

THE GEOLOGIC STORY OF LEHMAN CAVES¹

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INTRODUCTION

Lehman Caves displays outstanding, world-class examples of some little highly unusual cave features in addition to its stunning beauty. Most visitors will know a bit about stalactites, stalagmites, columns, flowstone, and curtains/draperies from previous cave visits and will be amazed at their abundance in Lehman Caves. But, few will be familiar with bubble tracks, ceiling drains, cupolas, condensation corrosion, directional popcorn, and cave shields....the features that really distinguish Lehman Caves as extraordinary. Tours that share their stories will stand out to visitors as special and not just “another roadside attraction.”

GEOLOGIC SETTING

RELEVANT ROCK UNITS

Four geologic formations (units) hold at least some relevance to Lehman Caves. The oldest unit, the Prospect Mountain Quartzite, probably has had little impact on the cave but it plays a dominant role in the surface scenery of the immediate area, including Wheeler Peak. The Prospect Mountain was deposited on a shallow ocean floor in the early Cambrian (Fig. 1), possibly as early as Late Proterozoic (Precambrian), as a quartz-rich sandstone and siltstone. This sedimentary rock (Fig. 2) was metamorphosed into a quartzite in the latter half of the Mesozoic (Jurassic through Early Cretaceous). (It is important when discussing metamorphic rock ages to recognize that there is the age when a rock first formed, in this case the making of quartz-rich sandstone and siltstone, and the age of the metamorphism, in this case into a quartzite. In some rocks, both dates may be obtained but often the process of metamorphism obliterates the evidence for the age of the earlier rock.)

Overlying the Prospect Mountain Quartzite is the Cambrian-age Pioche Shale, which is locally more correctly identified as a slate --- the metamorphic product of shale. It was likely metamorphosed at the same time as the Prospect Mountain Quartzite as the late Mesozoic was a time of extremely high geothermal temperatures in the area and lots of magma rising up towards the surface. In fact, much of the Pioche Shale was assimilated/replaced by a younger intrusion of granitic rock immediately adjacent to the cave (see below).

The most relevant rock unit to Lehman Caves is the Middle Cambrian Pole Canyon Limestone, which is more correctly identified as a marble (the rock type formed when limestone is metamorphosed) in this location. It has strong foliation (“marbling”) and no evidence of original bedding features nor preserved fossils in the cave walls. Lehman Caves has entirely formed within the Pole Canyon formation. In the cave, the foliation typically dips moderately to nearly vertical towards the east and in some places west,

¹ This paper presents a substantially simplified version of two papers in the GRBA files titled *Notes on the Geology of Lehman Caves from a November 2017 Reconnaissance Trip – Parts I & II*.

