Mid- to Late-Miocene hypogene speleogenesis tied to the tectonic history of the central Basin and Range Province, USA

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Abstract: Twenty-five caves displaying evidence of hypogene speleogenesis in White Pine County, Nevada, were studied between May 2022 and October 2023. Results demonstrate that the central Basin and Range Province is a major hypogenic cave region with speleogenesis dating back to the Middle Miocene. The U-Pb radiometric dates of cave mammillaries obtained so far cover a wide span of time, ranging between 14 Ma to 2 Ma. Tectonic shearing along the Snake Range Décollement up to about 22 Ma probably brackets the maximum age of speleogenesis. Thus, speleogenesis began between 22-14 Ma, which predates most of the Basin and Range extensional tectonism of the Late Miocene. Robust dates for the common mammillaries in the region have been hard to obtain mostly due to Pb contamination. There are elevated levels of Pb throughout the area, likely due to mineralized fluids associated with the décollement. While 11 mammillary samples have been assessed for U-Pb dating viability, four contained too much Pb for analysis. Hypogenic features in these caves include mammillaries, tilted folia, bubble trails, cupolas, ceiling vents/tubes, floor vents, acid lake basins, pseudoscallops (cusps), megacusps, and boneyard. A common and newly identified feature of these caves is extensive secondary deposits of a complex mixture with silt-sized calcite and quartz grains. Some quartz grains have calcite overgrowths, suggesting authigenic growth. We named these lithified, and very porous, deposits “calc-siltite”. Sulfuric acid speleogenesis (SAS) has been clearly demonstrated in only one cave, Lehman Caves, but is strongly suspected in at least four other study sites (Old Mans, Cathedral, #041709-NS-012, and #LC01 caves). However, the great antiquity of these hypogenic caves means that they have probably experienced climatic and surface geomorphologic changes resulting in extensive alterations by epigenic groundwater. The evidence specific to demonstrating SAS processes may have been removed or covered by later epigenic activities.

Keywords: Cave mammillary, calc-siltite, SAS, U-Pb dating, pseudoscallops, folia


INTRODUCTION

The karst terrain in White Pine County, Nevada, is among the most remote in the contiguous United States and one of the last regions mapped for surface topography and geology (Fig. 1). Most of the caves in this region are less than 100 m long and have limited relief. Lehman Caves (the proper name is plural although it refers to a single cave system with only one natural entrance) has been recognized for over a century as an outstanding cave, mostly because of its abundance of cave shields, turnips, and other calcite speleothems. A National Monument was declared in 1922 for the surface (2.59 km²) overlying the cave. The US Forest Service initially managed the cave and provided public tours. The National Park Service took over management in 1933. In 1986, the monument, including Lehman Caves, was merged with 312 km² of Forest land to become Great Basin National Park (GRBA). Despite this designation as a national park,
the cave and surrounding area have received only minimal attention from the scientific community.

The first geologists to study caves in east-central Nevada were from California in the late 1950s and early 1960s (Lange, 1958; Moore, 1960), when our understanding of hypogenic speleogenesis was primitive and cave origin was always interpreted as a “top-down” process. Over the next five decades, very limited geologic investigations in Nevada took place, and the National Park Service generally interpreted Lehman Caves as a product of epigenic processes, although staff members occasionally opined that there may have been a geothermally driven, hypogenic component of speleogenesis. In 2016, the National Speleological Society held their annual convention in the region, and knowledgeable cavers and speleologists visited Lehman and other nearby caves. They were impressed that many of these caves had hypogenic origins based on observations of hypogene speleogenesis features that are well described by Klimchouk (2007) and Klimchouk et al. (2017). Comments like these and a thorough review by the Park staff while they were writing a comprehensive cave management plan about seven years ago prompted federal cave managers to seek scientists and funding to study their caves. Significant funding became available in 2022 (Baker & Powell, in press), and the Wild Caves Project has immensely improved our understanding of caves in White Pine County.

Hypogenic speleogenesis was the second and most prevalent of five identified processes that contributed to cave development in this area (Hose et al., 2024). This paper focuses on the hypogene (or partially hypogene) caves, which resulted from one or more of three progressions: 1) Most caves in the region were originally hypogenic and developed in the Miocene; 2) The second most common type, prevalent in the Northern Snake Range, formed as open fissures shaped by tensional tectonic movements along high-angle rotational faults, probably between 17-8 Ma. Many of these “tectonic” caves were further opened by hypogenic solvents rising through the fractures and many were filled with mammillaries to form calcite veins along the fault; 3) The third most common type of speleogenesis in these mountains is epigenic, stream caves, but most of these have evidence of earlier hypogene speleogenesis.

The Wild Cave Project explored and made multidisciplinary inventories of 15 caves in Humboldt-Toiyabe National Forest and 28 caves within GRBA. One additional cave from adjacent Bureau of Land Management land (Indian Burial Cave) is included in this report because of important and informative data, but it was not part of the Wild Cave Project. From this investigation, 25 caves appear to have hypogenic origins and at least three of these caves formed along ancient open joints. Four or five of the hypogenic caves later captured streams that greatly modified them.

Agency management concerns led to usage of official agency identification numbers for some caves. While the locations are always accurate, they are not precise.

**GEOLOGIC SETTING**

Neoproterozoic to Permian strata dominate the Snake Range of easternmost-central Nevada (Fig. 2). Multiple deformational episodes have metamorphosed, deformed, and disrupted the continuity of the carbonate-rock section. The sedimentary sequence...
was intruded by plutons of Jurassic (160–155 Ma),
Cretaceous (110–90 Ma), and Cenozoic (36–28 Ma)
ages (Lee & Van Loenen, 1971; Lee et al., 1981; Miller
et al., 1999). Local magmatism occurred as part of an
episode of widespread, caldera-forming volcanism that
migrated southward across the Great Basin between
43–20 Ma (Armstrong & Ward, 1991; Brooks et al.,
1995), resulting in plutonism and eruption of thick
lava flows and tuffs in east-central Nevada during the
late Eocene and early Oligocene (Gans et al., 1989).

