casts a shadow coming down Mabels drop. *Dwight Livingston*

A Milwaukee M12 rotary hammer and impact driver powered the climb, with the steel screws used for temporary anchors and the park's huge 3/8ths stainless expansion bolts for rigging. The screws could be removed and even reused. Once a screw was removed, the empty quarter-inch hole was hard to see. I didn't notice one all week. Conveniently, a temporary hanger could be switched to permanent by drilling the hole to 3/8ths. We had five six-amp batteries and a four-place serial charger, which turned out to be overkill. The impact driver seemed to use no power, the rotary hammer needed a battery change only once, and the batteries charged back up quickly.

Mark made it about 30 feet up before it was time to head out. Yvonne and I had surveyed only just shy of the narrow end of the bridge. Near the last station Yvonne noted a special stalagmite that stood at the very lip, about two feet tall, ghostly white, and shapely as a flower. It looks much like

point a floor ledge started on the right side, turning our loft into a bridge, which crossed over the Mystery Room at a grazing angle, almost parallel, spanning about 60 feet. Our route on top sloped downward, and the sides came together, tapering to only a couple of feet between 60-foot drops on both sides. There the bridge connected to a wall and the start of a convenient upward-trending ledge. Bob had run a traverse line across the bridge and up the ledge, using only stalagmites and columns for anchors, really a spectacular piece of work. He reported a 20-foot diameter room past the ledge traverse and a lead onward.

Mark said they'd found footprints on the loft, just one set that approached the narrow part of the bridge but did not cross. We found no survey stations past the one above Mabels Room.

With all his static line laid for the traverse and none remaining for the lead, Bob returned to where he and Mark had found a dome above a cluster of columns. With Bob belaying, Mark began bolting up the dome. He placed the first bolt of the expedition, a quarter-inch Hilti hexhead masonry screw.

a calla lily and gave the passage its name, Calla Lily Loft.

We brought more rope with us the following day. Mark and Bob crossed the Calla Lily bridge to rig the lead while Yvonne and I followed with our survey. All this western end of the Calla Lily Loft was thick with stalactites, columns, crusts, and helictites, much like the area of the Mystery Room below us.

Dwight Livingston sketches boulders near H8A. *Yvonne Droms*

Yvonne Droms and a snake dancer in Saints Garden.
Dwight Livingston

In the 20-foot room, Bob and Mark found a new potential bolt climb—not very promising but worth a look to see what lay around a fold in the bedrock. They started rigging the short drop where Bob had stopped the day before, aiming to reach a constricted continuation of the Calla Lily Loft. Yet another through-hole to the Mystery Room lay below it, and there, about 20 feet down, Mark was surprised to find some webbing and an old quarter-inch Rawl split-shank bolt. We'd been scooped again. Someone had either crossed the bridge without leaving tracks or bolt-climbed up the north wall about where we planned to climb it. Later we learned that Park staff had no knowledge of when or by whom this had been done. Based on the obsolete bolt, we estimate it was placed sometime in the 1960s to 1980s.

Through the constriction, we found a small room, pool fingers, and the end of the Calla Lily Loft, about 160 feet west of the doughnut. Bob and Mark returned to their bolt climb, and Yvonne and I finished our survey. She climbed down to the old webbing to get a photo and to mark a nearby projection with flagging. We later backtracked to Mabels Room, descended and sighted the flagging Yvonne had placed. It was hard to imagine how they reached that point. The lower portion, up to a high shelf, might be lassoed easily and climbed, but the upper portion of steep flowstone falls did not look accessible. Dropping down from above, though, did look like a good way to reach that north wall shelf.

While Yvonne and I started some cleanup survey in the east end of the Mystery Room on Wednesday, Mark and Bob completed their bolt climb, reaching up 65 feet to find a narrow, 25-foot-long passage that Bob called Saints Garden.

On Thursday, Bob and Mark, armed with more rope, found that after bolting, the dome did indeed continue up. They completed 30 vertical feet of bolting and arrived at 14 by 14 walking passage, which soon ended at a larger room with a high lead to the west. They made short work of the climb and found a room with three leads: another bolt climb up flowstone, a deep pit, and a traverse across that pit to what looked like continuing large passage. Near the right wall lay a curiously shaped rock that looked remarkably like a sea turtle. Mark named this area High Adventure, which it was. Meanwhile Yvonne and I surveyed the Saints Garden dome and its terminal room, taking time to photograph the prolific pretty stuff, including a marvelous two-foot-tall snake dancer helictite, as well as calcite rims and small pools and former pools containing sparkling pool spar and shelfstone.

Nathan and Abigail arrived that night from Jemez Springs, New Mexico, ready to join the push the following day when Abigail, Nathan, and I surveyed the climbs rigged the previous day. I brought in a 200-foot piece of 11mm line and left it near where we found the old webbing. The climb was up a flowstone cascade that twisted to the south. We took a shot along the walking passage then surveyed a small offshoot, a room about ten by ten with a fascinating waterline etched halfway up the wall, a well-defined groove all around the room. The groove was consistently 1.5 inches high and 1.5 inches deep into the wall, with no sign of bedding or fracture, and quite level, as if etched by an aggressive pool surface. This may indicate a former acid lake basin with "negative rimstone," as described by Donald Davis in the August 2000 *Journal of Cave and Karst Studies*. The room, dubbed Etch-A-Sketch and also features nailhead spar near the floor at the entrance and dogtooth spar in the ceiling at the back. Further along the walking passage, we saw a pool about as big as a twin bed that was sheeted over with calcite, all but a small golf-ball-size hole right in the middle, through which one could see deeper blue water.

Mark Minton cleans the HF7 bolt climb. *Bob Alderson*

Mark Minton bolts the traverse above the HF20 pit. *Yvonne Droms*

Meanwhile, Bob descended the deep pit that dropped out of the uppermost passage he had climbed to the previous day. He lowered his 9mm Cancord rig past several ledges and emerged into the Mystery Room. This was the expedition's tertiary goal, the 220-foot window above the western clay slopes (H18). Unfortunately Bob's rope was about 50 feet too short, so he had to switch over and climb back up. Next Mark pursued the flowstone bolt climb with Yvonne belaying. It went up 40 or so feet to a blind alcove with no possibility of continuation. This was the highest point reached in our explorations.

At the end of the day, while Abigail, Nathan, and I surveyed until the last moment, Bob, Yvonne, and Mark rigged the north wall drop, using a secure natural anchor and sitting a rebelay at the old webbing. We all exited on this rig. On the way down, we viewed the north wall shelf and saw it was substantial, with enough room to walk easily, perhaps to some possible leads. The current rigging continues directly down into an aragonite forest downslope, but it should be easy to get off at the shelf and rig a line farther east where the drop is shorter and the bottom easier to access.

Mark Minton, Yvonne Droms, and Bob Alderson at HF4 and the base of the Saints Garden dome. *Dwight Livingston*

On Saturday, Aria joined us for our last day of exploration. We needed to remove much of the rope we had rigged, and I had some follow-up jobs to do down in the breakdown section at the west end of Mystery Room. Yvonne and Mark went to the canyon pit to bolt a traverse across it, Bob and Aria went to the last dome to survey it, Nathan and Abigail started derigging the Calla Lily Loft, and I took my Disto down the big clay slope to sketch profiles.

Abigail and Nathan removed the doughnut rope, leaving the utility line as we had found it. Then they took down the Saints Garden rigging and all the traverse lines along the ledges and the bridge of Calla Lily Loft. They climbed to High Adventure, derigged the dome that Bob and Aria

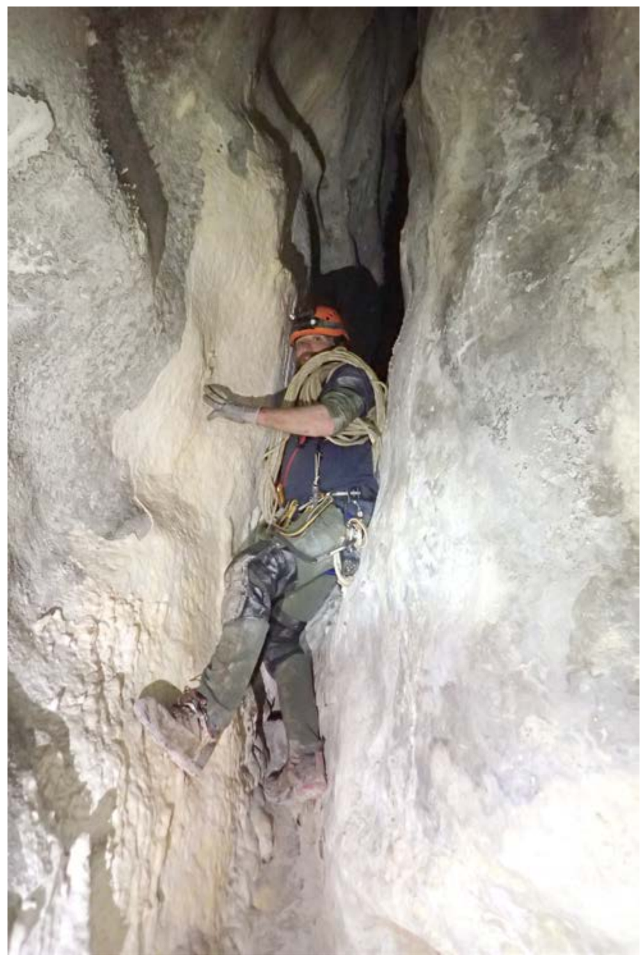
Aria Mildice on a J-hang rigged above the HF20 pit.

Yvonne Droms

had finished surveying, and finally descended the north wall rope.

Bob and Aria surveyed the dome and then joined Mark and Yvonne at the pit traverse. Mark completed bolting across, rigged an 11mm J-hang for crossing, and Bob derigged the traverse. They surveyed across, and the canyon passage continued west, dropping as it went. An overhanging drop required a rig, and below it the passage continued both east and west. Aria pushed the tight, grabby slot eastward, noting good airflow, until it choked out, perhaps just shy of re-entering the Mystery Room. To the west, the canyon continued another 65 feet. Aria found this part so full of grabby popcorn, aragonite, and helictites that she named it Sharps Container. It finally choked closed, killing the last lead in High Adventure. On the way out, they derigged their last little drop and later pulled down the short climb, but otherwise left ropes in place. Aria wanted the passages left semi-available for study. The north wall rope was left in place for later use, to check the north wall shelf leads and perhaps a bolt climb.

Sunday we packed, cleaned, and gave the park our data and pack of paperwork. The Mystery Room survey is almost complete, certainly just one more expedition.



Nathan Canaris in the fissure approaching HF20.

Yvonne Droms

Science

Babs Wortham checking the data logger for the paleoclimate research project, Lilburn Cave, Kings Canyon National Park. *Fofo Gonzalez*

Philip M. Smith Graduate Research 2020 Grant Recipients

Teresa Baraza (Funded $3,000)

Ph.D. Student
Department of Earth and Atmospheric Sciences
Saint Louis University
Advisor: Elizabeth Hasenmueller

Using Stable Isotopes and Trace Elements to Identify Microplastic Sources and Transport Mechanisms in a Karstic Cave System

Abstract: Microplastic (plastics < 5 mm) contamination is ubiquitous, and has been found in environments ranging from deep ocean floors to Artic Sea ice. Because plastics degrade slowly and are highly mobile, microplastics are one of the most concerning emerging contaminants of our time. Microplastics are dangerous to ecosystems not only because they can be ingested and cause internal issues to wildlife, but also because they can act as carriers of other contaminants such as heavy metals and organic compounds. Microplastic research has historically been focused in marine environments, and more recent studies have investigated microplastic contamination in surface freshwaters. However, currently, only one study has quantified microplastic contamination in groundwater. We propose a study that will investigate microplastic sourcing and transport in a cave system. To do so, we will collect water samples weekly under different flow conditions and more frequently during flooding events. Microplastics will be characterized by their type, size, color, and polymer type. We will perform hydrograph separations during floods, using stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$), to describe microplastic transport mechanisms through the cave system. Furthermore, we will use trace elements (e.g., B, Zn, As, Pb) to identify potential microplastic sources (e.g., wastewater, surface runoff). This study will provide new insight into how microplastic contamination moves through groundwater systems, which will help inform debris mitigation strategies.

Cameron de Wet (Funded $3,000)

Ph.D. Student
Department of Earth and Environmental Sciences
Vanderbilt University
Advisor: Jessica Oster

Assessing the Influence of Epikarst Hydrology and Geology on Dripwater and Speleothem Calcium Isotope Signatures

Abstract: Geochemical proxy records from speleothems provide crucial information for understanding past environments. Variations in speleothem carbon ($\delta^{13}C$) and oxygen isotopes ($\delta^{18}O$), and trace element ratios have been used to infer relative changes in paleo-rainfall across the globe. However, the complex controls on these proxy systems often preclude quantitative assessments of paleo-rainfall changes. New techniques for modeling calcium isotope cycling during prior calcite precipitation (PCP) along the seepage water flow path above a cave are yielding the first quantitative estimates of paleo-rainfall from speleothem records. However, there are open questions as to how karst geology, flow path geometry, and seasonality of rainfall affect calcium isotope cycling, as well as how best to relate PCP to specific rainfall amounts. This study stands to answer these questions by comparing modern cave system $\delta^{44}/^{40}Ca$ data between karst environments in California and Tennessee with differing geology, seepage water flow path geometry, and precipitation seasonality. By combining cave monitoring data with local rainfall records, I will determine the most important controls on dripwater and speleothem $\delta^{44}/^{40}Ca$ and use this data to constrain seepage water flow rates and their response to rainfall events. I will also collect data for other proxies that are influenced by PCP and water- rock interactions ($\delta^{13}C$, Mg/Ca, Sr/Ca) to cross-reference with the new $\delta^{44}/^{40}Ca$ datasets. Ultimately, this work will provide robust guidelines for implementing $\delta^{44}/^{40}Ca$ as a quantitative paleo-rainfall proxy in caves with variable background climate, host rock type, and hydrologic characteristics.