Era	Period		Geologic Map Unit (map symbol)	General Description	
Cenozoic	Quaternary		Talus (Qt*), Alluvium (Qa*), Lacustrine gravels (Qlg), Landslide deposits (Ql*), Glacial deposits (Qg*), Older alluvium (Qoa*)	Unconsolidated clay, silt, sand, and pebbles.	
	Quaternary and Tertiary		Conglomerate (QTc)	Clasts of Paleozoic units.	
	Tertiary	Neogene	Conglomerate (Tc*), Needles Range Formation (Tnr), Lacustrine deposits (Tl), Latite flows (Tlf), Rhyodacite flows and intrusive rocks (Trdi*), Older conglomerate (Toc), Muscovite-bearing rhyolite dikes and sills (Tmp*), Granite (Tgr*)	Tc, Toc: conglomerate Tnr: conglomerate and tuff Tl: lake deposits Tlf: feldspar-rich volcanic rock Trdi: volcanic flows Tmp: rhyolite dikes and sills Tgr: biotite-rich granite	
		Paleogene			
Mesozoic	Cretaceous		Granite (Kgr*)	Biotite and muscovite granite.	
	Jurassic		Granite (Jg*)	Granitic pluton with a variety of minerals.	
	Triassic		No rock units of this interval mapped within the vicinity of Great Basin National Park.		
Paleozoic	Permian		No rock units of this interval mapped within the vicinity of Great Basin National Park.		
	Pennsylvanian		Ely Limestone (PNe)	Fossiliferous limestone forming ledges and slopes.	
	Mississippian	Chainman Shale (Mc)		Shale and siltstone. Forms slopes.	
		Joana Limestone (Mj)		Massive, cliff-forming limestone.	
	Devonian	Pilot Shale (MDp)		Calcareous shale with thin interbeds of limestone.	
		Guilmette Formation (Dg*)		Slope- to cliff-forming limestone.	
		Simonson Dolomite (Ds*)		Fossiliferous dolomite.	
		Sevy Dolomite (Dse*)		Dolomite. Fossils rare.	
	Silurian	Fish Haven and Laketown Dolomites (OSfl*)		Dark brown to light grey, ledge- and cliff-forming dolomites.	
	Ordovician	Eureka Quartzite (Oe*)		Cliff-forming quartzite.	
		Pogonip Group (Op*)	Lehman Formation (Opl*)		Limestone and silty limestone.
			Kanosh Shale (Opk*)		Shale and fossiliferous limestone.
			Juab Limestone (Opj*)		Fossiliferous, ledge-forming limestone.
			Wahwah Limestone (Opw*)		Limestone and silty limestone.
			Fillmore Limestone (Opf*)		Limestone and shaley limestone.
			House Limestone (Oph*)		Limestone.
	Cambrian	Notch Peak Limestone (OCn*)		Cherty, cliff-forming, fossiliferous limestone.	
		Corset Spring Shale (Ccs*)		Slope-forming shale.	
		Johns Wash Limestone (Cjw*)		Cross-bedded, oolitic limestone.	
		Lincoln Peak Formation (Clp*)		Slope-forming limestone and shale.	
		Pole Canyon Limestone (Cpc*)		Members a-e consist of slope- and ledge-forming to massive limestone.	
		Pioche Shale (Cpi*)		Shale, siltstone, and quartzite.	
		Prospect Mountain Quartzite (CZpm*)		Cliff-forming quartzite.	
Neoproterozoic	Late Proterozoic	McCoy Creek Group (Zm*)	Osceola Argillite (Zmoa*)	Laminated slates and siltstone with various degrees of metamorphism.	
			Shingle Creek Shale (Zmsc*)	Shale.	
			McCoy Group quartzite (Zmq*)	Well-bedded quartzite and conglomerate beds of variable thickness. Ledge- and slope-former.	

Figure 1. General stratigraphic column for the Great Basin National Park area. * indicates a unit mapped within the park. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps.

with only minor internal folds. Like the Prospect Mountain and the Pioche, the Pole Canyon was probably initially metamorphosed in the late Mesozoic (Jurassic and Cretaceous). However, it appears that the Pole Canyon at the cave site is much more strongly metamorphosed than the Limestone elsewhere in the Snake Range. Therefore, the Pole Canyon Limestone experienced further, more intense and localized metamorphism, probably during in the middle Tertiary. At that time, the overlying Snake Range Décollement (see below) formed as well as the intrusion of the fourth and youngest local rock unit, the granitic “sill”, which replaced much of the Pioche Shale.