A low-angle, east-dipping detachment fault, the
Snake Range Décollement, separates a lower plate
of deformed and metamorphosed Cambrian and
Precambrian quartzite, mylonite-marble, and schist,
from an upper plate of highly faulted, generally
unmetamorphosed upper Paleozoic rocks (Miller
et al., 1983). The décollement formed in the Eocene to
Oligocene (Miller et al., 1983) and accommodated
tens of kilometers of top-plate-to-the-east offset
(Bartley & Wernicke, 1984; Gans et al., 1985; Lee
& Sutter, 1991; Long et al., 2022). A previous paper
(Hose et al., 2021) proposed a maximum age of 17
Ma on the assumption that speleogenesis had to
post-date cooling and extension-related cooling
continued until at least 17–15 Ma (Miller et al., 1999).
However, the late-stage cooling is interpreted by
Gans et al. (1985) to post-date ducile stretching and
mylonitization. Lee et al. (2017), using $^{238}$U-$^{206}$Pb zircon
ages, bound the timing of ducile extension between
37.806 ± 0.051 Ma and 22.49 ± 0.36 Ma, hence a more
defendable maximum date for speleogenesis is likely
22 Ma. Hypogenic caves formed in both the upper and
lower plates.

After the décollement event, the area was cut by
steeply dipping normal faults in Miocene time. This
resulted in uplift of the Snake and Schell Creek Ranges
and relative dropping of the Snake Valley to the east
of the Snake Range, Spring Valley between the Schell
Creek and Snake Ranges, and the Steptoe Valley to
the west of the Schell Creek Range (Figs. 1 and 3;
Miller et al., 1999; Rowley et al., 2017). A regional
episode of rapid extension about 17 Ma ago (Miller
et al., 1999; Stockli, 2005; Colgan & Henry, 2009),
early in the formation of the present Basin and Range
physiographic provenance, resulted in most of the
uplift and exposure of the Snake and Schell Creek
Ranges. A Basin and Range-related, fault-bound
basin separates the Southern and Northern Snake
Range (Miller et al., 2023).

Alpine glaciation carved the Southern Snake Range
and left remnant cirques, arêtes, and moraines during
the Pleistocene. The increased moisture from the
surface deposited extensive secondary speleothems,
particularly in Lehman Caves, and commonly
camouflaged or destroyed evidence of original
(hypogene) speleogenesis.
SOUTHERN SNAKE RANGE CAVES

Lehman Caves

Located in the northeast part of Great Basin National Park, Lehman Caves is on the east flank of the Southern Snake Range. Its elevation of 2,080 m asl is about 500 m above the adjacent Snake Valley to its east (Fig. 1). The cave is about three kilometers long and the largest cave system discovered in Nevada (Fig. 4).

Lehman Caves

Great Basin National Park

Fig. 3. Idealized cross-section of east-central Nevada modified after Gans et al. (1985) from Gébelin et al. (2011).

It formed in Pole Canyon mylonitic marble at the top of the lower plate of the Snake Range Décollement. Foliation is near vertical throughout the cave, but the cave profile is nearly horizontal. It has abundant speleothems that make it one of the most decorated caves in the United States. In the past, geologists and the Park generally interpreted the cave as a product of epigenic processes acting after mountain building, even in recent unpublished reports such as Lachniet & Crotty (2017). Their conclusion was derived from the cuspate indentations in the walls throughout the cave that were interpreted as cave scallops. These features have since been re-identified as pseudoscallops (DuChene & Hose, 2020; Hose et al., 2021) or “cusps”, using the terminology of De Waele et al. (2024). However, the combined recognition of Lehman’s hypogene origin and the documented end of most relative uplift of the Snake Range by 8 Ma led Hose et al. (2021) to state that Lehman Caves is most likely more than 8 million years old.

Abundant dripstone, flowstone, and other secondary, calcite speleothems make it difficult to study the cave’s genesis. Radiometric dating of stalagmites revealed one stalagmite to have an age of 2.2 Ma (Lachniet & Crotty, 2017), providing a minimum age for speleogenesis. However, the fortuitous placement of a nearly impermeable cap of quartzite over the northern half of the cave allows a glimpse of the cave’s likely appearance prior to the extensive Plio-Pleistocene deposition of speleothems. In particular, the Gypsum Annex is markedly different from the southern, tourist-trail part of the cave.

Fig. 4. Map of Lehman Caves.
While passages are clearly developed along fractures, nearly all passages end abruptly. Cupolas and cupola chains are abundant. The only natural entrance is a cupula breached by surface erosion with no evidence of a stream entering or exiting the cave. Cupolas, bubble trails (Fig. 5), ceiling channels, half-tubes along the ceilings, pseudoscallops (cusps), and perhaps keyhole-shaped passages showing no association with stream activity provide strong evidence of hypogene speleogenesis (De Waele et al., 2024). Walls in the Gypsum Annex are mostly coated with sub-aerial crusts of calcite and gypsum (Fig. 6a). Metatyuyamunite is commonly associated with sulfuric acid speleogenesis (SAS) (Polyak & Mosch, 1995; Polyak, 1998; Onac et al., 2001). It is scattered within the crusts throughout the passage (Hose et al., 2021; Havlena et al., 2024; Fig. 6b) and yielded a uranium-thorium date of ~170 ka.

Several cave trays hang above coralloidal stalagmites in a notable constriction within the Gypsum Annex passage (Fig. 6a). Trays are flat-bottomed radiating clusters of aragonite or calcite, first described and explained by Martini (1986) as speleothems dominated by evaporation rather than CO₂ degassing. If water dripping through the center of a tray has not yet attained calcite saturation, drips hitting the floor will splash and evaporate further, creating a cluster of coralloids around the impact point. As these extend upward, a coralloidal stalagmite with hollow center may grow up around the drip shaft. If the stalagmite touches the bottom of the parent tray, contact with undersaturated water above will inhibit further upward coralloid growth, leaving a narrow horizontal gap between the tray and stalagmite.