Rachel Kaiser (Funded $3,000)

Ph.D. Student
Department of Environmental Sciences
Tennessee Technical University
Advisor: Tania Datta

An Interdisciplinary Approach to Understanding the Presence of Antibiotic Resistance and Antibiotic Resistant Bacteria in Urban Karst Groundwater Systems

Abstract: The presence of antibiotics and antibiotic resistant bacteria (ARB) in source waters, such as groundwater, is a growing global concern. Bacteria resistant to life-saving antibiotics can have detrimental impacts to environmental and human health. These emerging pathogens have recently been established as a major concern due to human health impacts and dilution of the effectiveness of available antibiotics; however, there is little to no research work done on the presence and impacts of ARB in urban karst groundwater systems. Every continent in the world has karst landscape features, with nearly a quarter of the human population living on or near karst regions and using karst groundwater aquifers as drinking water sources, which may be potentially contaminated with ARB. Therefore, the purpose of this research is to determine the presence, type of resistance, and level of resistivity of ARB in karst groundwater systems. Moreover, how the unique nature of these karst systems, their water quality, and adjoining land-use impacts the presence and level of resistivity in ARB is not well studied. Addressing these data gaps will aid in informing regulations to protect water resources and human health.

Using Stable Isotopes and Trace Elements to Identify Microplastic Sources and Transport Mechanisms in a Karstic Cave System

Teresa Baraza, M.S.

Graduate Advisor: Dr. Elizabeth Hasenmueller
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Article based on this research was published in *Water Research* 242 (2023)

Abstract

Microplastic (plastic < 5 mm) contamination is ubiquitous, and has been found in environments ranging from deep ocean floors to Artic Sea ice. Because plastics degrade slowly and are highly mobile, microplastics are a concerning emerging contaminant. Microplastics are dangerous to ecosystems not only because they can be ingested and cause internal issues to wildlife, but also because they can act as carriers of other contaminants such as heavy metals and organic compounds. Microplastic research has historically been focused in marine environments, and more recent studies have investigated microplastic contamination in surface freshwaters. However, only one study has quantified microplastic contamination in groundwater. We therefore investigated microplastic sourcing and transport in a cave system. To do so, we collected water samples weekly under different flow conditions and more frequently during flooding events. Water samples were analyzed for microplastic content and characteristics as well as total suspended solids (TSS), major and trace ion chemistry, and O and H isotopes. Microplastics were found in the water during all flow regimes. Microplastic content was positively correlated with discharge, TSS, and other tracers of surface runoff (e.g., Al, Pb, K), suggesting higher plastic transport during floods. We also performed hydrograph separations during floods, using $\delta^{18}O$ and $\delta^{2}H$ measurements, to assess which water sources are associated with enhanced plastic loads. Our isotope hydrology findings demonstrated enhanced plastic transport with event water. This study provides new insight into how microplastic contamination moves through groundwater systems, which will help inform debris mitigation strategies.

Introduction

With the dramatic increase in plastic production in the second half of the 20th century, plastic contamination in the environment has increased exponentially.[1] Microplastics (plastics < 5 mm in diameter), which were first detected in the 1970s on the Sargasso Sea surface,[2] have since been found worldwide at the ocean's surface[3,4] and floor,[5,6] along shorelines,[7] in rivers,[8-10] in groundwater,[11] and even in Arctic sea ice.[12] Due to their small size, microplastics are highly susceptible to ingestion by organisms, causing multiple health issues such as organ damage, intestinal blockage, and suffocation.[13] Microplastics have also been found to act as carriers of other types of contaminants such as organic pollutants.[13,14] When ingested by small organisms, microplastics can introduce toxins to the base of the food chain and cause other issues such as endocrine disruption.[13,15,16] Thus, microplastic particles pose a significant threat to ecosystem and human health.

Research on plastic contamination has historically been focused on marine environments.[17-19] However, recent studies have identified that ~ 80% of plastic contamination in the ocean is land-sourced, with rivers being the main mode of plastic transport.[8,20-22] The pervasive presence of microplastics on land suggests that microplastic particles could potentially be reaching deeper hydrological reservoirs, putting groundwater ecosystems and resources at risk. Karst aquifers are characterized by the presence of dissolution features in the carbonate rock, such as conduits and sinkholes. The high connectivity in karst systems causes these aquifers to have complex water flowpaths (i.e., fast flowpaths through conduit openings and slow flowpaths through the rock matrix). This type of architecture also enhances the connectivity between the surface and subsurface, making karst aquifers highly susceptible to anthropogenic contamination such as road salts,[23] fecal bacteria,[24,25] chemical fertilizers,[26] and wastewater.[27]

Previous studies have suggested the potential for microplastics to contaminate groundwater,[28] but, to date, only one study quantifies microplastics in these environments.[11] Panno et al. (2019) identified microplastic contamination in springs and wells from a karst region in Illinois, USA, during baseflow conditions. They found that microplastics positively correlated with other anthropogenic contaminants (e.g., nutrients, bacteria), suggesting that the microplastics originated from septic tanks. While the Panno et al. (2019) study shows that microplastics can indeed intrude groundwater resources, no systematic studies of microplastic debris transport in groundwater have been conducted. Our study therefore explored microplastic sourcing and transport in a karst aquifer under various flow regimes.

Methods

Water sampling was performed weekly at Cliff Cave, which is the second longest cave in St. Louis County with over 1.3 km of surveyed conduits (Missouri, USA; Fig. 1),[29] from February 2020 to January 2021. High frequency sample collection (~ 30–40 minute intervals) occurred during four flood events in the fall and winter of 2020. All samples (n = 252) were analyzed for TSS, major and trace elements, and $\delta^{18}O$ and $\delta^{2}H$ isotopes. A subset of samples (n = 106) were characterized for microplastic concentration, morphology, and color. Stage and water quality data (e.g., specific conductivity (SpC), pH, turbidity) were collected continuously with in situ devices at the cave entrance during the study period. Stage data were converted to discharge using regular discharge measurements and a rating curve developed over the monitoring period.

Site Hydrology and Geochemistry

Using topography and an average discharge-recharge area relationship,[30] we estimated the cave's recharge area to be 2.2 km^2. The estimated recharge area encompasses 67 reported sinkholes, features a losing stream, and is about 63.0% developed (Fig. 1). The stream issuing from Cliff Cave had discharge values ranging from 0.003 to 19.580 m^3/s (average = 0.018 m^3/s) during the study period. The cave

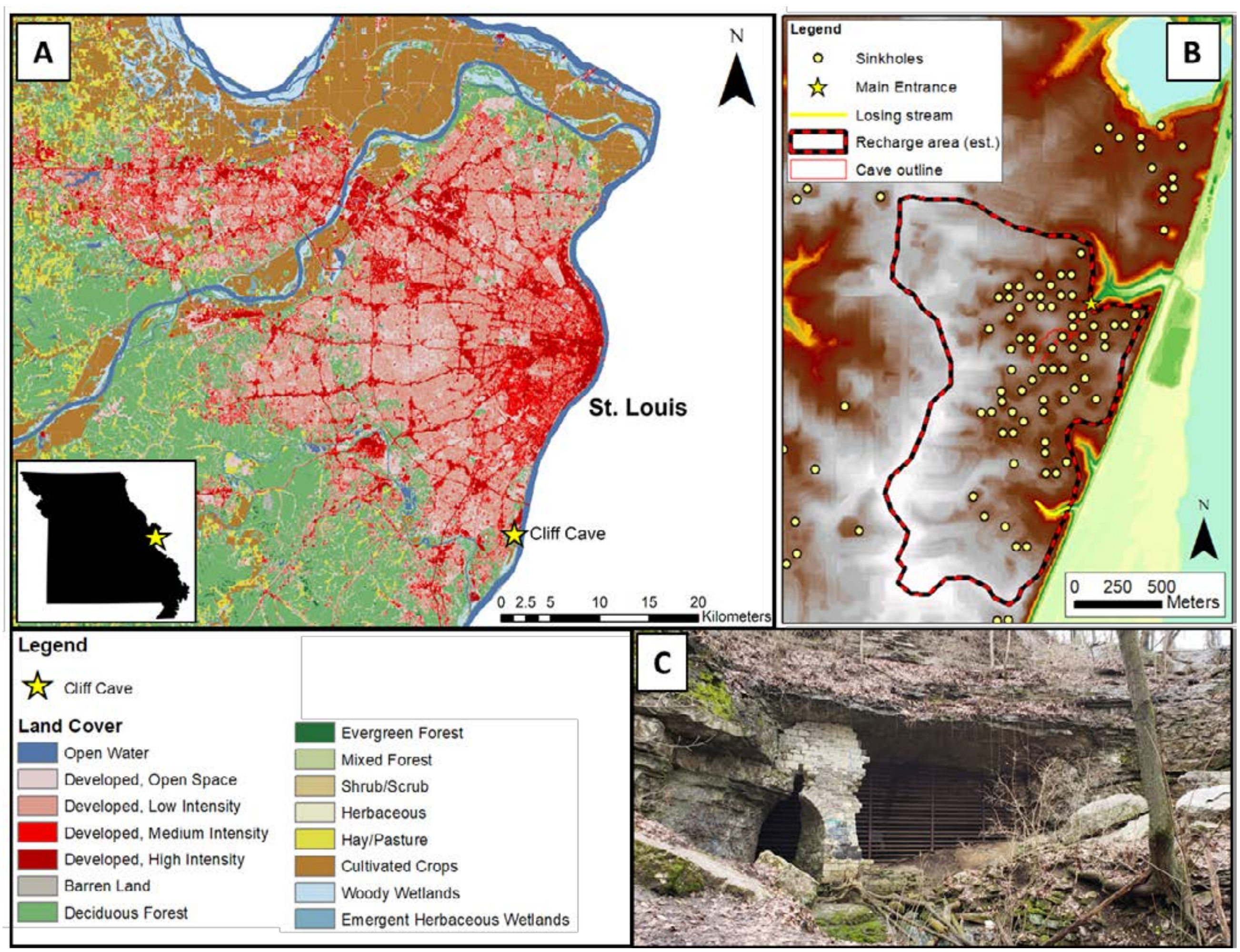

Fig. 1. A. A land use map showing the location of Cliff Cave, south of St. Louis, Missouri. B. A digital elevation model showing an estimated recharge area for the cave based on topography, sinkhole and losing stream distribution, and an average discharge-recharge area relationship.[30] C. The main entrance to Cliff Cave (Photo credit: T. Baraza).

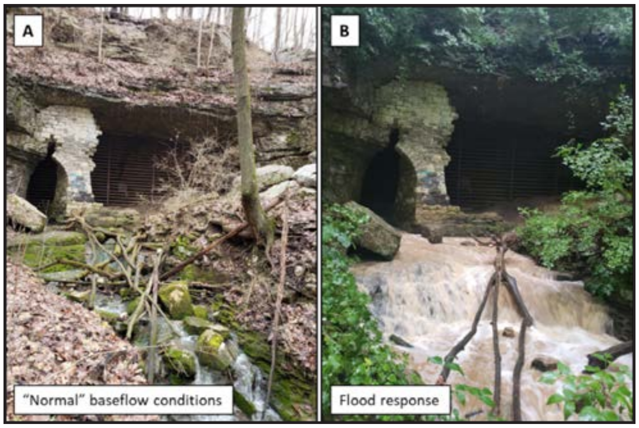

Fig. 2. The stream issuing from the main entrance of Cliff Cave during baseflow (A) and flooding (B) conditions.

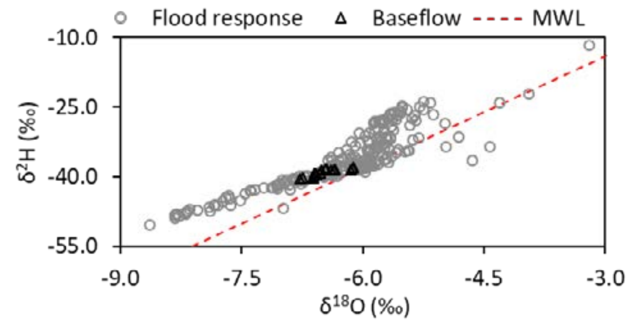

Fig. 3. The δ18O and δ2H values of the cave stream water during baseflow (black) and flood (gray) conditions. The meteoric water line (MWL; red) is plotted for reference.

stream's discharge changed rapidly in response to rainfall events (Fig. 2). Of the 31 flood events during the study period, lag times ranged from 0.2 to 5.3 h, averaging at 1.5 h. The stream's rapid response to rainfall indicates that conduit flow is the dominant flow type. The dominance of conduit flow in the system is supported by the presence of numerous sinkholes on the surface immediately above the cave.

Water quality monitoring revealed the cave stream's geochemistry also responded rapidly to rainfall events. Turbidity averaged 13.5 NTU during the study period, but sharply increased during flood events, with a maximum recorded value of 1227.3 NTU. Grab samples for TSS ranged from 0.8 to 731.4 mg/L, averaging at 30.8 mg/L. Baseflow samples, collected at least 3 days after a rain event, had less variation in their $\delta^{18}O$ and $\delta^{2}H$ values (-6.5 ± 0.2 ‰ and -39.0 ± 0.8 ‰, respectively) than samples collected during flood events (-6.2 ± 0.8 ‰ and -36.3 ± 6.1 ‰, respectively; Fig. 3). Hydrograph separations using $\delta^{18}O$ and $\delta^{2}H$ data were performed for floods in November 2020 and December 2020, when the isotopic signature of rainfall differed from that of the pre-event water (baseflow) in the cave stream. We observed an initial flush of baseflow (*Qb*) at the onset of the floods, followed by a dominance of event water (i.e., recent rainfall; *Qe*) during the peak flows and falling limbs of the floods (Fig. 4).

Microplastic Transport through a Cave System

We characterized microplastics in 40 of the weekly grab samples and 66 of our flood samples. A total of 429 particles were identified as suspected microplastics (average = 13.3 counts/L), with the majority being fibers (85%). The predominant microplastic color was clear (59.7%), but blue and black were also common. While we did not observe seasonal patterns in microplastic concentration, morphology, or color, we found a weak, but significant, positive correlation between microplastic concentration and total rainfall in the 2 days preceding sample collection (R2 = 0.14; p = 0.02). More plastic being transported following precipitation events suggests that microplastic transport may be higher during wetter periods.