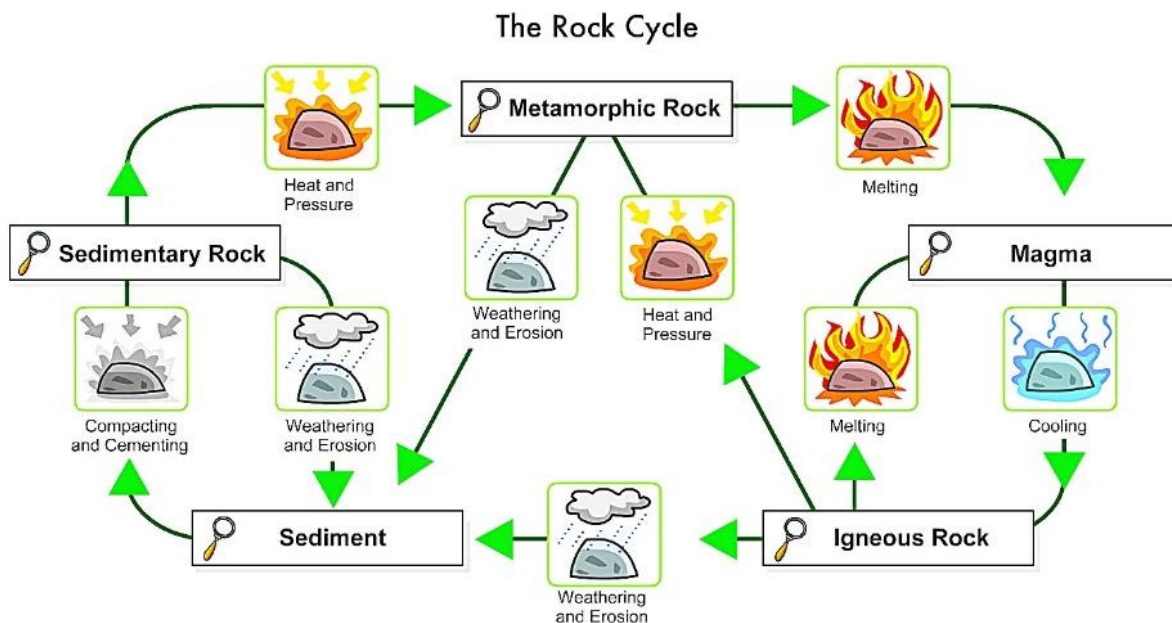


Figure 2. Basic rock cycle diagram showing the differ, fundamental rock types and the processes that form them.

SNAKE RANGE DÉCOLLEMENT AND BASIN-AND-RANGE FAULTING

The Snake Range is probably best known among geologists as the site of the huge Snake Range Décollement. Décollements are generally unusual geologic features found in several locations throughout the Basin and Range. In this case, before the Snake Range rose to current heights, the upper rock layers slide to the east on a very shallow-dipping fault about 17 million years ago. The upper block became highly contorted and fractured, and those rocks now form the Confusion Range to the east (Fig. 3). The lower block remained nearly intact and now forms the Snake Range. The Pole Canyon Limestone, already metamorphosed by the earlier granite intrusion, was at the top of the lower block in this area and became further metamorphosed by the heat and pressure of shearing above it. This metamorphic event would have wiped out evidence of previous faults and joints in the limestone/marble. Hence, all current-day fractures in the Pole Canyon occurred after 17 million years ago.

Once the heavy load of thousands of feet of younger rocks slid off the area, the Snake Range began to rise. The mountain building accelerated around 10-8 million years ago as Basin and Range faulting dropped the adjacent Snake and Spring Valleys while the Snake Range rose (Fig. 4a and b).

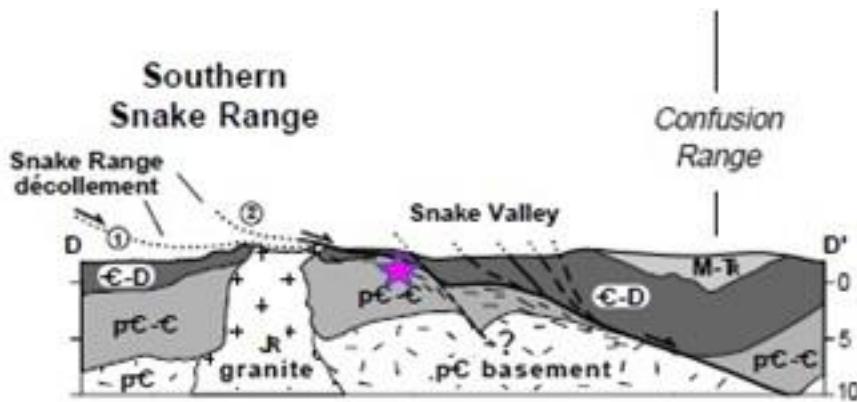


Figure 3. Simplified geologic cross-section from west (left) to east (right) through the Southern Snake Range today from Miller et al. (1999). Added pink star marks approximate location of Lehman Caves.