Trays do not always develop matching contact-free stalagmites, but where they do, they are definitive evidence of the tray process of temperature-gradient-driven atmospheric condensation/evaporation cells, which are a subaerial aftermath consistent with hypogene speleogenesis.

The most compelling evidence of SAS is at the junction between the two branches of the Gypsum Annex (Fig. 4) where remnants of an acid lake basin are displayed (Davis, 2000; Fig. 6d). The prominent rillenkarren on upfacing slopes, cusps on overhanging slopes (and throughout the cave), corrosion notches, a “corrosion table” floor (De Waele et al., 2024), and high steep walls with a rounded ceiling and half-tubes above provide compelling evidence of SAS (De Waele et al., 2016; Hose et al., 2021). The characteristic steep-walled feeder channel is almost certainly filled and covered by crusts that have sloughed off the walls and ceiling.

Acid lake basins were first described by Davis (2000) as sites above a source vent of corrosive fluids and/or gases. Corrosion notches undercut the adjacent walls. Upward-facing slopes above the water line may be grooved by fields of rillenkarren. Hose et al. (2021) documented several active acid lake basins (which they referred to as “acid pools”) in Cueva de Villa Luz, Mexico. Each site in Villa Luz has sulfidic, subterranean springs rising through steep-walled vents in the room’s floor, corrosion tables and notches, rillenkarren fields on upward-facing slopes, highly acidic gypsum paste covering etched (pseudoscallop) surfaces, and rounded ceilings (Fig. 7). Figure 6 in De Waele et al. (2024) shows a model acid pool basin. They state that this type of manifestation of corrosion tables and notches are exclusively developed in SAS cave, which agrees with our observations.

Numerous encrusted, coralloidal stalagmites are throughout the Lehman Caves (Fig. 6c). Coralloidal stalagmites, paired with trays, are interpreted by us as products of geothermally driven atmospheric condensation/evaporation speleothem growth, and are consistent with earlier SAS, but not compelling proof. They could have followed speleogenesis driven by hypogene, deep-sourced carbon dioxide.

While white crust lining the walls and floor of the Gypsum Annex is nearly ubiquitous, gypsum was detected in only about 60% of samples taken (Havlena et al., 2024). The rest were either calcite or high Mg-calcite with abundant silica. The δ³⁴S of gypsum was heavy compared to other reported hypogenic caves, ranging from +9.7 to +26.1‰. Havlena et al. (2024) suggest that the most likely explanation for the secondary mineral deposits in the Gypsum Annex is precipitation during later surface infiltration. This is consistent with the relatively young age of the metatyuyamunite.

There is abundant evidence of hypogenic speleogenesis throughout the cave but the only evidence of a sulfidic environment remaining in the southern part of the cave are localized pseudoscallops.
(cusps). It is likely that Plio-Pleistocene meteoric infiltration into all parts of the cave not protected by the meta-quartzite cover rock removed gypsum or covered other evidence of SAS. On the other hand, hypogenic waters entering these parts of the cave may have lacked sulfidic components.

Among other currently unexplained oddities are several exposures of a massive, white, tightly cemented rock with drip-formed drillholes under flowstone. One drillhole is 42 cm deep. This massive deposit shows no internal structure and is made up of nearly pure calcite with traces of silica (Fig. 8a, b). The material was a soft sediment at the time the dripholes formed and probably lithified into a solid rock during the Plio-Pleistocene when meteoric waters infiltrated and precipitated the extensive flowstone and other calcite speleothems. The nature of the original soft sediments is unknown but suspected to have been a calc-siltite deposit. Calc-siltite is a complex mixture of silt-sized calcite and quartz grains common in hypogenic caves of the region. The sediments are generally lithified into highly porous, clumpy floor and slope deposits. Calc-siltites are discussed in more detail in the Old Mans Cave section below.

Fig. 6. Hypogenic and SAS evidence from the Gypsum Annex in Lehman Caves. a. Sub-aerial crusts of calcite and gypsum in a keyhole-shaped passage in Lehman Caves. Photo by Dave Bunnell; b. Yellow metatyuyamunite crystal aggregates disseminated in the matrix of a probable calcite and dolomite or gypsum crust. Note that the aggregate sizes are less than 0.5 mm in diameter; c. Encrusted, coralloidal stalagmites underlying cave trays. Blue, sub-horizontal lines mark the base of cave trays. Photo by Dave Bunnell; d. Ancient acid lake basin near the junction of the two main branches in Gypsum Annex. Rillenkarren were formed by streaming and dripping sulfuric acid on the upward-facing walls at the time of active speleogenesis. Pseudoscallops formed under the sulfuric acid-soaked gypsum paste on the downward-facing slope under the overhang of the corrosion notch. The term “pseudoscallops” has been historically applied to “cusps” in Lehman Caves (DuChene & Hose, 2020; Hose et al., 2021). Photo by Dave Bunnell. Figure from Hose et al. (2021).

Fig. 7. a. Schematic cross-section of the Yellow Roses Room, an active acid lake basin in Cueva de Villa Luz, Mexico (after Hose et al., 2021); b. Photograph of the Acid Pool Room, another active acid lake basin in Villa Luz. The fish are typically about 3-cm long. Photo by Stephen Alvarez.
Lehman Annex and Root caves

Lehman Annex and Root Caves, near Lehman Caves, display strong evidence of hypogenic speleogenesis overprinted by much younger epigenic secondary deposits, including calcite-covered roots, dripstone, flowstone, rimstone dams, and shields. Evidence of hypogenic origins includes bubble trails, ceiling channels, cupolas, ceiling vents, and minor boneyard (megacusps). Like their neighbor Lehman Caves, their mylonitic marble bedrock is very densely fractured, which provided abundant secondary permeability. The fractures likely resulted from lithostatic stress release following the Snake Range Décollement event and the subsequent Basin and Range uplift and extension. The caves are within and near the top of the lower plate, below the detachment fault. Also, like Lehman Caves, dissolution of these smaller caves was strongly controlled by these fractures.