Total microplastic concentration was positively and

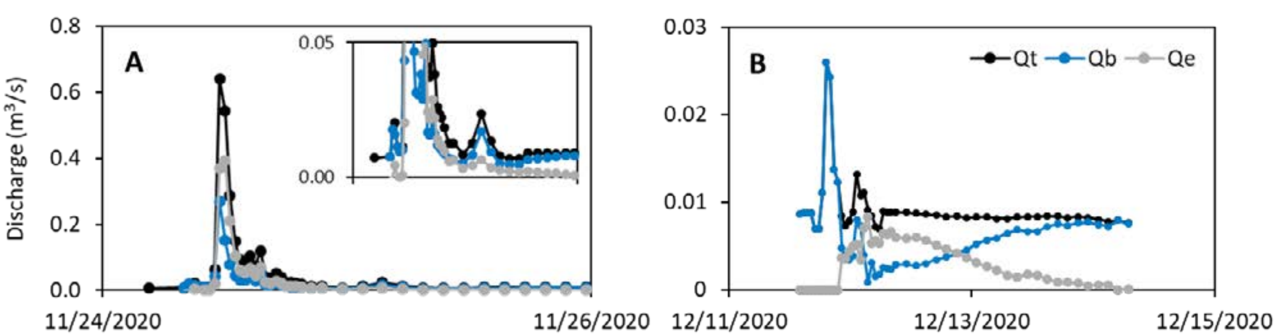

Fig. 4. Flood hydrograph separations performed using δ²H data. The hydrograph separations show the timing of the baseflow (Qb) and event water (Qe) components of the total discharge (Qt) for the November 2020 (A) and December 2020 (B) floods.

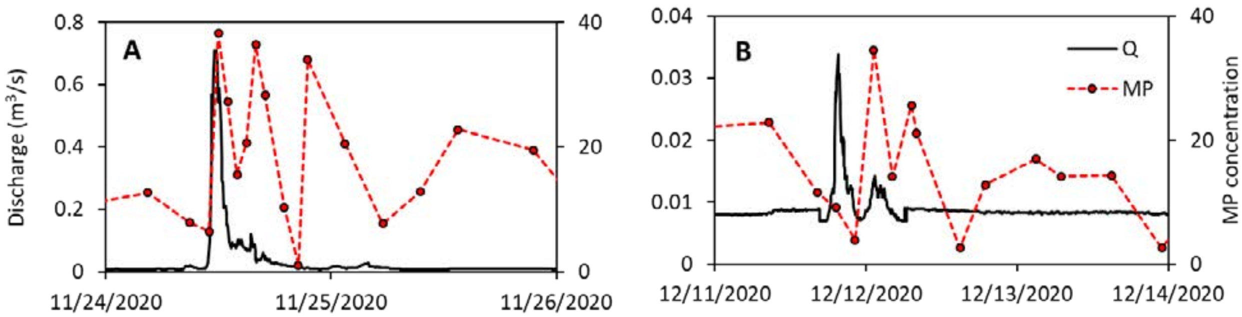

Fig. 5. Discharge (Q) and microplastic (MP) concentration during floods sampled in November 2020 (A) and December 2020 (B).

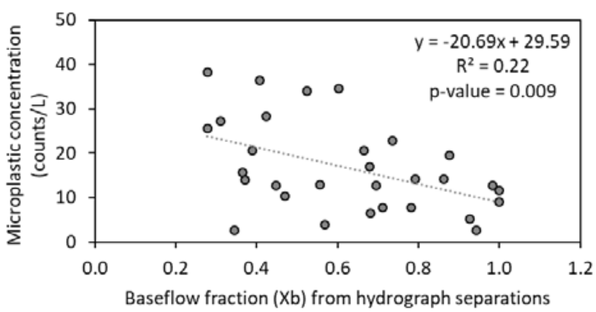

Fig. 6. Negative correlation between microplastic concentrations and fraction of discharge due to baseflow (Xb) during flood events. Values for Xb were calculated with a two-component hydrograph separation method using stable water isotopes $\delta^{18}O$ and $\delta^{2}H$ as geochemical tracers.

significantly correlated with discharge and TSS ($R2 > 0.14$, p-value < 0.05), as well as with trace elements such as Pb, Al, K, and P ($R2 > 0.06$; p-value < 0.05). These results indicate increased microplastic transport during high discharge events, when large amounts of sediment are transported through the cave along with surface recharge from rainfall. Indeed, total microplastic concentration significantly and negatively correlated with pH, SpC, Ca, and Mg, also suggesting that the plastics were transported along with acidic and dilute surface runoff ($R2 > 0.07$; p-value < 0.05). We also observed a slight decrease in microplastic content at the onset of the floods (Fig. 5), when discharge due to baseflow is predominant (Fig. 4), as well as a negative significant correlation between microplastic content and the baseflow fraction Xb derived from hydrograph separations ($R2 = 0.22$, p-value = 0.009; Fig. 6). Thus, our geochemical data support the idea that plastic contamination originates from the surface and is transported along with recharge waters from rainfall events (Qe), rather than legacy plastic being remobilized from within the cave.

Conclusions and Ongoing Work

Our study results show that microplastics are present in cave streams, suggesting that fragile cave ecosystems are at risk from these emerging contaminants. We observed that microplastic transport increased during flood responses, when acidic, dilute, and sediment-rich surface recharge entered the cave through sinkholes and fractures. Ongoing analysis of microplastic polymer types, combined with microplastic morphological and color characterization, may aid in the identification of plastic sources. Our study provides much-needed insight into the distribution and transport of microplastics in karstic and groundwater systems. These results can be used for future debris mitigation strategies.

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An Interdisciplinary Approach to Understanding the Presence of Antibiotic Resistance and Antibiotic Resistant Bacteria in Urban Karst Groundwater Systems

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Significant Findings

The World Health Organization and the Center for Disease Control have determined the presence of emerging pathogens, such as antibiotic resistant bacteria (ARB) and antibiotic resistant genes (ARGs), as a global health concern [1,2]. Bacteria resistant to life-saving antibiotics can have detrimental impacts on environmental and human health. The impacts can be especially threatening in karst regions, where nearly a quarter of the human population resides or relies on karst aquifers as drinking water sources [3]. The prevalence of ARGs is understudied within this resource, which could be a reservoir and pathway of ARGs, negatively impacting human health [4–7]. Karst groundwater systems are extremely susceptible to urban pollution sources, such as leaking septic tanks and sewage collection pipelines, wastewater treatment plant effluent, and stormwater conveyances, which can easily transport ARB, ARGs, and residual antibiotics throughout the aquifer system [8–10]. Moreover, unlike surface streams, karst groundwater systems are oftentimes a buffered environment with respect to sunlight, pH, and temperature, which may create

Antibiotic Group	Gene	Antibiotic Group	Gene	Antibiotic Group	Gene
Total Bacteria	16S rRNA	B-Lactam	blaSHV	Methicillin	mecA
Aminoglycoside	aac(3,Aô)-Ii(acde)	B-Lactam	blaTEM	Macrolide	mefA_10
Aminoglycoside	aac(6')-Ii	B-Lactam	blaVIM	Macrolide	mefA_3
Aminoglycoside	aac(6')-Iia	Phenicol	cat	Unclassified/Fluoroquinolone	mfsA
Aminoglycoside	aac(6,Äô)-aph(2,Äù)	Phenicol	catB3	Animal marker	Pig2Bac
Aminoglycoside	aac(6,Äô)-Ib	B-Lactam/ Cephalosporin	cblA	Fluoroquinolone	qacA
Aminoglycoside	aadA	B-Lactam/ Cephalosporin	cepA	Fluoroquinolone	qacC
Aminoglycoside	aadE	B-Lactam/ Cephalosporin	cepA_2	Fluoroquinolone	qacE
Aminoglycoside	aadE-like	Multidrug	cfr	Fluoroquinolone	qnrA
Multidrug	acrA	Multidrug	cfr_2	Fluoroquinolone	qnrB
Multidrug	acrF	B-Lactam/ Cephamycin	cfxA	Fluoroquinolone	qnrC
Aminoglycoside	aph(2,Äù)-I(de)	Chloramphenicol	cm1A1	Fluoroquinolone	qnrS
Aminoglycoside	aph(2,Äù)-Ib	Animal MST marker	CowM2	Animal MST Marker	Rum2Bac
Aminoglycoside	aph(3,Äô)-Ia, -Ic	Animal MST marker	CowM3	QC marker	SalmonDNA
Aminoglycoside	aph(3,Aô)-III	Carbapenem	crAv-064	Aminoglycoside	spc
Peptide	arnA	Diaminopyrimidine	dfrA27	Aminoglycoside	strB
Peptide	bacA	Diaminopyrimidine	dfrF	Sulfonamide	sul1
Peptide	bacA_1	Indicator Bacteria	Ecoli-23S	Sulfonamide	sulA
Peptide	bacA_2	Indicator Bacteria	Enterococci-23S	Tetracycline	tetB
B-Lactam	blaACC	Macrolide	ermA	Tetracycline	tetM
B-Lactam	blaAMPC	Macrolide	ermB	Tetracycline	tetO
B-Lactam	blaBIC	Macrolide	ermC	Tetracycline	tetQ
B-Lactam	blaCMY	Macrolide	ermF	Tetracycline	tetW
B-Lactam	blaCMY-1/MOX	Macrolide	ermG	Tetracycline	tetX
B-Lactam	blaCTX	Fosfomycin	fosB	Multidrug	tolC
B-Lactam	blaDHA	Human MST Marker	HF183	Glycopeptide	vanA
B-Lactam	blaGES	Human MST Marker	HumM2	Glycopeptide	vanB
B-Lactam	blaIMI	NA-Captures Resistance	intI1 (Barraud)	Glycopeptide	vanR
B-Lactam	blaIMP	Macrolide	macB	Glycopeptide	vanUG
B-Lactam/ Carbapenem	blaKPC	Unclassified or multidrug; antibioitc efflux	mdtF	Glycopeptide	vanX
B-Lactam/ Carbapenem	blaNDM	Unclassified or multidrug; antibioitc efflux	mdtL	Streptogramin	vatA
B-Lactam/ Carbapenem	blaOXA	Nucleoside	mdtO	Streptogramin	vatB

Table 1. Resistome Gene Panel.

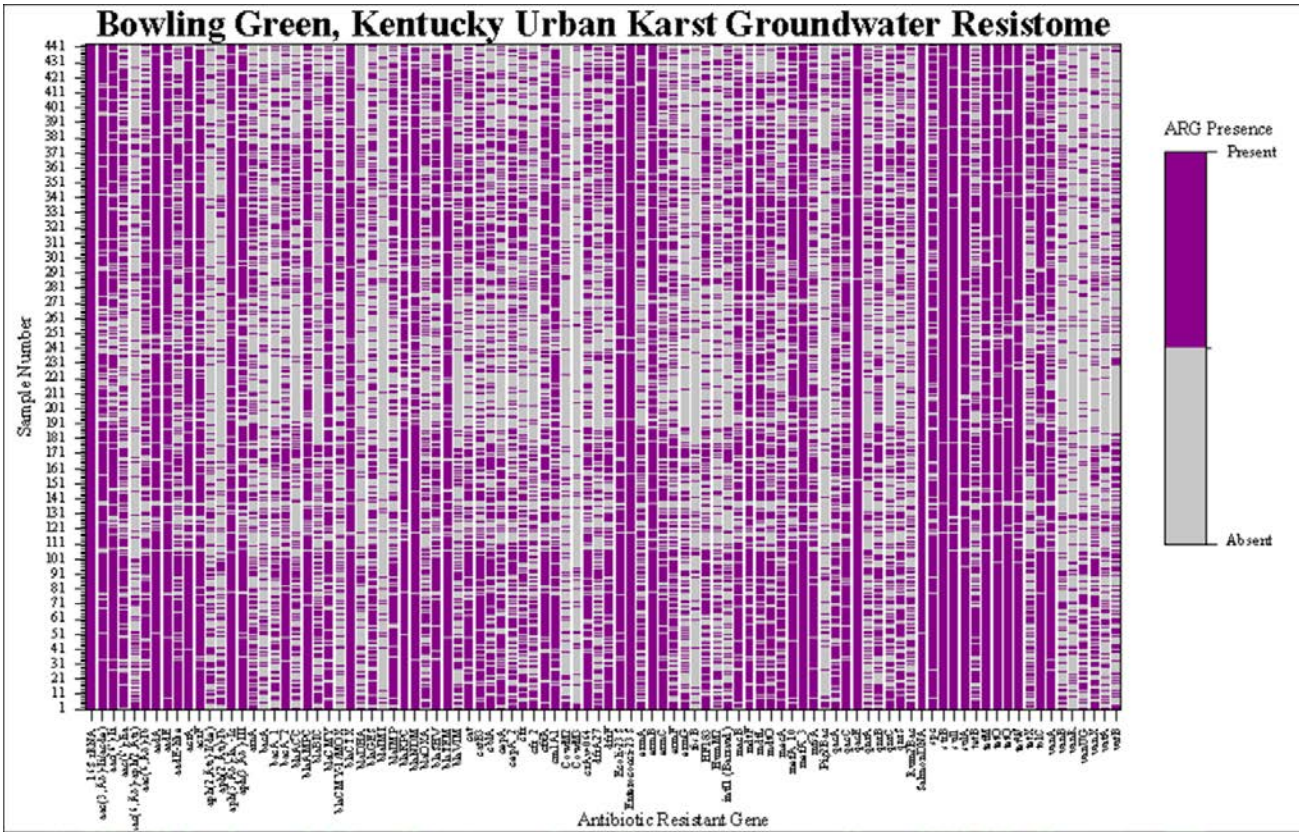

Figure 1. Presence and Absence Heatmap of all Bowling Green, KY samples.

a more hospitable environment for the potential proliferation and dissemination of ARGs year-round [3,11–13]. During baseflow conditions, karst systems are also capable of storing pollutants in the epikarst critical zone, such as sediments, antibiotics, and nitrates, in high concentrations between storm events and the extended residence time of the pollutants can provide essential resources for the growth of bacteria and the transfer of ARGs [10,13].

The detection of antibiotics and antibiotic resistance is beginning to be studied in karst environments and there is documented antibiotic resistance in Lechuguilla Cave in New Mexico [14], Domica Cave in the Slovak Karst National Park [15], a rural karst aquifer in Northwest France [16], Parsik Cave located in a rural area of Turkey [17], through karst systems in China [8,9,18], and in private wells in Midwest Ireland [19]. However, the interconnected nature of the karst landscape makes it difficult to determine sources of resistance, such as human or animal, within rural and urbanized karst areas [8,12,20]. The prevalence of resistance has been documented in rural and agricultural karst areas, but the influence of anthropogenic activities is overlooked thus far. Urban karst systems, which potentially introduce a variety of ARB and ARGs, have received minimal attention thus far. This overlooked potential source of ARGs could be contributing to resistance within the groundwater system that is disseminated beyond urban areas, and extensively threatening environmental and public health. Understanding the risk of ARGs to the environment and human health in urban karst groundwater settings is a primary gap in the current knowledge and there has been little research conducted on ARGs in urban karst groundwater systems, specifically in the United States [11,21–26]. The overarching goal of this research is to understand the urban karst groundwater resistome, population of ARGs, and relative abundance of ARGs within the urban karst groundwater system of Bowling Green, KY. The data collected in this research will be analyzed alongside water quality, landuse, and spatiotemporal trends.