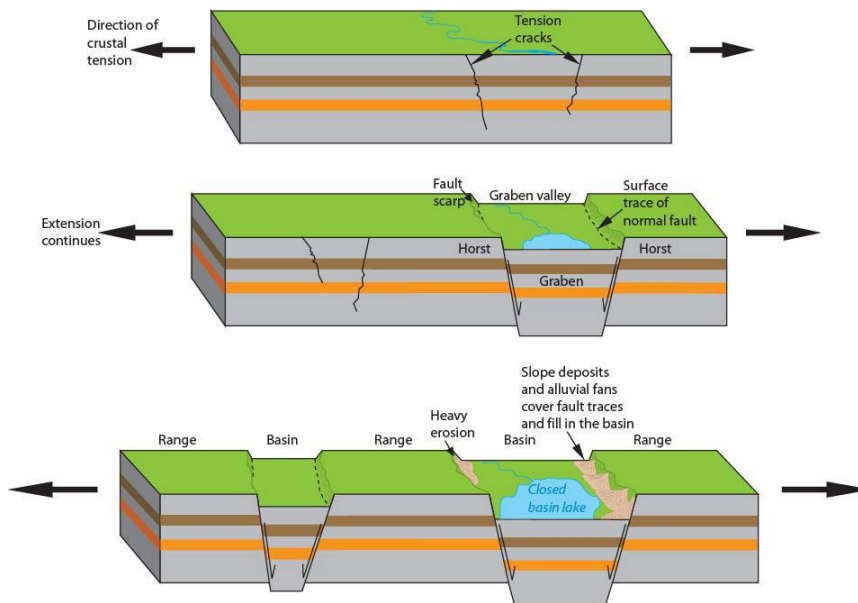


Figure 4a (above). Cartoon explaining the generic type of post-décollement "basin-and-range" faulting that typifies the Great Basin. The Snake Range is a "horst" block and the Snake and Spring Valleys are "grabens".

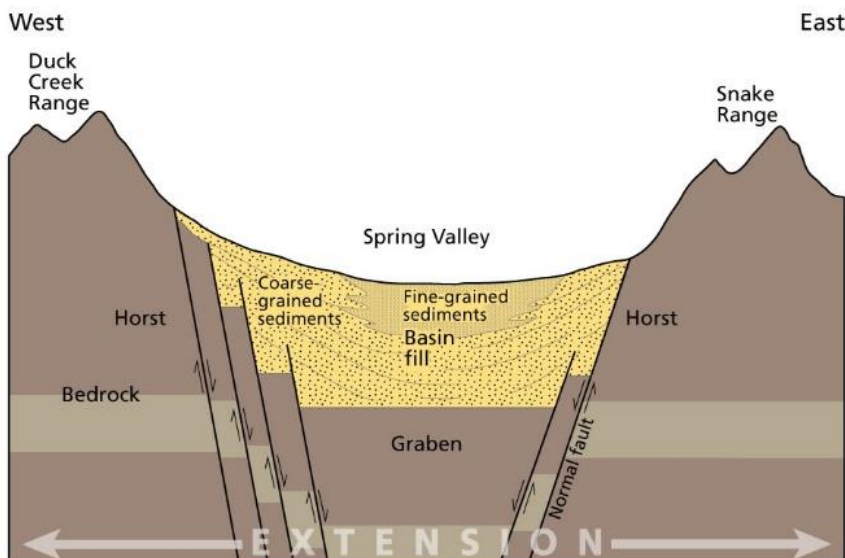


Figure 4b (right). Cartoon cross-section showing extensional (basin-and-range) faulting on the west side of the park. Both figures from

https://www.nature.nps.gov/geology/education/images/GRAPHICS/basin_and_range.jpg

CAVE GEOLOGY

THE BEDROCK – POLE CANYON “LIMESTONE”