Of special interest is the presence of calc-siltite in Lehman Annex. This cave also has massive, structureless gypsum up to 60 cm thick on the cave floor at one place. The origin of these sediments is unclear. Perhaps it is a remnant of SAS and represents gypsum paste that sloughed off the walls and ceiling during active SAS. Mammillary-looking speleothems appear to be in a localized pool along with possible folia at the back end of the cave (Fig. 9). We interpret them to not represent a regional water table.

Indian Burial Cave

Other caves in the Snake Range have not experienced the intensive overprint of later calcite speleothem growth as Lehman Caves, and they provide valuable insight into the speleogenesis of the region. One particularly interesting, nearby site is Indian Burial Cave, which is now permanently closed to all visitation, including research, and has not received a detailed geologic inventory or investigation.

Fig. 8. a. Massive, white calcite with trace amounts of silica underlies flowstone deposits throughout Lehman Caves. It is exposed where the flowstone has been breached by commercial trails; b. Apparent drillholes in the massive, white calcite in Lehman Caves demonstrate that the original sediments were soft and unconsolidated prior to deposition of the flowstone, which now coats the drillholes. Blue line encircles a bisected drillhole. All scales added to photographs in this paper are divided into centimeters, including the single black bar in figure 8b, unless otherwise identified.

Fig. 9. Apparent pool mammillaries appear to have shelves that grew as the top of the water rose and fell in Lehman Annex Cave. These features have been interpreted to be folia (Green, 1959). Since mammillaries and folia are closely related and commonly develop in the same pools, drawing a line distinguishing one from the other, in some cases, is subjective. Note old calcite rafts in the upper right. Width of photo is ~60 cm. Photo by Jean Krejca.
Indian Burial Cave formed within the Middle to Late Devonian Guilmette Formation (McGrew & Miller, 1995), a limestone that is extremely fractured at the cave site and riddled with an extensive web of narrow calcite-filled veins cementing the cracks. The cave is relatively small (160 m long and 38 m deep) and located in the eastern foothills of the Southern Snake Range (Fig. 1) at an elevation of 1,725 m asl. It is the lowest known cave in the region.

The entrance room formed at the intersection of at least three near-vertical faults. Two of the faults trend approximately east-to-west and one strikes about north-south. A recent geologic map of the area (Rowley et al., 2017) shows north-northwest-trending normal faults on each side of the elongated, narrow limestone hill hosting Indian Burial Cave, suggesting that the hill is a small horst elevated by Basin and Range extensional faulting. The north-south-trending fault that passes through the entrance pit is likely a high-angle, normal fault that formed during the Basin and Range extensional phase (~17-8 Ma).

The cave has ample evidence of hypogenic speleogenesis, including bubble trails, keyhole passage (with no evidence of streams), cupolas, and ceiling vent tubes. Under a thin calcite crust on the entrance chamber walls is porous punk rock, calc-siltite (Fig. 10a). Some gypsum crust was also noted but there is no clear evidence of SAS.

The most interesting feature of Indian Burial Cave is tilted folia covering older mammillaries (Fig. 10b). Mammillaries formed near the top of an aquifer filled with slow-moving, super-saturated water before the adjacent valley was lowered to below the elevation of the cave. Most of the caves in this discussion are near the eastern edge of the range, and therefore developed before the floor of the Snake Valley dropped lower than the cave passages of the Northern Snake Range. These conditions existed before 10 Ma. Recognizing that these features had to be deposited before local mountain building ceased, we used U-Pb dating that established the age of the Indian Burial mammillary at 12.70 ± 0.75 Ma (Fig. 10c). This date provides a minimum age of about 13 million years for the cave. The extensive shearing and fracturing during the décollement event provide a likely maximum age of the cave of 22 Ma.

Snake Creek and #SC-04 caves

Two caves in the Snake Creek drainage within Great Basin National Park are within the Ordovician Notch Peak Formation (a mixed limestone-dolomite unit) and appear to have formed by hypogenic processes. Bedding outcrops within the caves are undulating and sub-horizontal. The linear morphologies of the caves suggest that fractures controlled their development. The cave entrances are at about 2,050 m asl.

The best evidence of hypogenic origins of these caves is numerous cupolas in cave #SC-04 and cupolas, bubble trails, boneyard, and a couple of ceiling vents in Snake Creek Cave. Mammillaries coat the walls in much of Snake Creek Cave. The general outlines of the passages are compatible with hypogene speleogenesis, and there is no evidence of epigenic
speleogenesis. Nor is there evidence to dismiss an epigenetic origin nor unequivocally confirm the hypogene speleogenesis. We attempted U-Pb dating of a Snake Creek Cave mammillary sample but it contained too much lead for a successful date. There are also calc-siltite deposits in both caves.

**Cave #BC-05**

Formed in the Middle Cambrian Pole Canyon marble along strongly developed fractures, Cave #BC-05 is a single-chamber that appears to have taken flowing water from the nearby stream and was likely once a chamber within the nearby Baker Creek system. Two intersecting bubble trails lead into a ceiling vent, providing evidence of an initial hypogenic origin (Fig. 11).

**Baker Creek cave system**

The Baker Creek Cave System has over 1,300 m mapped with a vertical relief of about 73 m and a maximum elevation of about 2,190 m asl. This cave system has a complex history of speleogenesis that includes, in chronologic order, hypogene speleogenesis (likely in the Miocene), epigenic invasion and accompanying deposition of extensive stream-carried sediments, and then crevasse entrances opening through mass wasting.

While the cave system currently carries a part of adjacent Baker Creek, there is abundant evidence of early hypogenic speleogenesis: bubble trails, cupolas, subtle boneyard, floor vents, and classic passage shapes. There is no indication of SAS, although the later invasion of meteoric waters may have covered or destroyed the evidence.

**Cave #NC-01**

Cave #NC-01 is a small (just under 50 m long), stream resurgence cave at about 2,335 m asl in Great Basin National Park. Dominantly epigenic, the cave has likely bubble trails and cupolas in the enlarged and rounded higher level of the passage (Fig. 12a). A possible small mammillary deposit has been reported in the upper level. Unusual horizontal calcite deposits just above stream level may be folia (Fig. 12b).