The resistome of the Bowling Green urban karst aquifer was defined, in partnership with the US Environmental Protection Agency, utilizing high-throughput quantitative PCR with a 96 gene panel targeting clinically associated antibiotic groups [27] and resistant genes as well as human and animal microbial source tracking (MST) markers (Table 1).

Weekly samples were collected at ten sites within the city for 46 weeks and 29 weeks at one of the sites due to the well drying up, totaling 443 samples analyzed across the panel, resulting in over 50,000 data points to defined the resistome. Through this method a general presence/absence of ARGs was determined (Figure 1) and relative

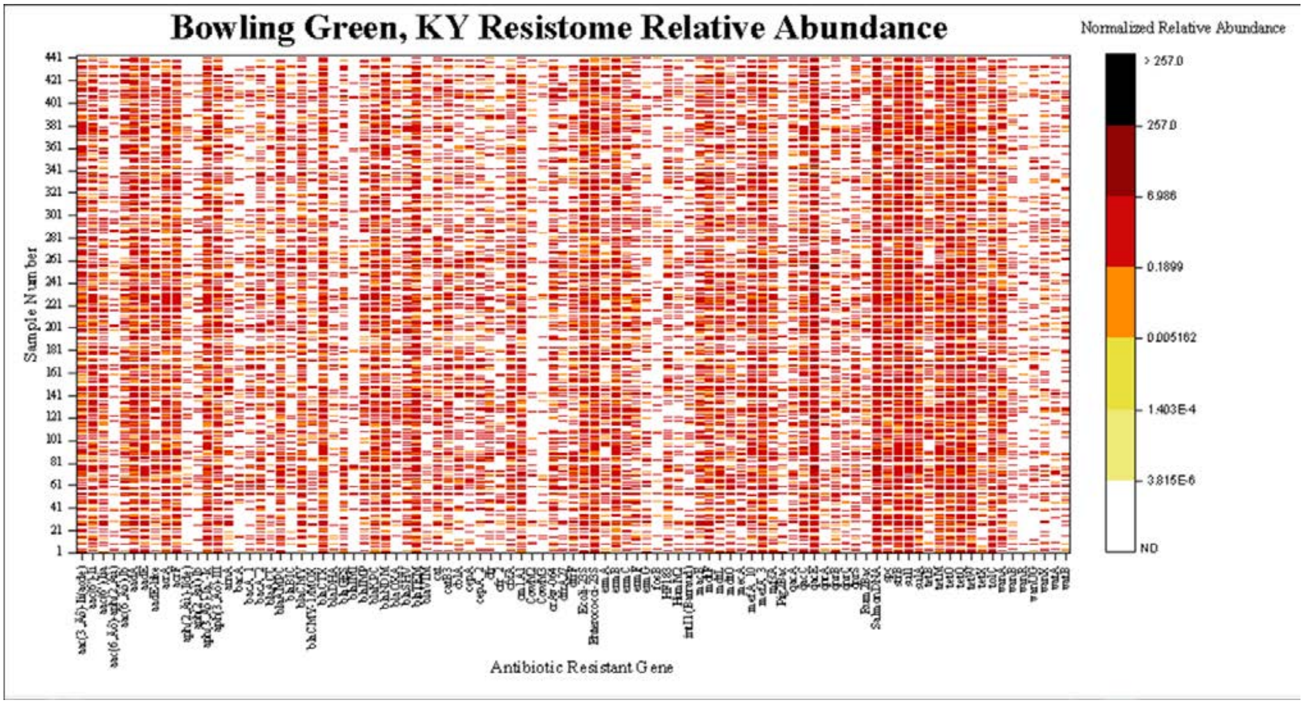

Figure 2. Relative Abundance Heatmap of all Bowling Green, KY samples.

abundance was calculated to highlight concentrations of the genes throughout the study period (Figure 2).

The presence/absence analysis detected all targeted genes throughout the study area and sampling period (Figure 1). The sampling sites are all located within the city limits of Bowling Green within four groundwater basins. The sites are predominantly impacted by residential landuse; however, the basins exhibit mixed landuse with commercial, public, industrial, and agricultural landuse. The clinically relevant panel and human MST markers detected throughout this study indicates anthropogenic influence to the resistome. The aminoglycoside, multi-drug, beta-lactam, carbapenem, fluroquinolone, macrolide, sulfonamide, and tetracycline antibiotic groups exhibited extensive presence throughout the sampling sites and sampling period. The targeted indicator bacteria, E.coli and Enterococcus, were also present throughout the study area and sampling period regardless of seasonal trends, indicating a potentially buffered environment as well as continuous anthropogenic inputs, such as leaking sewage lines and septic tanks, to the system.

The relative abundance of the ARGs were determined utilizing the $\Delta\Delta$Ct equation (2(-(ARG Ct- 16S rRNA Ct))) [27,28], which reflects the relative concentrations of the ARGs and how they changed throughout the study area as well as throughout seasons (Figure 2). Reflecting the antibiotic groups detected in the presence/absence results, the associated ARGs were captured at significant abundance regardless of season. The weekly detection of clinically relevant ARGs within this study indicates a primarily anthropogenic influence towards the resistome within this system. The sample sites are influenced by the mixed landuse within the basins, as the animal MST markers were detected, however, the relative abundance was lower than the other targeted genes and human MST markers. Due to the excessive overuse of antibiotics in both human and animal health, it is difficult to define an exact point source. Regardless, ARGs were detected in the groundwater system, which is a threat to public health through potential exposure pathways, including consumption.

The constant presence of ARG, as well as detectable relative abundance, within the groundwater system is a serious concern for environmental and public health. The groundwater system contributes to the area's drinking water supply and the presence of ARG threatens public health through this exposure pathway. Current treatment systems are not equipped to completely remove ARG from treated water and the introduction of ARG to the human microbiome through consumption can result in drug-resistant illness, which is responsible for over 700,000 deaths annually [29]. The complex hydrologic nature of karst groundwater systems may be contributing to the rapid development and dissemination of resistance through the aquifer as a result of the environment being buffered from extreme temperature changes, pH, and sun light, which typically kills bacteria in surface streams. There is limited data available for karst, specifically urban karst, groundwater systems and antibiotic resistance, however, this research highlights an extensive reservoir of antibiotic resistance.

This research contributes to further understanding the resistance crisis in water resources and can aid in future development of water quality regulations and standards.

Financial Report

Funds were requested to conduct the resistome analysis of the water samples within this study. Due to the extensive cost of metagenomic analysis on water samples, full metagenomic analysis of the samples was not fiscally possible, but high-throughput quantitative PCR was used to define the resistome. This approach was done in partnership with the United States Environmental Protection Agency using their Fluidigm high-throughput quantitative PCR equipment. Analysis was conducted by the PI and CRF funds were used to purchase supplies including Preamp PCR MasterMix through Fluidigm. The total cost for this analysis was $12,230 and the $3,000 given by CRF was spent in full.

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Geology of the Historic Route of Mammoth Cave, Kentucky

November 9, 2018 (rev. January 29, 2019)

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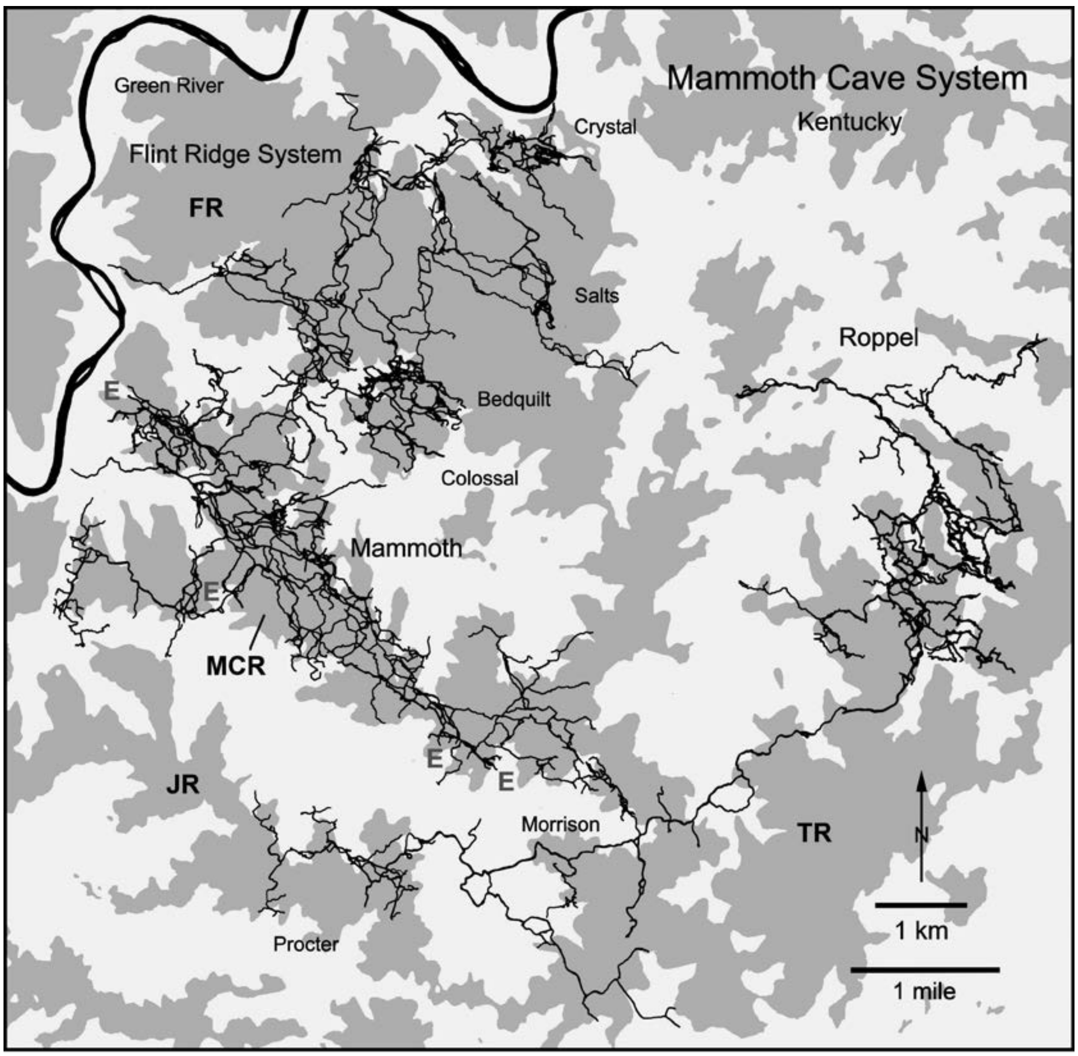

Figure 1: ***Generalized map of the Mammoth Cave System, from surveys by the Cave Research Foundation. The Roppel Cave portion (outside Mammoth Cave National Park), has been mapped mainly by the Central Kentucky Karst Coalition. Sandstone-capped ridges are shown in gray. MCR = Mammoth Cave Ridge, FR = Flint Ridge, JR = Joppa Ridge, and TR = Toohey Ridge. E = major entrances to tours in the National Park.***

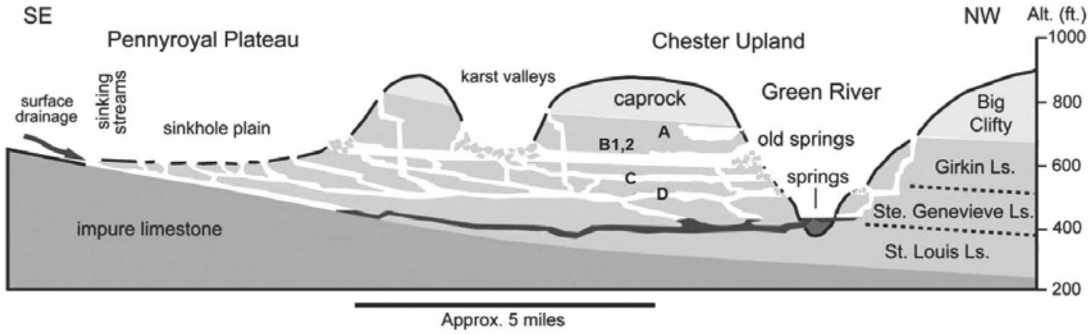

Figure 2: Highly simplified geologic cross section through Mammoth Cave, showing its relation to the Pennyroyal Plateau, Chester Upland, and Green River valley. The various cave levels (A, etc.) are shown in their approximate positions. Level A received its water from a nearby entrenched valley – not through the caprock (see "Crystal" in Fig. 1).

Introduction

Mammoth Cave has been one of the world's most famous caves for the past two centuries, mainly because of its size and long history. Since 1972, it has been the world's longest known cave and now contains 412 miles (663 km) of surveyed passages. They were all formed by the dissolving action of underground water, first as minor trickles along favorable routes (for example along bedding planes and joints), and enlarged by gradually increasing flow. A simplified map of the cave and geologic cross section are shown in **Figs. 1** and **2**.

Not so well known is the fact that the cave contains a detailed and probably unique record of the past several million years of geomorphic and glacial history of the east-central USA. The following is a brief outline describing some of the more significant aspects of the cave's geology and developmental history.

Origin and Pattern of the Cave

The passages in Mammoth Cave developed as underground tributaries of the Green River, which is a major branch of the Ohio River. The Ohio follows roughly the southern limit of Pleistocene glaciation, and so the cave has an almost direct link to the erosional and glacial history of the east-central USA. At the land surface, most of the evidence for the dramatic events in the Ohio River's history has either been removed by surface erosion or buried by sediment. However, the record for the past 3 million years or more is well preserved in Mammoth Cave, particularly in its passage pattern and sedimentary deposits.

Mammoth Cave occupies almost the entire thickness of these Mississippian limestones: Girkin, Ste. Genevieve, and roughly the upper half of the St. Louis (see **Fig. 3**). At least 60 individual beds are recognizable throughout the cave, despite minor variations in composition, texture, and thickness. Variations in rock type provide many bedding-plane partings, which provide routes for most of the groundwater flow and cave development in the Mammoth Cave area.