The cave formed entirely within the Pole Canyon Limestone, which is a formal name for the unit but inaccurately describes the marble rock in the cave walls, floors, and ceilings. The current layers one sees in the marble is not bedding planes, like one expects in a limestone, but are called “foliation”.

The Pole Canyon Limestone was formed on a shallow, relatively warm ocean floor near the equator about 520 million years ago. It was mostly made up of sea critter shells (which are composed of calcium carbonate--- CaCO_3 ---and other organic debris and formed layers. Much later, probably between about 150 and 70 million years ago, the Pole Canyon Limestone was buried about six kilometers (maybe four miles) under the Earth’s surface and experienced high temperatures as well as pressure from the weight covering it. At this time, the Pole Canyon became plastic, partially melted, and a low-grade marble resulted throughout a broad region. Marble and limestone both are mostly the mineral calcite (CaCO_3) but some of the original features were obliterated. Later, about 28 million years ago, a magma that cooled and formed a granite immediately adjacent to the cave further metamorphosed the Pole Canyon and garnets grew within the rock.

The Pole Canyon rocks enveloping Lehman Caves are much more extensively metamorphosed than Pole Canyon rocks in much of the Range. That may result from the “contact” metamorphism when the adjacent granite intruded but it is likely there was also a third, different metamorphic event caused by the shear stress from movement along the Snake Range Décollement fault. This metamorphism wiped out all evidence of fossils and original features and resulted in a higher grade metamorphic rock called a “mylonite”, which only forms along major fault zones.

The marble bands differ slightly. The gray (or blue) bands have more magnesium (Table I) and organic material (carbon) than the white bands.

	Blue lime.	White lime.	Blue lime.	Stalagmite.
SiO_2	0.24	0.19	0.57	0.10
Al_2O_3	0.16	0.19	0.13	0.04
Fe_2O_3	0.24	0.24	0.63	0.01
CaO	53.74	55.28	53.96	55.00
MgO	1.54	0.26	0.91	0.18
SO_2	0.03	0.09	0.05	0.14
Water, 100° C.....	0.06	0.02	0.26	0.36
CO_2	43.86	43.67	43.35	43.37
Ignition loss	0.22	0.03	0.13	0.89
Total.....	100.10	99.97	100.01	100.10

Table I. Chemical analyzes presented by Hastings (1921) of the Pole Canyon marble at the cave site.

STRUCTURAL GEOLOGY

The bedrock is very heavily fractured with abundant joints and faults in the walls and ceilings. Many, probably

most, of the fractures in the cave walls have no displacement between the two sides and should be called “joints”. As the Pole Canyon formation was deeply buried until the middle Tertiary, it has experienced considerable uplift and removal of the overburden through décollement faulting, later Basin and Range faulting, and erosion. Removing this overload stress undoubtedly prompted tension-release fractures in the rock. The faults in the cave, places where one side of the crack has moved relative to the other side, are most likely related to the Basin and Range faulting, which peaked between 10 and eight million years ago. Some fault surfaces have distinctive, parallel lines or scratches called “slickensides” (Fig. 5). They



are visible at several spots along the commercial trail and show the last direction of movement between the two sides.

Figure 5. Slickensides on the cave wall. The last movement between the two sides was up-and-down.

WHEN AND HOW DID THE CAVE FORM?

Lehman Caves' geology is remarkably understudied compared to most major caves so we don't have as clear of understanding as we hope to develop in the future. One thing is clear, however, the cave is very old and unrelated to the current surface conditions. How old? Probably between 10 and 2.2 million years old. It also formed very different than the manner described in most beginning geology textbooks.