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Fig. 11. Bubble trails merge at a ceiling vent in BC-05 cave.

Fig. 12. a. The upper level of #NC-01 Cave has rounded walls and ceiling of a phreatic, possibly hypogenic tube and displays bubble trails, cupolas, and a small, possible mammillary deposit. The active stream passage immediately below is a narrow but passable canyon; b. Secondary laminations on the wall above the stream in the lower passage of cave #NC-01 may be incipient folia. Scale is 10 cm long.
**Adit caves**

#LC01 and #LC02 are natural, entrance-less, hypogenic caves that were intersected by a mine adit on the west side of the Southern Snake Range. The mine originally targeted tungsten and beryllium and was abandoned in the years following World War II (Unrau, 1990). The mine intersects two naturally occurring karst pockets formed along fault/fracture systems, which had no previous, humanly navigable connection with the surface.

#LC01 and #LC02 (Fig. 13a, b) caves are small (~16 and ~10 m long, respectively), decorated fissures about 300 m and 600 m, respectively, from the surface. Cave #LC02 has a small pool of cold water, presumably infiltrated from the surface.

Passage morphologies, the lack of natural entrances, and probable gossan deposits within cave #LC01 and in the entrance chamber of cave #LC02 are indicators of hypogenic processes. The probable gossan supports a hypothesis of SAS. These passages probably formed contemporaneously and from the same fluids as the mineral deposits exploited by the adjacent mine. Metallic sulfides were most likely deposited initially, followed by lowering of the water table which allowed oxygenated meteoric water to contact the ore body. This allowed oxygenated water to react with sulfide deposits releasing sulfuric acid and forming deposits of limonite. The sulfuric acid then reacted with the limestone bedrock.

Although small and lacking much in the way of specific, stand-out features, these two cave passages are important because they do not have thousands of years of packrat scat or accumulated dirt and dust as the other hypogenic caves in the region. They also have not had a lot of human traffic, so they represent relatively undisturbed examples of hypogenic caves in the Pole Canyon Limestone. Their presence suggests that there may be many more entrance-less, hypogenic caves in the Snake Range.

**Caves #LP06 and #LP04**

A pair of caves formed by hypogenic processes are high on an alpine ridge in Great Basin National Park. Both caves, #LP06 and #LP04, and the gully between them have abundant mammillaries, which suggests that these caves along with the intervening gully were once one cave system. The two caves, like many hypogenic caves, are single chambers with rounded walls and ceiling, abruptly ending side passages, and ceiling vents. Cave #LP06 extends about 7 m in and is about 12 m wide. Cave #LP04’s plan dimensions are about 13 x 6 m. These rooms may have been side chambers of a larger system that encompassed the adjacent gully. The complete lack of stream deposits or other epigenic speleogenetic products within the caves provides strong evidence that they formed from hypogenic processes. While the chambers are small, their present location at about 3410 m above sea level makes these caves particularly informative. They are likely very old and developed before mountain building ended. An attempt to date the age of mammillary deposit from these caves produced a possible age of around 6 Ma, but the isochron results are not robust and the date, of course, only represents the minimum age of speleogenesis. This relatively young age might be due to complexities related to the sample causing subsample scattering of results. Considering sample complexity, an age of 5.4 ± 1.4 Ma was generated (Fig. 14).
Miocene hypogene speleogenesis
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Fig. 14. $^{238}\text{U}/^{206}\text{Pb}$ vs. $^{204}\text{Pb}/^{206}\text{Pb}$ Tera Wasserburg concordia (model 3) age for sample NV-LP06-1 from Cave #LP06. The isochron and age were generated using IsoplotR (Vermeesch, 2018). The initial $^{234}\text{U}/^{238}\text{U}$ activity value was assumed to be $2.0 \pm 0.2$.

Fig. 15. a. Dated Cathedral Cave sample came from the radial crystals on the wall of the cave; b. $^{238}\text{U}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$ Tera Wasserburg concordia (no model) age for sample NV-Cathedral from Cathedral Cave. The isochron and age were generated using IsoplotR (Vermeesch, 2018). The initial $^{234}\text{U}/^{238}\text{U}$ activity value was assumed to be $2.0 \pm 0.2$.

NORTHERN SNAKE RANGE CAVES

Smith Creek Canyon caves

The caves in Smith Creek Canyon, an east-west intermittent drainage on the eastern flank of the Northern Snake Range, show abundant evidence of hypogenic processes with no suggestions of stream flow or other epigenic input beyond some flowstone and dripstone. The six caves (Cathedral, #041709-NS-017, #041709-NS-018, Smith Creek, Council Hall, and Ladder) that the Wild Cave Project team visited in Smith Creek Canyon clearly formed through hypogenic processes. Further up the Smith Creek Canyon walls is Cave #014709-NS-017. These caves have remnants of mammillaries that formed near the top of a slow-moving, super-saturated aquifer before the steep-walled Smith Creek Canyon was carved below their elevations and before the Snake Valley dropped significantly below their passages. These conditions likely occurred before 10 Ma. Some U-Pb dates from cave mammillaries in the Northern Snake Range are older than 11 Ma. Speleogenesis had to post-date the Snake Range Décollement event 38-22 Ma ago, providing a maximum age for cave development.

Although speculative, the steep-walled morphology of the canyon and the trend of the cave passages on both sides of the canyon suggest that Smith Creek may have once been a major, underground trunk conduit passage that eventually drained the aquifer within the slowly rising Northern Snake Range into the incipient Snake Valley. If so, surface erosion ultimately breached the roof of the main passage, and the many caves, shelters, arches, and other karst features in the canyon walls are the remains of tributary passages in a major, ancient, phreatic cave system.