Relation of the Cave to the Evolution of the Surrounding Land Surface

Clues to the geomorphic history of the cave include (1) elevations of former springs along the Green River, where major passages terminate at the valley walls; (2) passage gradients and changes in gradient; (3) solution features that indicate the nature of water flow, and (4) sedimentary deposits left by the streams that formed the passages. These features and events are fairly recent by geologic standards (all probably less than 10 million years old), but they account for the development of the cave and its surrounding landscape.

As a cave develops at and below the water table, dissolution takes place around the entire perimeter of each passage to form tunnels with rounded cross sections that are usually widened along the bedding. Above the water table, free-flowing cave streams dissolve their floors deeper to form canyon-like passages, which meander like small surface streams because of irregularities along the bedding planes that serve as the main paths of water flow. Joints are sparse in the local limestone, but where they influence the cave origin they form straight fissure-like passages, or segments of passages.

The most recent series of continental glaciations in North America began roughly 3 million years ago (~3 Ma). In the mid-Pleistocene, about a million years ago, there was a gradual change in the frequency and intensity of glacial episodes from ~40,000-year cycles to ~100,000-year cycles, accompanied by an increase in glacial ice mass

(Pena & Goldstein, 2014). Prior to this transition, thick surface sediment apparently interfered with the bonding between the glaciers and the continent surface, so the ice tended to break into independent blocks rather than cohere as thick masses. Eventually much of the sediment had been scoured off the continental surface, so that glaciers were more solidly grounded in contact with bedrock, allowing the ice to thicken and survive longer, although not necessarily to extend farther south. The uppermost passages in the cave, and the sediment they contain, apparently date from the last few million years of the Pliocene Epoch and can be correlated with the various geologic events of approximately the last 5-10 million years.

Prior to about 1.5 million years ago, the major river in east-central North America was the Teays (pronounced "Taze"), which drained westward to the Mississippi River through the middle of what are now the states of Ohio, Indiana, and Illinois. At about 1.5 Ma the Teays was overrun by glaciers, which buried the

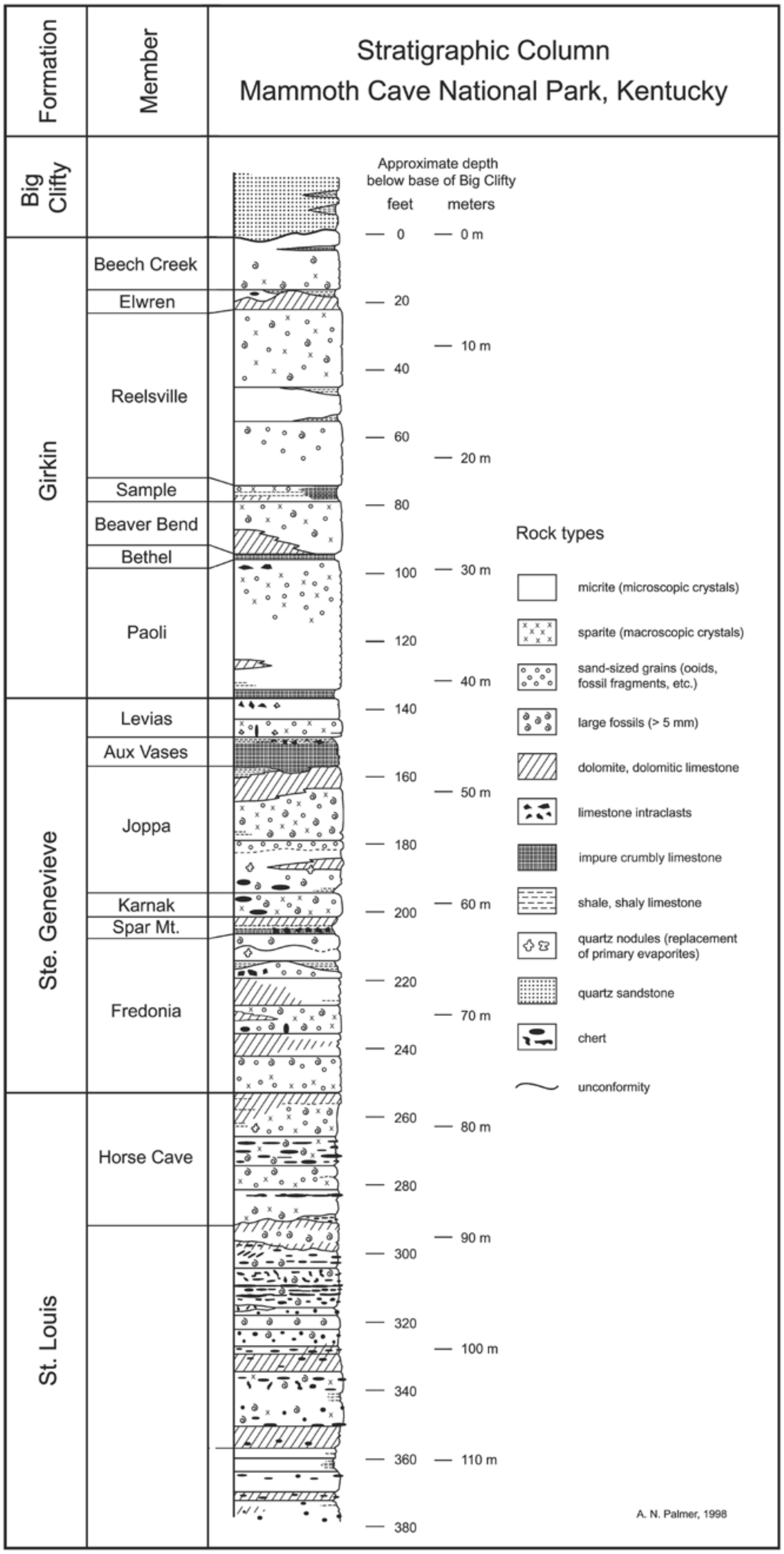

Figure 3: Stratigraphic column for the Mammoth Cave System. Certain terms are simplified for use by non-geologists. In the vicinity of the Historic entrance the various units in the Girkin and upper Ste. Genevieve are about 30 to 50% thinner than shown here, but all are still present. Stratigraphic mapping by A. and P. Palmer, following the names applied in the central Kentucky region by Pohl (1970), and modified slightly according to recent adjustments by USGS and Kentucky Geological Survey. Official names and boundaries tend to change with time, but the physical strata remain the same. The exposure of St. Louis Limestone in Mammoth Cave, shown here, is about 65% of the total St. Louis thickness.

valley in sediment and diverted its drainage into the Ohio River. Previously the upstream end of the Ohio was located near the present Ohio-Indiana border. Virtually overnight (geologically speaking!) the Ohio became the largest river in the Eastern USA. Its valley was rapidly entrenched by the greatly enhanced water flow. Later glaciers fell short of it and had no further significant influence over its path. Diversion of the Teays into the Ohio appears to have had a great effect on Mammoth Cave, as shown later.

There is much sediment in the cave, with maximum thicknesses up to about 70 feet (~20 m), deposited mainly by the same water that formed the passages. It consists mainly of quartz sand and gravel with local beds of silt and clay. The nature of the original water flow can be determined from these deposits. More importantly, the length of time since the sediment was carried underground can be calculated. This technique was recently developed by Darryl Granger of Purdue University (see Granger et al., 2001). Exposure of quartz pebbles and sand to solar radiation at and near the land surface produces tiny amounts of the isotopes ^{26}Al and ^{10}Be (radioactive isotopes of aluminum and beryllium), with the ^{26}Al/^{10}Be ratio stabilizing at about 7.0. Sinking streams carry this sediment into caves that are actively enlarging. At depths more than about 10 m (30 ft) below the surface, the two isotopes decay, but at different rates (^{26}Al faster than ^{10}Be), and by analyzing the isotopic concentrations in the lab, the time of burial can be calculated—i.e., the time since the cave passage was last actively enlarging. The lab technique is delicate and very time-consuming. Also, it must be clear that the sediments came directly from the surface, rather than from higher levels in the cave. Uncertain data can usually be resolved by analyzing the records from several passages at the same level.

Passages in the cave vary greatly in size from narrow crawlways to large galleries up to nearly 100 feet in width and/or height. Cave passages continue to grow by dissolution as long as they transmit fresh water from the surface, but enlargement ceases when their water diverts to new routes as the Green River erodes its channel deeper. Passages with continuous down-dip orientations indicate an origin by vadose water (gravitational, above the water table). A change in passage direction from down-dip to strike orientation (or to no systematic orientation relative to the structure) indicates the position of a former water table at the time the passage was forming (**Fig. 4**). Vertical shafts and narrow, sinuous, down-dip canyons are typical vadose cave features. Phreatic passages (originating at or below the water table) can be distinguished by tubular shapes, with wandering patterns that commonly follow roughly strike-orientated paths. Dips of strata in the Mammoth Cave region are generally less than half a degree, so they and the gradients of cave passages can be determined only with precise leveling surveys.

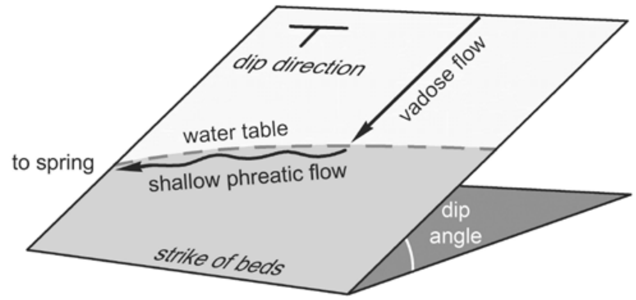

Figure 4: Limestone in the Mammoth Cave area has prominent bedding but few major joints and faults. This diagram shows the effect of structural dip (slope of the limestone beds) on vadose and shallow phreatic water flow. The resulting cave passages tend to follow the same trends, with vadose flow (above the water table) following the dip, forming canyon-like passages and minor tubes perched on resistant beds. At the water table, the passages tend to change to strike-oriented trends. This pattern is valid for most passages in Mammoth Cave. Both large and small variations in dip and strike tend to affect passage trends.

The uppermost passages in Mammoth Cave are all partly filled with stream-deposited sand and gravel (and completely filled in places). These passages consist of large canyons that were dissolved downward from their roof levels as much as 25 meters, with periodic interruptions at times when sediment partly filled the passages. They

Level	Altitude	**Al/Be age of sediment** – adjusted for 2010 recalibration) – Granger et al., 2001 **(Ma = millions of years ago)**
A	620–690 ft (190–210 m)	(2.6 Ma) – young deposits over more ancient ones; not present on the tour routes
B1	600–620 ft (183–190 m)	4-6 Ma – wide pre-glacial canyons; thick residual material at surface
B2	570–600 ft (174–183 m)	3-5 Ma – ditto
C	550 ft (168 m)	1.5-1.6 Ma – major glaciation to north, but little effect on cave; Green River stable
D	500 ft (152 m)	~1.3 Ma – after diversion of Teays River into Ohio; abrupt 15 m drop of water table

Table 1.

correlate in elevation and origin with a vast karst plain to the southeast of the National Park, the Pennyroyal Plateau (**Fig. 2**), which contains abundant sinkholes and is covered by irregular thicknesses of (mostly) stream-deposited sediment. This sediment correlates approximately in time and elevation with the sediment fill in the upper levels of the cave. In many cave passages some of the sediment has been partly excavated by later streams. The major passage levels in the cave are outlined in **Table 1**.

Level A is presently known only from Collins Avenue in Crystal Cave, at the far northeastern part of the cave. Its ceiling is located only about 10–20 ft (3–6 m) below the Big Clifty Sandstone. Its uppermost sediment was deposited about 2.6 million years ago—more recently than the sediments at level B. The ceiling of Collins is far higher in the cave than the level B passages, and its irregular profile shows development below the water table. Collins is much older than B but was apparently re-flooded at a later date and filled partly with sediment. Further sediment dating will be needed to clarify this passage relationship.

There are many passages below level D, but they show poor vertical organization and no dominant pattern. Many lie below the present Green River elevation, presently about 425 ft (130 m), but are now flooded because of a post-glacial rise in river level of at least ten meters.

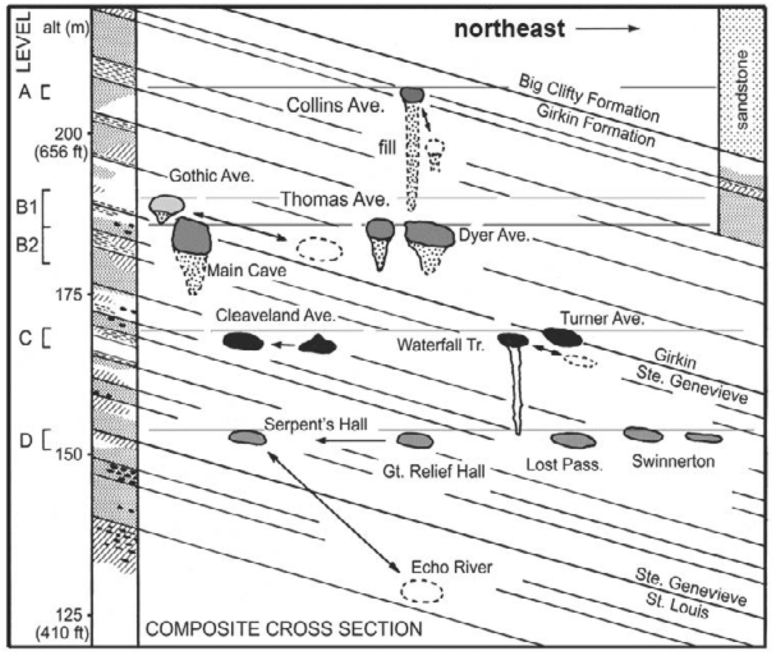

Figure 5: Plot of major passage elevations vs. stratigraphic position in the northern parts of Mammoth Cave Ridge and Flint Ridge, within a kilometer of the Green River, where levels are most clearly developed. Some passages, such as Echo River, deviated below the water table in phreatic loops, but returned to their original levels beyond the loops (hence their high vs. low positions linked by arrows). Despite irregularities in the beds and passages, it is clear that the levels are independent of stratigraphic control. The gray lines connecting the passages at each level are truly horizontal on the diagram – the apparent slope of those lines is an optical illusion caused by the dip of the beds. Test them with a ruler!