Before going any further with this discussion, there are several points worth remembering as we contemplate how this cave formed:

1. The entire cave may not have formed in the same way or at the same time.
2. There may have been several periods of cave development, each using different processes. At this time, we see four, clearly different periods of change in the cave but the story is likely more complicated. Much more research will be needed to fully understand this special cave.
3. The cave void *MUST* have formed *before* the beautiful decorations. And, the cave development (called "speleogenesis") might have been (and probably was) millions of years before most of the decorations (called "speleothems") started filling in the void.

STAGE 1 – SULFIDE-RICH, HYPOGENIC SPELEOGENESIS

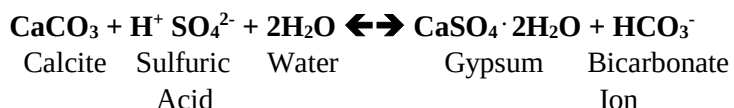
Off the beaten path and in the far northwest part of the cave, the Gypsum Annex reveals important clues about the earliest history of the cave. This area is mostly devoid of the beautiful calcite speleothems (e.g., stalactites, stalagmites, columns, and shields) that populate the rest of the cave and a geologist can more clearly see evidence of how the cave (or, at least this passage) formed. In the Gypsum Annex, we see compelling evidence of sulfide-rich, hypogenic speleogenesis.

The Gypsum Annex, and likely all of the cave, was formed by warm, sulfur-rich waters rising from deeper in the earth while the Pole Canyon marble was still buried deep below the surface (but after the marble had cooled following the last metamorphic event). Waters rising from deep in the earth are called "hypogenic" and were likely also high in carbon dioxide content (like soda water). We don't yet know where the water or the sulfur came from, but sulfur-rich warm/hot springs are still common in the Great Basin so it is not hard to envision such water flowing through the cracks in the Pole Canyon marble many

years ago. Now, the thing to know about sulfur-rich water and limestone is that the water doesn't easily dissolve the limestone until it is very close to the top of the water table and the sulfur can mix with free oxygen (O₂). When this happens, sulfuric acid (i.e., battery acid) forms and it is extremely corrosive. So, water-filled tubes began to form where sulfur-rich water from below mixed with fresh water seeping in and carrying free oxygen from the surface. Since the waters were most aggressive near the top of the tubes, we look to the ceilings of the cave for evidence....bubble trails (smooth grooves in overhanging walls and ceilings), cupolas (smooth-walled ceiling domes), and ceiling drains (round tubes in ceilings and high on walls that look like drains but go up). These features are abundant throughout the cave and tell the trained eye that the cave formed from hypogenic waters. Carbon dioxide-rich waters also become much more aggressive as they reach the top of the water table and form the same sort of features, but the CO₂-charged waters are far less potent than the sulfur-rich waters.

The Gypsum Annex is a special place because the walls and ceilings are mostly lined with gypsum (CaSO₄ · 2H₂O) crusts which formed as the sulfur-rich, hypogenic waters receded a bit and the passage filled with sulfur-rich air just above the water table. Once the cave sat in this position, the cave passage continued to enlarge through a complex but fascinating process.

Sulfide-rich waters continuing to rise from a deep source were warmer than the cave's wall rocks. As the water rose, two relevant changes took place: 1.) The reduced overlying rock and water pressure allowed hydrogen sulfide (H₂S) or sulfur dioxide (SO₂) gas bubbles to form and travel along the ceiling of the underwater passage, ultimately being released into the air-filled passage at the top of the water table. If the water was also rich with carbon dioxide, which is usually the case, CO₂ bubbles also travelled along the ceiling. 2.) As the sulfur-rich gases approached the air-filled passage, free oxygen became available which oxidized the sulfur gases. A potent acid, sulfuric acid, formed and attacked the marble passage walls. The most common reaction is:



Two products come from this reaction: gypsum (calcium sulfate) and a bicarbonate ion. In air-filled passages, the ascending thermal waters heated the air, including the water vapor/humidity in the passage, to a temperature higher than the cave walls. This inequity caused condensation on the marble/limestone walls and ceilings as happens in a steam room but this condensation was sulfide-rich. The surface of those walls and ceilings were converted to gypsum.