Cathedral Cave

Cathedral Cave, the lowest elevation project cave in the Northern Snake Range, is a moderate-size, horizontal cave at 1,980 m asl with mammillaries preserved in alcoves and niches. Cathedral Cave has abundant evidence of a hypogenic origin, including numerous cupolas, a ceiling channel, boneyard and ceiling pendants, a distinctive keyhole-shaped passage cross-section, bubble trails, and ceiling vents. One area has apparent pseudoscallops and other characteristics of an acid lake basin (without the feeder tube), strongly suggestive of SAS. The highly desiccated deposit of mammillaries is consistent with a hypogenic origin. The general shape of the passages also fits this interpretation. The cave appears to have formed from pure hypogenic processes prior to subaerial condensation corrosion.

A speleothem, thought to be an extensively corroded mammillary (Fig. 15a), was dated by U-Pb techniques to be $2.21 \pm 0.14$ million years old (Fig. 15b). Although embedded in the wall, this date suggests that this ancient deposit may be some sort of speleothem other than a mammillary. Unfortunately, the more certain mammillaries are out of reach in cupolas and other ceiling alcoves.

Cave #041709-NS-017

This cave is a simple tunnel with a rounded ceiling, abundant cupolas, and ends abruptly. It has extensive mammillary deposits but its mammillaries have not yet been sampled or dated.
Cave #041709-NS-018
Cave #041709-NS-018 is the next higher cave in Smith Creek Canyon. It has well-developed boneyard, bubble trails, cupolas, rims, hollow coralloidal stalagmites, and trays. Iron-oxide-rich secondary deposits are common in the cave. These features suggest an SAS origin. There are also calc-siltite deposits, and coral pipes and silticles (first described in Lechuguilla Cave, New Mexico, USA, by Davis, 2000) have developed within the calc-siltite.

Mammillaries are abundant. One uranium-lead date of a mammillary from about 1,970 m asl provided a poorly constrained isochron of 13.9 ± 3.8 Ma (Fig. 16). This date fits a date from Discovery Cave (see section below) of 11.4 Ma but is dramatically different from the Council Hall Cave date (see below) of 4.2 ± 1.5 Ma in the same drainage.

Smith Creek Cave
About 1,980 m asl is Smith Creek Cave, another clearly hypogenic cave with abundant mammillary deposits that coat walls and ceilings throughout the entire cave. The cave exhibits extensive cupolas, ceiling channels, and ceiling vents. The ramiform passage outline also suggests hypogene speleogenesis. There is no evidence of SAS, but we saw no evidence to dispute such an origin. Mammillary samples have been collected but radiometric dating has not been attempted yet.

Ladder Cave
Ladder (~2,073 m asl) Cave, the highest elevation project cave in Smith Creek Canyon, is a tunnel passage with rounded ceilings, abundant cupolas, and abruptly ending side passages. It has some boneyard-type speleogens and several very large ceiling vents near the southern portion of the cave. Extensive mammillary deposits are severely corroded, but are typically preserved in cupolas and other niches. Mammillary deposits from this cave have not yet been sampled or dated.

Council Hall Cave
Council Hall Cave, at ~2000 m asl in Smith Creek Canyon, is a massive, single chamber (Fig. 17a) with a floor that has been extensively disturbed by archeological and paleontological investigations. The overall shape and size of the chamber suggest a hypogenic origin but there otherwise is little evidence within the cave of its speleogenesis. However, a large, upsloping tube passage adjacent to the cave, which surely was once a large ceiling vent connected to Council Hall Cave (Fig. 17b), supports the hypogenic interpretation.

Speleothems are limited. The most dramatic, and probably abundant, are cave mammillaries preserved in pockets high on the walls and as float on the floor. The wall samples are highly desiccated, and most are too high to reach for a sample. However, several float pieces on the floor are well formed and likely came out of the excavation pits. It appears that the chamber walls were almost entirely covered with mammillaries, but most have spalled off the walls or been extensively corroded. Burial in the sediments likely helped preserve the pieces that had fallen. A piece of mammillary was dated using U-Pb isotopes and gave a poorly constrained date of 4.23 ± 1.98 Ma (Fig. 17c). This is an unexpectedly young result.

CAVES IN OTHER DRAINAGES OF THE NORTHERN SNAKE RANGE

Old Mans Cave
Old Mans Cave to the south is on the east flank of the Northern Snake Range and known for its spectacular displays of boneyard/megacusps (Fig. 18a). Two obvious floor sources of corrosive gases at the back of the cave (Fig. 18b), abundant cupolas, and numerous ceiling tubes confirm its hypogenic origin. A possible
acid lake basin with corrosion notches, cupolas, boneyard, corrosion table, and a steep-walled (feeder?) fissure in the floor supports a hypothesis of SAS origin (Fig. 18c).

Calc-siltite

Extremely porous calc-siltite deposits are abundant in Old Mans Cave (Fig. 19a). Scanning electron microscope (SEM) examination revealed these deposits to be complex mixtures of silt-sized calcite and quartz grains (Fig. 19b). Some grains are rounded and thus transported either from the surface or, perhaps, from within the cave. The silica silt could be the insoluble residue from speleogenesis. Some of the quartz grains are overgrown by calcite (Fig. 19c), suggesting authigenic growth within the calc-siltite deposits. Some authigenic calcite has lithified the calc-siltite (Fig. 19a). This material comprises the core of several deposits of coral pipes throughout the cave (Hose & Strong, 1983) and makes up silticles (Davis, 2000). Old Mans Cave is one of two original type localities for coral pipes (the other is Mitchell Caverns, California.) A particularly large deposit of calc-siltite forms a mound in the lower part of the cave (Fig. 18d) and it is abundant throughout. We do not understand the origin of the calc-siltite deposits, although we suspect that they are related to corrosion residue. They are found in most of the hypogenic caves in east-central Nevada and may be the original material in Lehman Caves that was cemented by meteoric infiltration to form the massive, white material below the younger flowstone (Fig. 8). Caves with a strong epigenic overprint, like the Baker Creek system, may have previously had calc-siltite deposits that were removed or re-distributed by later epigenic processes.