To demonstrate that A—B1—B2—C—D are true levels, in the geomorphic sense (rather than controlled by favorable strata), we plotted the elevations of the major passages vs. stratigraphic position. In **Fig. 5** it is clear that the levels are not controlled by the stratigraphy.

Below level B2 there are many spacious passages, but none as large in cross section as those at levels A and B. The lower levels are also much more complex, with diversion routes and complex junctions. Many of their passages have small cross sections that require stooping and crawling. The lower levels also have relatively little sediment, except in local areas near the Green River where water has frequently ponded during floods.

Passage levels reported here are rounded to the nearest 10 feet (~3 m). They include only those parts of the passages controlled by the elevation of the Green River. Between the levels shown here are hundreds of passages, mainly canyons and small tubes of vadose origin (formed above the water table). Dates shown in the list in **Table 1** were determined by the Al/Be method by Granger et al. (2001), as described, but have been adjusted to slightly older dates because of a recent recalibration of ^{10}Be decay rate (about a 15% increase in age). Passage elevations were obtained from leveling surveys throughout most of the cave and then rounded to the nearest 10 feet (Palmer, 1981). They are remarkably consistent, except in passages that formed far from the Green River, which do not represent stable water tables. Where a passage elevation is reported here, some uncertainty is assumed, but it is generally less than a meter or two.

The sharp 50-foot drop in elevation between levels C and D was apparently caused by diversion of the Teays River into the Ohio. The only connections between these levels are through narrow canyons or abrupt shafts. The cave streams drain directly into the Green River, so the sudden drop in the Ohio was translated upstream through the Green River via waterfalls and rapids, causing the water table at the cave to drop abruptly, so that major passages at level C were abandoned to form level D. The date of this diversion was shown to be roughly 1.5 Ma by the Al/Be dating and will be refined by further tests. Recent evidence suggests that the abrupt drop in water table may have resulted more from entrenchment of the Tennessee River farther south, rather than diversion of the Teays (Granger et al., 2018).

The effect of the diversion of water from level C to level D is best observed south of the Historic Route in Cleaveland Avenue (spelling is correct; **Fig. 5**). This is a large tube seen on several of the public tours. It follows the local strike of the beds with remarkable precision, indicating water-table control. In **Fig. 1** it is shown projecting westward from the main part of the cave (north of the "MCR" label, originally continuing much farther than shown on the map. When the Green River dropped abruptly after diversion of Teays drainage into the Ohio, water in Cleaveland Avenue was diverted straight down the dip to form a long NW-trending canyon passage (Pass of El Ghor) that extended down to the next level, Silliman Avenue, at what is now 500 ft above sea level. In most cases such a passage would then remain at a roughly constant elevation, following the strike of the beds, as Cleaveland Avenue did. Instead, however, Silliman Avenue looped downward about 23 meters below the water table along favorable beds and then rose back up toward the water table as it approached the Green River—as seen in River Hall on the Historic Tour. The entire passage is genetically part of level D, despite its large range of altitudes. The long lower portion of this loop is now accessible at and near the water table, which coincides with the present level of the Green River. The complex evolution of this section was untangled by the leveling surveys and stratigraphic mapping.

Below Level D is a complex of younger passages, now partly or completely flooded. Many extend below the present level of the Green River, at an elevation of roughly 425 ft (130 m). Late Pleistocene valley filling has raised the river level roughly 15–20 m, flooding the lowest (and mainly youngest) passages in the cave.

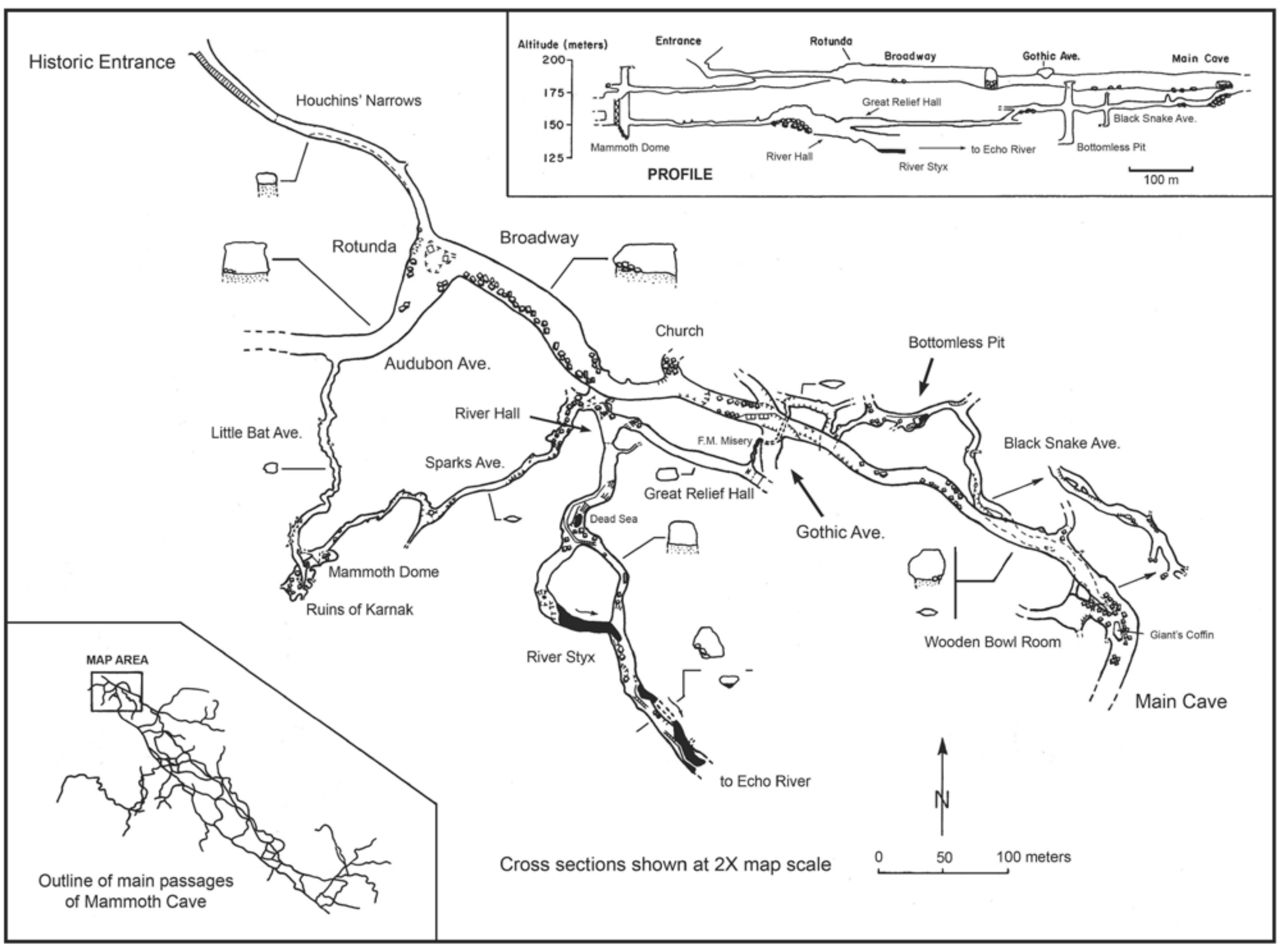

Figure 6: Simplified map and profile of the Historic Route, from personal surveys showing locations of features described in the text. Much more detailed maps have been produced since by the Cave Research Foundation.

Figure 7: Historic Entrance, in the middle Girkin (Photos by ANP.)

Figure 8: The Rotunda at the junction of the entrance passage with Broadway to the left and Audubon Avenue to the right. Relics of early 19th century saltpeter mining are displayed in the center.

Before the Al/Be dating method was developed, paleomagnetic studies of sediments in the cave by Vic Schmidt of University of Pittsburgh revealed a reversal of magnetic polarity at level C, indicating an age greater than ~780,000 yrs (Schmidt, 1982). The highest levels in the cave also showed reversed polarity, suggesting ages >2 Ma, although the exact dates were uncertain because of the non-continuous nature of the deposits. But the Al/Be dates confirm Schmidt's suggestion, and together they validate the overall interpretation of the cave's history.

Geologic Guide to the Historic Route

This tour gives the clearest view of the various passage types, levels of cave development, and limestone strata. It includes a long loop, which eliminates almost all re-tracing of our path (see map, **Fig. 6**). It also extends through almost the entire sequence of limestone beds shown in the stratigraphic column (**Fig. 4**). These include (from top to bottom, in the order seen on the tour), the Girkin Formation, the Ste. Genevieve Limestone, and about the upper 10 m (roughly 17%) of the St. Louis Limestone. On the Historic Tour, the various units in the Girkin and upper half of the Ste. Genevieve are only about half as thick as they are elsewhere in the cave. On the other hand, the underlying strata are thicker than average, so the total limestone thickness exposed on the tour is not substantially different from that shown in **Fig. 4**.

Features of interest described in this guide are identified in **Fig. 6** and are described in detail in the following pages. The NPS tours also emphasize the historical aspects of the cave, particularly its exploration, archeology, and use for saltpeter mining. Remnants of a saltpeter mining operation from the early 1800s are still preserved. These include wooden vats for leaching saltpeter from the cave sediment, and an impressive system of hollow wooden pipes for conveying water between the leaching vats and the surface.

1. Historic Entrance

The tour begins at the Historic Entrance (**Fig. 7**), which formed when a small tributary valley of the Green River intersected one of the main cave passages. The entrance descends steeply through the Girkin Formation and leads to the main level of the cave at an altitude of about 600 feet (180 m). A short passage located mainly in the Paoli Member (Houchins Narrows) leads to an impressive junction, the Rotunda (**Fig. 8**).

2. Rotunda (Level B1)

Remains of a 19th century saltpeter mining operation are seen here. Two large passages branch from the Rotunda—Broadway (straight ahead), and Audubon Avenue (to the right)—both are at the same elevation, because they were once a single continuous passage. These passages, as well as Houchins Narrows, were originally much taller, but their lower two-thirds have been filled by sediment as much as 80 feet (25 m) deep. Breakdown has also modified their upper sections, as shown by the sharp angular ledges along the ceilings. The breakdown process is very rare in the cave today, since the passages have stabilized over time. From the passage pattern it is clear that the water must have come from Broadway, because it leads for miles in a direction away from the Green River into the heart of Mammoth Cave Ridge. Both Audubon Avenue and Houchins Narrows were apparently fed by water from Broadway and drained to the Green River, but at different times. Audubon leads to the right for about 1000 feet (300 m) along the strike of the beds and ends in breakdown at the edge of the Green River valley. Houchins Narrows leads straight down the dip of the limestone beds to the Green River valley, and was apparently formed by diversion of the cave stream from Audubon to this new, more direct, route after the Green River had cut down to a lower elevation. Ancient breakdown of the ceiling has reversed the ceiling gradient of the passage. All of the passages in this area were later filled for most of their depth by sediment (as shown in cross section where younger passages have intersected them).

The medium-bedded Paoli unit occupies nearly the entire height of the Rotunda. It consists of 21 feet (6.4 m) of light gray finely crystalline limestone. Near the ceiling is an irregular recessed ledge formed by the Bethel unit, a shaly and relatively weak limestone only a few feet thick, with the thicker-bedded Beaver Bend forming the ceiling. The bottom unit of the Paoli, a silty limestone, is very crumbly and forms a sharply recessed niche of dark-gray rock a few feet above the floor of Audubon Avenue. This bed can be traced throughout the cave and is a good indicator of relative passage altitudes and stratigraphic position. It correlates with the Popcorn Sandstone Bed of the Paoli Limestone in Indiana.

3. Gothic Avenue junction (Levels B1-B2)

The tour follows the passage known as Broadway in the original upstream direction. Here the sediment has been partly removed through lower-level routes by stream action late in the history of the passage, so the floor descends into the Ste. Genevieve Limestone as far down as the Joppa Member, while the ceiling remains at the base of the Beaver Bend Member of the Girkin. Some sediment was also moved around by saltpeter miners early in the 19th century.

As shown on **Fig. 6**, Broadway is joined by Gothic Avenue, which enters from the right. It is clear that Gothic forms the upper part of Broadway and accounts for the high ceiling at this point. Remains of old saltpeter works

Figure 9: Pipes constructed from hollowed-out tulip tree trunks to convey water from the entrance and nitrate-rich liquid back to the surface (~1812).

Figure 11: Gothic Avenue (at ceiling level) joins Broadway at the "Church" (note pulpit-like projection on the left) but is filled with sediment around the corner. The low passage to the right leads to the junction shown in Fig. 12.

Figure 10: Saltpeter vats from the early 19th century: Cave sediment was placed in them and nitrates were leached out by pouring water through it.

Figure 12: Gothic Avenue (Level B1, at ceiling level) enters the Main Cave (Level B2). Gothic is in the Paoli Member (Girkin) and the Levias Member (Ste. Genevieve) lies below. Note the recessed bed at the base of the Paoli. See Fig. 6 for passage configuration.

from the time of the War of 1812 are displayed (**Figs. 8–10**). Cave sediment was collected and dumped into wooden vats, and then water was poured through to dissolve and carry out nitrates, which were used for gunpowder. The water was carried in from the surface through wooden pipes, and the nitrate-rich solution was returned to the surface by pumping it through a second set of pipes. Remains of a pump are still visible in the Rotunda, although not recognizable as such. Nitrates from the cave were calcium nitrate—and it had to be converted to potassium nitrate before it could be used for gunpowder. The liquid was poured through wood ashes to replace the calcium with potassium, and the resulting fluid was boiled down and shipped to a young company on the east coast, DuPont, which made the final conversion to gunpowder.

Gothic Avenue and Main Cave are each only about half the height of Broadway. Gothic Avenue is located in the Paoli unit. The lower passage, in the upper Ste. Genevieve, is just called Main Cave. This is a strange junction. When Main Cave formed, it intersected Gothic Avenue in two places—at the "Church" (**Fig. 11**) and farther upstream where it cuts across path of Gothic Avenue (**Fig. 12**), where the ceiling height represents the combined height of the two different levels. Gothic Avenue is a tube 15–20 feet high (4.5–6 m) where it first crosses the Main Cave (**Fig. 12**), but where it rejoins Main Cave at the "Church" it is a canyon about twice as high. How Gothic Avenue became a canyon over the short intervening distance is uncertain, because that loop of the passage is completely filled with sediment. It is possible that a lower-level tributary joined Gothic in this hidden interval.