Discovery Cave

On the east flank of the Northern Snake Range and at an elevation of ~2,260 m asl, the fascinating Discovery Cave holds an abundance of speleoo-didities and hypogenic features. The cave is a relatively short, dry cave with walking, stooping, and short easy crawling passage, abruptly ending side passages, and a nearly unparalleled concentration of unusual, spectacular speleothems (Fig. 18a) representing ancient, phreatic/hypogenic growth with more recent sub-aerial dripstone, flowstone, and efflorescent minerals. There is no evidence of epigenic speleogenesis nor of stream flow. Condensation-corrosion has been an important process in the cave, as well. Like Indian Burial Cave, tilted folia deposits cover mammillar deposits in Discovery Cave. Our U-Pb analysis demonstrated that calcite mammillary coatings are 11.41 ± 0.41 million years old (Fig. 18b). Hence, the cave itself must be older than 11 million and younger than 22 million years old.

Fig. 18. a. Boneyard (megacusps) in Old Mans Cave, Northern Snake Range, Nevada. Photo by Dave Bunnell; b. Apparent, sub-aerial site of rising, corrosive gases in predominantly calc-siltite floor sediments in the Vent Room in Old Mans Cave. Photo by Jean Krejca; c. Boneyard Room in Old Mans Cave has a deep, steep-walled floor slot (feeding fissure?), corrosion notches, a possible corrosion table under the extensive calc-siltite sediments, cupolas, rounded ceiling, and boneyard, which are suggestive of an acid pool basin and SAS. Photo by Jean Krejca.
Steeply east-dipping, listric normal faults are common in the Middle Cambrian limestone of the eastern flank of the Northern Snake Range. They typically have indeterminate offset and are interpreted to be Middle to Late Miocene, Basin and Range features. Many have open gaps between the curved hanging walls and footwalls with radial-crystal (mammillary-like) calcite fillings. The bedrock surrounding Discovery has particularly striking examples. Discovery and some other caves described in this paper are interpreted to have enlarged and developed along such an ancient open gap between fault walls. Once dissolution by hypogene waters stopped and the water table lowered, mammillaries coated the walls of the void, followed in some areas by folia deposition. Continued uplift tilted the previously horizontal folia to a dip of 6° to the west, likely the result of continued listric normal faulting along other fault planes.

Fig. 19. a. Calc-siltite deposits are in many of the hypogenic caves investigated in this study; b. SEM of calc-siltite deposits showing quartz and calcite silt. Note area of crystals growing together (arrow); c. SEM of calc-siltite deposits showing quartz silt with calcite overgrowths (arrows show underlying quartz). Also present are fine microbial filaments; d. A particularly large mound of calc-siltite in the lower level of Old Mans Cave. Photo by Kenneth Ingham.

Fig. 20. a. Quills are among the many unusual speleothems in Discovery Cave. The quills have grown over the mammillary deposits, and they are interpreted as sub-aqueous. In places, they seem to merge with the underlying mammillaries, which raises intriguing questions about how they might inform our understanding of the cave’s early, phreatic/hypogenic history. Photo by Dave Bunnell; b. $^{238}\text{U}/^{206}\text{Pb}$ vs. $^{204}\text{Pb}/^{206}\text{Pb}$ 3D isochron age for sample NV-Discovery from Discovery Cave. The isochron and age were generated using IsoplotR (Vermeech, 2018). The initial $^{238}\text{U}/^{234}\text{U}$ activity value was assumed to be $2.0 \pm 0.2$. 

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**Cave #041709-NS-012**

At about 2,700 m asl and east of the crest of the Northern Snake Range is cave #041709-NS-012, another small but intensely decorated cave with mammillaries. Cave #041709-NS-012 has evidence of hypogenic origin, including numerous cupolas, and nothing to suggest epigene speleogenesis or ever being a stream conduit. There is significant evidence that suggests SAS. Calcite overlying probable limonite and hematite (Fig. 21a, b), mammillaries coating apparent iron-oxide sediments (Fig. 22), possible rims, possible secondary quartz and chalcedony or opal (Polyak & Provencio, 2001; Polyak et al., 2016), possible secondary barite-celestite (Fig. 23), and the presence of a galena mine nearby (and topographically lower) all support the likelihood that this cave is the product of deep-seated, geothermally driven hypogene speleogenesis, and probably SAS.

This mineral assemblage is characteristic of oxidized sulfide ore deposits and, coupled with the known presence of nearby exploitable galena (lead sulfide), suggests that Cave #041709-NS-012 is in an area where base metal sulfides were emplaced. Metal sulfides, particularly pyrite, may have been present in the cave and were altered by supergene oxidation, which would produce sulfuric acid. If Cave #041709-NS-012 is in the zone of supergene enrichment, it could explain the unusual mineralogy (for a cave) and the indications of sulfuric acid dissolution.

Mammillaries in #041709-NS-012 are generally well-preserved, and their deposition occurred after the SAS dissolution of the cave. Unfortunately, an attempt to date a mammillary from the cave was not successful due to an overabundance of Pb contamination.

**Snake Canyon Cave**

High (2,839 m asl) in the Schell Creek Range (Fig. 1) is Snake Canyon Cave. On the west side of the range, a fracture opened due to Miocene Basin and Range extensional tectonism. The incipient cave appears to have been enlarged by hypogenic speleogenesis, although extensive spalling of the ceiling and resultant breakdown blocks on the floor have destroyed most evidence of its origin. The shape of the passage, which ends abruptly, and the complete lack of vadose or stream features along with one distinctive dome/cupola and mammillaries on the wall led to the conclusion that the cave is hypogenic. We attempted to date one mammillary sample but ICP analysis showed too much Pb.

**Ragged Cave**

Ragged Cave is high (2,350 m asl) on the east flank of the Schell Creek Range and currently serves as a resurgent spring cave. However, there is clear evidence that both hypogene and epigene speleogenetic activities have modified this cave. Cupolas are in the ceiling above the entrance chamber and a rounded “keyhole” feature in the passage leading beyond look phreatic (although not necessarily hypogenic). A deeply incised bubble trail and ceiling vents further into the cave also supports the hypothesis of an early hypogenic origin. However, the cave today intermittently carries a stream which has modified the floor. The cave is now in an epigenic phase of development.

**Black Dome Cave**

Black Dome and two smaller caves near the top of a knoll within the southern Ruby Mountains, in the
northwest corner of White Pine County, Nevada, likely developed from hypogenic processes. They are within a Tertiary jasperoid breccia and near a major (mostly gold) mining district. Black Dome has mammillaries, which we attempted to date but excessive lead prevented success.

**COMMON CHARACTERISTICS ON GREAT BASIN HYPOGENIC CAVES**

There are numerous characteristics common to most of the region's hypogenic caves (Supplementary Table S1). Bubble trails and cupolas have been identified in nearly all the caves discussed here. Mammillaries, some overlain by folia, are common although they are extensively corroded in many of the caves. Keyhole-shaped passages and half-tube ceilings are common, as are abrupt terminations of passages, all of which have no evidence of streams. Porous calc-siltite deposits have been described in about half of the caves. They are mostly made up of calcite silt, lesser quartz silt, and trace amounts of clay (Fig. 19b, c). Some of the passages in Lehman Caves have massive, featureless, white, secondary deposits of nearly pure calcite with traces of silica, which we hypothesize formed when meteoric waters infiltrated and cemented the previously loose sediments. A classic acid lake basin is present in the Gypsum Annex of Lehman Caves (Fig. 6d), while the Boneyard Room Old Mans Cave (Fig. 18c) and an area in Cathedral Cave have many of the characteristics of acid lake basins. Extensive condensation corrosion is common in most of the caves, as predicted by Dublyansky & Dublyansky (1998) for hypogenic caves in a desert environment.

It is not surprising, given the millions of years history of these caves, that some have been invaded by vadose water and heavily altered. Passages have undoubtedly been enlarged by streams and condensation corrosion. Surface water intrusion into the passages during the Plio-Pleistocene epochs resulted in extensive speleothem deposits, particularly in Lehman Caves.

**RESULTS: RADIOMETRIC DATING OF MAMMILLARIES**

The presence of hypogenic caves at high elevations in both the Northern and Southern Snake Ranges, along with tilted folia in two caves, prompted the Wild Cave Project to prioritize obtaining radiometric age dates. Thus far, samples have been collected from 10 caves and analyzed by the University of New Mexico's Radiogenic Isotope Laboratory. Our results to date are shown in Supplementary Table S2. The dates obtained cover a wide span of time, ranging from ~13-14 Ma to 2 Ma. However, robust dates have been hard to come by due to Pb contamination probably from nearby ore deposits, due to mineralized fluids associated with the décollement, and from sample preservation/complexities.

A mammillary sample from Indian Burial Cave was the first date obtained. The mammillary sample was collected at an elevation of about 1,700 m asl, which is the lowest cave passage in the region. We expected it to be one of the youngest caves, but its 13.15 ± 0.42 Ma (Fig. 10c) age is the oldest, robust date we have obtained so far. Perhaps Indian Burial Cave's position in a horst focused rising water to start intense dissolution earlier than in the region as a whole?

Cave #041709-NS-018's date extends to about the same time (13.9 ± 3.8 Ma) as Burial's date but is much less constrained (Fig. 16). Other successful (and semi-successful) dates for mammillaries at higher elevations include Discovery Cave (11.41 ± 0.41 Ma), Cathedral Cave (2.21 ± 0.14 Ma but may not be a mammillary), Cave #LP06 (5.4 ± 1.4 Ma), and Council Hall (4.23 ± 1.98 Ma). Excessive Pb determined by ICP prevented analysis of samples from five caves (Cave #LP04, Cave #041709-NS-012, Snake Creek, Snake Canyon, and Black Dome), as well as a second, higher elevation sample from Cave #041709-NS-018. These preliminary results, however, are encouraging.

**FUTURE WORK**

This part of the Great Basin of the western United States contains many caves that are either undocumented or have had only cursory examinations. The Wild Cave Project attempted to catalog and categorize caves in White Pine County, Nevada, through mapping and detailed inventory of speleothems and speleogenetic features. In the Snake and Schell Creek Ranges, caves are developed in Paleozoic carbonates above and below the regional Snake Range Décollement and they may provide insight into its timing as well as internal geometric characteristics of this major detachment fault. The Snake and Schell Creek Ranges, and the Ruby Mountains are only three of dozens of north-oriented mountain chains in the states of Nevada and Utah that have extensive carbonate deposits and host other hypogenic caves. Hypogenic caves are known from many other ranges in the Basin and Range Province. Many of these caves contain mammillaries suggesting the possibility of obtaining a larger pool of reliable age-dates that may provide valuable constraints on the timing of tectonic events as well as volcanism and ore emplacement. No areas in the Basin and Range Province outside of White Pine County have received detailed geologic inventorying and study of their caves.

Another interesting question for further investigation is the relationship between the timing and massive unloading of the lower plate by the décollement event. Might the hydrogen sulfide that likely contributed to speleogenesis in at least some of the caves been a product of dynamic stress on the lower Cambrian Pioche Shale (Fig. 2)?

We continue to look for mineral deposits that could better inform our understanding of hypogene speleogenesis. Several caves in the study contain extraordinary speleothems and other secondary mineral deposits, such as folia, ruptured and intact button balloons, metatyuyamunite, and poorly understood calcite quills, that deserve further study.

Pockets of dogtooth spar (Discovery Cave) and dramatic, tilted paleofill (Old Mans) within the bedrock demonstrates a pre-Miocene, possibly Paleozoic,
era of karstification that has not been previously recognized or studied. We have also not yet correlated the occurrence of caves with known sulfide mineral deposits in the North and South Snake Ranges, which may prove enlightening. We are gaining knowledge of hydrologic conditions that may have existed contemporaneously with and after development of the regional décollement, but prior to the development of the current structural landscape. Continued work on the region’s paleohydrology would prove useful.

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