Both Gothic Avenue and Main Cave can be followed in their former upstream directions for long distances. Where did their water come from? Gothic Avenue can be followed only about 1000 before it is blocked by breakdown and sediment fill, but Main Cave intersects it again farther to the southeast, where it is given different names. The upper level (B1) terminates at the edge of the valley that separates Mammoth Cave Ridge from Flint Ridge (**Fig. 1**). The passage has no observed continuation into Flint Ridge, so it was clearly fed by a surface stream that sank into the limestone that floors the valley. Main Cave continues all the way to the Violet City Entrance, half-way along the length of Mammoth Cave Ridge. That part of the cave is shown on the Violet City Lantern Tour. Main Cave was apparently formed by sinking streams entering the Chester Upland from the adjacent Pennyroyal Plateau. The passage once continued much farther to the southeast but has been truncated into several segments. The longest segment, several miles long, is shown on the Grand Avenue Tour.

Note how dry this part of the cave is. It's overlain by the Big Clifty Sandstone and the entire thickness of the Girkin Limestone. Both of them contain thin shale beds that tend to shunt infiltrating water laterally to the edges of the ridge. Crusts of gypsum ($CaSO_4 \cdot H_2O$) have formed on some of the walls by evaporation of sulfate-rich water seeping in from the surrounding rock. Most of the sulfate is produced by oxidation of small crystals of pyrite (FeS_2) in the limestone, as confirmed by relatively negative sulfur isotope values in the gypsum. Moister parts of the cave contain no gypsum because the conditions are not evaporative enough, and the sulfates are carried away in solution.

Passages in this part of the cave are dark with soot from torches and kerosene lanterns. Much of the soot was left by reed torches used by "Indians" of the Early Woodland culture who visited the cave repeatedly for a couple of thousand years, mainly to escape winter weather, to mine gypsum for various purposes—and perhaps occasionally just to explore.

Leveling surveys show that this part of the Main Cave follows the local strike of the beds, which implies an origin along the water table. The Rotunda is located at the nose of a gentle anticline, in which the strike makes a sharp bend into Audubon Avenue (**Fig. 5**). The far upstream part of the Main Cave extends up the northwesterly dip of the beds, indicating an origin above the local water table. In the up-dip direction the cross section eventually becomes tall and canyon-like.

4. Black Snake Avenue (Level C)

The Historic Tour continues a short distance beyond Gothic Avenue to a large breakdown block ("Giant's Coffin"). Here the tour exits to the right through a narrow canyon that formed when the last remnants of the original cave stream abandoned the Main Cave to form lower levels. The canyon descends through the light-gray Joppa and Karnak units into the Wooden Bowl Room, which was named for a

Figure 13: Black Snake Avenue is a minor representative of Level C, with a rather small recharge area. One of several small cut-arounds is shown here, where the cave stream diverted along a favorable bedding plane.

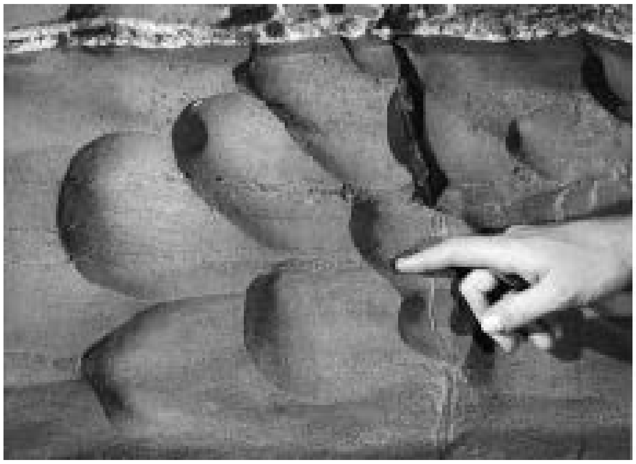

Figure 14: Solutional scallops in the cave wall show the direction of former water flow (steep sides = downstream; light source is from the left). The flow velocity can be estimated from the average length of the scallops—small ones indicate high velocity (see next page for calculation). The finger points upstream. A thin deposit of gypsum (CaSO4·2H2O) has formed where seepage has entered the cave and evaporated.

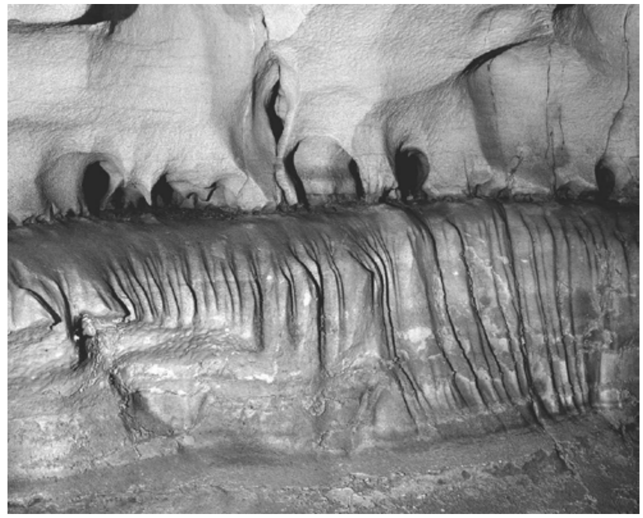

Figure 15: Anastomoses—the holes along the bedding plane were formed by water injected into bedding-plane partings during floods. As the floodwater subsided, the water drained out to form rills in the underlying wall. This passage has not contained an active stream for more than a million years.

Native American artifact discovered there. Several passages intersect at this point. The resistant Karnak unit forms the flat ceiling of this wide, low room. The walls are composed of the Spar Mountain unit, which is smooth and dolomitic in its upper bed and dark gray, sandy, and crumbly below.

A short but steep staircase descends through the upper Fredonia Member (use the railing!) to a tubular passage at level C called Black Snake Avenue (**Fig. 13**), so named for its dark walls and wiggly pattern). This passage, and others at this level, were formed about 1.5 million years ago during a long stable period in the continent. This is the most persistent and uniform level in the cave and includes some of the largest passages. Black Snake is one of the smallest, because it had only a small source area for water. It is at the same elevation as Cleaveland Avenue in **Fig. 5**.

The water that formed this passage was only a small remnant of the large stream that formed Main Cave. Most of the water had already been diverted to alternate paths by that time. Black Snake Avenue follows the thick, crystalline unit located just below –220 feet in Fig. 4. The passage elevation is at about 550 feet above sea level (168 m; level C), but migrates downward slightly in the former flow direction. Sand and gravel are sparse in this passage and have not been dated, but sediment in other passages at this elevation has been dated at about 1.6 Ma. The passage curves to the right and passes directly beneath the Main Cave. The solid limestone ceiling above us shows that the sediment that partly fills the overlying Main Cave could not have been thicker than about 25 feet (~8 m).

Figure 16: Spiky surface formed by dissolution of the passage ceiling by water seeping along the ceiling from a nearby active shaft (Sidesaddle Pit).

Note the solutional scallops in the bedrock of the lower walls. These resemble ripple marks in sediment, but are formed by dissolution and have sharper edges (**Fig. 14**). As with ripple marks, they show the direction of former water flow—the steep edge of the scallop is at the upstream end. Unlike ripple marks, scallops can be used to estimate the former velocity of flow, which is inversely proportional to their lengths (Curl, 1974). A simple estimate of former water velocity (at moderate water temperature) can be

Figure 17: Overlook into Bottomless Pit.

obtained by dividing number 250 by the average lengths of well-formed scallops. Thus scallops 5 cm long indicate flow velocities of about 50 cm/sec (~1.7 ft/sec). Usually the scallop size varies with height above the floor, reaching a minimum (i.e., most rapid velocity) somewhere above mid-way up the wall.

In places, Black Snake Avenue contains narrow fissures extending upward into the ceiling. In the past it was proposed that the fissures were formed by descending vadose water mixing with the phreatic water that filled Black Snake Avenue, as the result of contrasting CO_2 concentrations. Instead, this kind of fissure enlargement was almost certainly formed by periodic high flow that filled the passage under pressure and injected water into the overlying fissure. This process can be observed today in the lowest passages in the cave. Support for this idea is shown by solution rills emerging from bedding planes, where periodic floods once filled the passage under pressure, injecting water into the bedding planes. As the floods receded, water drained back out, forming rills that run straight down the walls below the bedding planes (**Fig. 15**). This repeated flooding also formed mazes of small tubes along the bedding planes, and also widened joints exposed in the ceiling. These floodwater features are handy clues to the history of cave development.

Water drips into this part of the passage because it lies close to the edge of Mammoth Cave Ridge, where the sandstone cap is thin. Water that drains through the sandstone contains very little dissolved limestone, and as a result it readily dissolves the limestone to form vertical shafts (e.g., Sidesaddle Pit). The water drains out at the shaft bottoms along bedding planes, especially along the tops of poorly soluble beds such as shaly limestone. Note the vertical rills in the shaft walls, which are produced by dripping water, especially during high flow. Some of the water seeps along the ceiling of the passage we are in, held in place by surface tension, and over time it has dissolved the ceiling upward a few millimeters and left scattered spikes of limestone, from which drips of water fall (**Fig. 16**).

The most impressive shaft in Black Snake Avenue is Bottomless Pit, which gapes to a depth of 105 feet (32 m) below the level of the trail and rises 60 feet (18 m) above (see **Fig. 17**). Years ago a sign, "Bottomless Pit, 105 feet," provided much amusement for the literal-minded. A bridge now spans the pit, but the earliest explorers were treated to the thrill of crawling around it on a narrow ledge. Water drains out of the shaft bottoms through narrow canyons, feeding still-active cave passages near the level of the Green River.

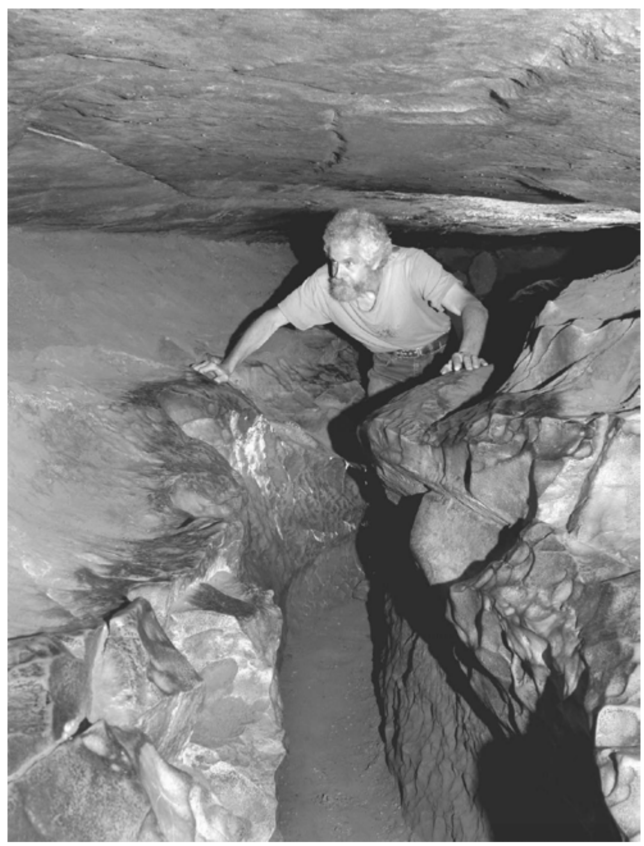

Figure 18: Fat Man's Misery leads to Great Relief Hall.

Figure 19: Great Relief Hall is a significant passage at Level D. The dark, mottled bed near the floor is a conspicuous marker that can be traced throughout the entire cave system. It is shown at −240 feet in the stratigraphic column (Fig. 4) as a dolomitic bed near the bottom of the Fredonia Member of the Ste. Genevieve. Note the chert dikes in the ceiling. Chert (very fine-textured SiO2) is common in many other places in the cave, but more typically forms nodules.

5. Great Relief Hall

Our route turns left at what looks like a minor junction, while the Black Snake passage continues a long distance ahead at Level C, with the name Pensacola Avenue. Our left-hand jog leads to a steep descent to a lower level, called Buchanan's Way, a total of about 50 feet (15 m) lower at Level D. A short distance beyond and to the right is a low tunnel, Lively's Pass, which leads to an overlook into Bottomless Pit part-way down the shaft. Buchanan's Way, like Black Snake Avenue, is floored by bedrock with a thin veneer of sand and gravel. The sediment thickness increases up ahead, and to continue would require crawling.

Instead we again turn left, into a narrow winding passage with a T-shaped cross section. This is "Fat Man's Misery," as indicated by a sign—absent for a couple of decades with the sensitivity of visitors in mind; but it has since returned. Visitors like to include it in photos. The passage is easily traversed with one's legs in the stem of the T and hands to either side (**Fig. 18**). Toward the end the floor rises a bit, requiring us to crouch or drop to our knees for a couple of feet. This passage discharges us into a large gallery called Great Relief Hall, in reference to our ability once again to stand upright. The installation of rest rooms at this point has added further meaning to the name.

Great Relief Hall is a wide tubular passage at level D (**Fig. 19**). Its ceiling is formed by the base of the thick-bedded unit F3, which here contains many joints enlarged upward by solution when the passage was still actively forming. It also contains dark, irregular nodules of chert (flint; finely crystalline SiO_2) that protrude from the ceiling because of their resistance to dissolution. The lower walls of this

Figure 20: Echo River Spring is the outlet for most of the streams in the Historic section of Mammoth Cave. Nearby River Styx Spring is also visible at the base of a trail leading from the Historic Entrance.

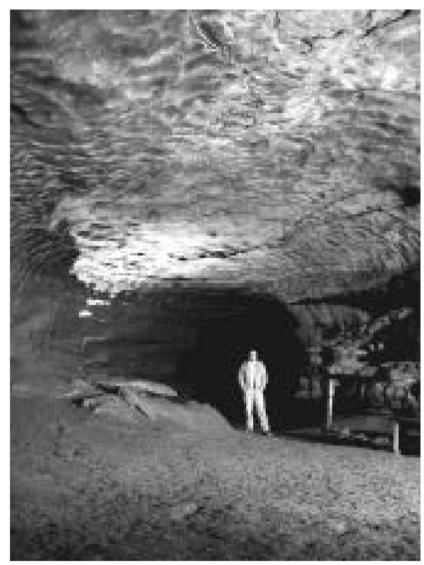

Figure 21: Solutional scallops in the ceiling of River Hall indicate upward flow from Echo River and River Styx. The Ste. Genevieve / St. Louis contact is visible as a widened bedding plane on the right, near the ceiling.

Figure 22: Below River Hall it is possible to visit the lowest levels on the tour route, located in the St. Louis Limestone at the same elevation as the Green River. Water levels fluctuate with those of the river, and this area is not always accessible during high flow. This pool is called the Dead Sea. This area is part of a downward loop in Level D.

passage have a moth-eaten appearance caused by solution pockets in a dolomite bed (unit F2). It also forms the lower walls in **Fig. 18**. This is a good stratigraphic marker that re-appears at least twice in the route ahead. Can you recognize it at those locations?

To the left, in the former upstream direction, hidden by the rest rooms, Great Relief Hall is blocked by ancient collapse blocks. No bypass has yet been discovered in that direction, so the extent and nature of the original water source are uncertain. To the right, formerly downstream, Great Relief Hall descends abruptly into River Hall, where a larger, lower passage joins from the left. These lower passages are guided mainly by stratigraphic boundaries and do not follow the well-ordered levels that we have seen so far. They are genetically part of Level D, even though their elevations are below the usual 500 feet.

6. River Hall and Sparks Avenue

River Hall is located at an elevation of 470 ft (143 m) and formed at the junction of Great Relief Hall and a larger passage that rises from the left. This left-hand passage was the former downstream end of Echo River, a still-active river passage that collects much of the water from the southeastern end of Mammoth Cave. Today its water drains out of Echo River to the Green River through a passage that is now submerged below the water table. (The spring can be seen from one of the surface trails along the river banks—**Fig. 20**.) When the water originally flowed upward into River Hall, it found its way to the Green River by a route that is now blocked by breakdown. Large scallops in the ceiling of River Hall confirm this pattern of upward water flow (**Fig. 21**). Below River Hall, deep pools and streams communicate with the Green River (**Fig. 22)**.

The ceiling of River Hall is formed by the thick-bedded F1 unit at the base of the Ste. Genevieve Limestone. The contact with the underlying St. Louis Limestone is the top of the projecting ledge half-way up the wall. Farther up-dip (to the southeast), this contact lies at a much higher elevation, and some of the cave passages extend as much as 130

Figure 23: Leopard's Arch, a solutionally widened fracture in Sparks Avenue that serves as a route to a slightly higher level.

feet (40 m) into the St. Louis. The stratigraphic column in **Fig. 4** includes the lowest beds so far observed in the cave.

The tour route leads up and out of River Hall past a series of brass caps that identify high water levels during floods over the past century. There is no danger from this flooding because the water rises very slowly. However, in the remote past, this was an area of severe floods, as shown by scallops that indicate water rising out of River Hall into upper levels. This is an example of catastrophic flooding that occasionally passed through parts of the cave around a million years ago. Any such flood would have been produced by intense rainfall and/or snowmelt, giving plenty of warning of rising waters if any of us happened to be there. At the Earth's surface, evidence for this sort of catastrophic event is quickly erased by erosion and weathering; but it can be preserved for very long times in dry cave passages.

Ahead, the walls and ceiling close in and the tour enters Sparks Avenue, a wide, low passage with a T-shaped cross section along the Ste. Genevieve—St. Louis contact. The walls are obscured nearly everywhere by banks of sand and gravel deposited by the original stream. The gravel consists of white quartz pebbles weathered out of Pennsylvanian conglomerate that once capped Mammoth Cave Ridge. The sand could have come from any of the sandstone formations that overlie the limestone. In places, fissure-like solution pockets extend upward into the ceiling along joints **(Fig. 23)**. There are many scallops in this passage—in fact, the "leopard" in Figure 23 is named for the many shadows formed by scallops, which look like the spots of a leopard (if one's imagination is up to the task). Because of great turbulence at this point when the passage was still active, it is difficult to tell the original direction of water flow. However, sand on the floor contains cross beds that indicate water movement in the direction of the tour, so the water really did flow upward in this area, and Sparks Avenue therefore formed below the water table. Upward flow is common in parts of most caves, but far less so in the prominently bedded limestones of Mammoth Cave.

7. Mammoth Dome

Sparks Avenue leads to the impressive Mammoth Dome (**Fig. 24**), one of the tallest vertical shafts in Mammoth Cave, 192 feet high (58.5 m). It extends from about the Reelsville unit at the top, through the entire Ste. Genevieve Limestone, and 29 feet (8.8 m) into the St. Louis Limestone. The top of the St. Louis lies 7 ft (2.1 m) below the public trail.

Figure 24: Mammoth Dome. Note the solutional rills (flutes) in the walls formed by a periodic waterfall. During heavy rainfall there is a strong shower in this shaft that sprays the entire observation deck. The Ste. Genevieve—St. Louis contact is located below the horizontal notch in the wall just below the level of the walkway.

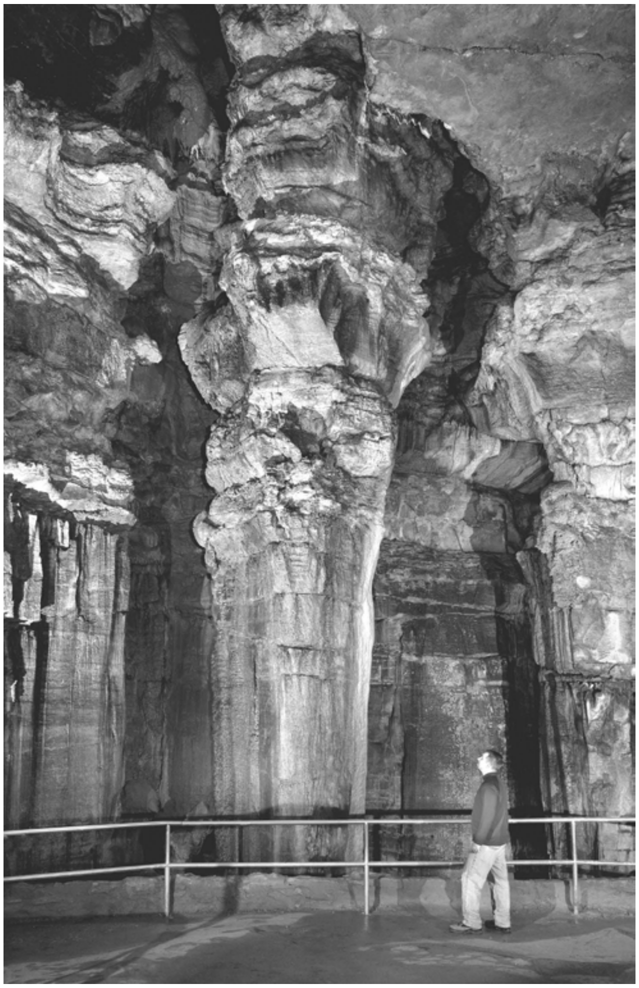

Figure 25: The Ruins of Karnak, in an alcove of Mammoth Dome, consists of solutional pillars of the Fredonia Member (Ste. Genevieve Formation) capped by beds of Spar Mountain and Karnak. (See stratigraphic column, Fig. 4).

Note the difference between the gray Ste. Genevieve and the brownish St. Louis. The thick-bedded, coarse-grained, highly fluted bottom bed of the Ste. Genevieve contrasts nicely with the thin, shaly, dolomitic beds of the St. Louis. Incoming water sprays from the top of the shaft and filters out through rocks that choke the floor. During wet weather the trickle becomes an impressive waterfall. Its source is apparently a sinkhole at the edge of Mammoth Cave Ridge, not directly above the dome.

Mammoth Dome is part of what might be called a shaft complex. Instead of a single pit, several sources of water have formed a maze of interconnecting shafts and canyons. Several canyons open from the walls of the shaft, and, by peering straight up through a haze of descending water drops, we can see a narrow, wiggly canyon at the very top that supplies the water.

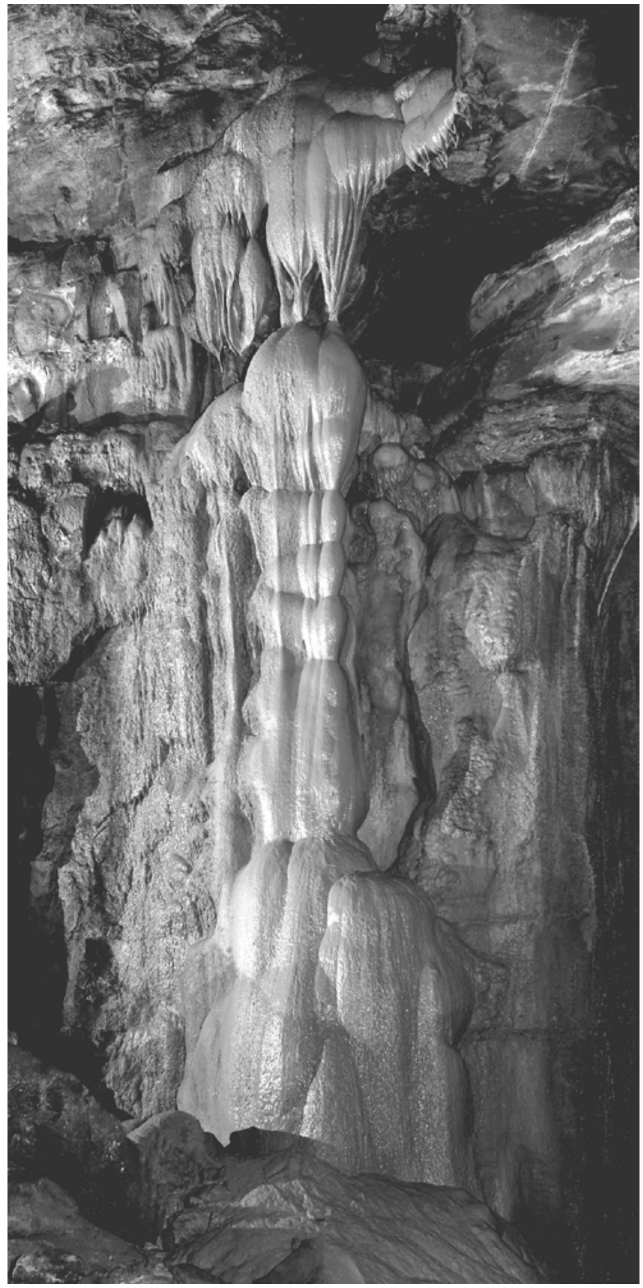

Figure 26: Flowstone cascade at the far western end of the Mammoth Dome complex.

Climbing the stairs out of Mammoth Dome brings us to a tall room lined by openings to other shafts and canyons. To the left are the Ruins of Karnak, which consist of massive pillars of the Fredonia Member of the Ste. Genevieve sculpted by descending water (**Fig. 25**). At the very top of the pillars is three feet (one meter) of the dull gray, granular Spar Mountain Member, overlain by a flat ceiling formed by the base of the more resistant Karnak Member. Early explorers were fond of borrowing names from antiquity and mythology. The Ruins of Karnak are

Figure 27: Metal staircase leading from the Ruins of Karnak to Little Bat Avenue at level B2. The beds at the head level of the climbers is the Karnak Member of the Ste. Genevieve Limestone.

named for the similar-looking ancient ruins near the village of Karnak on the banks of the Nile River in Egypt. However, the Karnak Member (the rock bed), is named for a small town in southern Illinois where the rock was first studied. Oddly, the town is also named for Karnak in Egypt. Both names coincide here in the cave simply by chance.

Note the white calcite deposit ("flowstone") ahead of us near the ceiling, and the pillar of golden flowstone nearby (**Fig. 26**). These were formed as the result of water trickling down through the overlying soil and then directly into the limestone. The high CO_2 content acquired by the water as it seeps through the soil has been mostly consumed by limestone dissolution. As the remaining CO_2 escapes into the cave air the dissolved limestone becomes supersaturated and precipitates calcite as flowstone. This deposit partly covers the walls of older shafts, which formed when the water originally passed through sandstone before encountering the limestone. The change in water chemistry from dissolving the shafts to precipitating the flowstone is a visible indication of the erosional retreat of the sandstone at the top of the ridge.

8. Return to the surface

By now we are well aware of the most striking part of the room—a massive metal staircase that leads almost to the top of Mammoth Dome (**Fig. 27**). The view is spectacular, at least as underground views go. But for those who dislike heights, it is best to focus instead on the steps ahead, following another person. The tour leaves the metal staircase at the shaly recessed base of the Joppa unit, but continues

Figure 28: Little Bat Avenue leads straight into Audubon Avenue at level B1 (shown here). From here it's a short walk to the cave entrance. The feeling of open space is enhanced by the fact that most of our tour has been through relatively small passages—but those are best for viewing the geology.

its ascent along a straight staircase through the Joppa to a final overlook into Mammoth Dome. Pause here to peer downward! The trail doubles back into a dry upper-level passage, Little Bat Avenue. This is a tubular passage at level B2, which originally drained water into Audubon Avenue long before Mammoth Dome formed. Little Bat Avenue follows the contact between the Aux Vases and Joppa Members of the Ste. Genevieve. The Aux Vases (upper part of the passage) is unusually thin here, consisting of only 1.7 feet (50 cm) of dark-gray, granular limestone. The underlying J2 unit is thick-bedded, fine-grained dolomitic limestone that forms rather smooth walls. We have seen these beds before, in the Main Cave, but not so clearly. The tube suddenly opens into the great void of Audubon Avenue (**Fig. 28**).

In this part of the cave, which has been explored for hundreds of years, there would seem to be little chance for further discoveries. But in the past 15 years, three major passages have been discovered by cavers in the Park Service and Cave Research Foundation. They noticed an inconspicuous hole behind breakdown in Audubon Avenue, which led to a large passage used extensively by early Indians and which apparently had lain undisturbed for thousands of years. It does not contain major artifacts, but the traces of mineral excavation and tool-making are valuable to archeologists. Later they discovered a similar passage at a lower level, and still later they explored and mapped a wet crawlway at the bottom of a 40-foot shaft containing an active waterfall, not far from Ruins of Karnak. It opened into a meandering river passage with a bare bedrock floor interrupted by several waterfalls. Exploration ended at a deep water-table pool that filled the passage at the level of Green River. So even the well-known parts of Mammoth Cave are still revealing surprises.

Audubon Avenue leads directly to the Rotunda, to complete a long and intricate loop through the cave. The tour exits through the Historic Entrance.

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