The above chemical reaction is exothermic and releases significant energy. "Chemoautotrophic" microbes bacteria that do not require sunlight nor photosynthesis but make their living on the heat released by chemical reactions are active and abundant facilitators of the reaction. Thus, the conversion of the exposed marble/limestone to gypsum does not result in a solid, dense mass of gypsum but instead commonly forms a paste-like coating of micro-crystalline gypsum, sulfuric acid, and abundant biomass. When the gypsum paste eventually dried up and the bacteria living inside died, the walls were left covered with gypsum crust. We still see the crust in the Gypsum Annex but it may have covered the walls of the entire cave as the Snake Range rose and the water table dropped.

Then, why is the gypsum crust missing in the tour-portions of the cave? Gypsum, the ubiquitous product of sulfidic speleogenesis, is extremely soluble in water and the rest of the cave became very wet as abundant surface-derived water entered the cave after the enlargement phase passed. The flowing and dripping water not only deposited calcite speleothems but also likely dissolved and removed any earlier

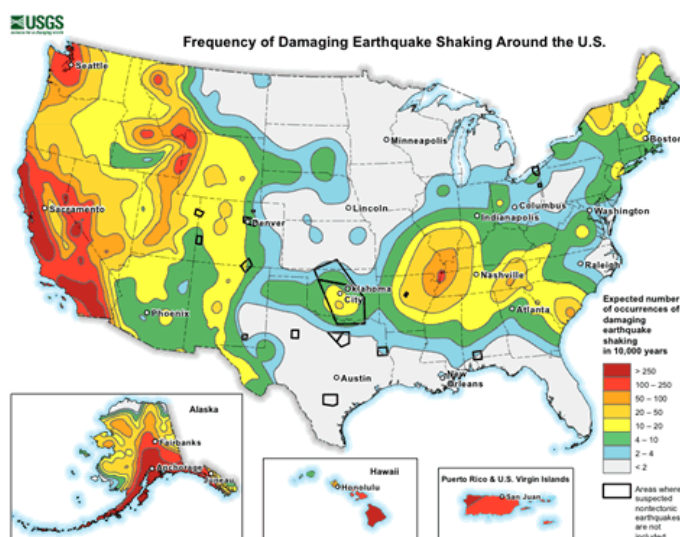
formed gypsum. The northwest part of the cave lacks much calcite, suggesting an impermeable cover between the Gypsum Annex and the surface protected the gypsum from invading surface waters.

STAGE 2 – SECONDARY DEPOSITS – FINDING STABILITY IN A NEW ENVIRONMENT

Once completely drained of hypogenic waters (more than 2.2 million years ago), the cave worked to achieve stability in its new environment. Three types of debris covered to the cave floor before the dramatic speleothems formed. First, as soon as the water table dropped below the cave passages, gypsum paste fell off the walls and ceiling to cover the floor with gypsum sand and dust. What remained on the walls dried out and formed crystalline gypsum crust. The second type of debris is mud, silt and sand. Some of this material is the insoluble residue from the dissolved marble which settled to the cave floor as the cave was actively enlarging. Some of it washed in from the surface, particularly near the natural entrance area. The third type of debris resulted from collapse of boulders and rocks from the ceilings and floors, almost entirely in the distant past. There were numerous causes of the “breakdown” in the cave.

1. The cave walls and ceilings display a remarkable number of fractures and many appear to have spread further apart since the void first formed. These “flaws” in the bedrock probably constitute the biggest reason for the abundant breakdown in the cave. The joints and faults are weaknesses in the bedrock which are prone to failure and the faults provide zones of movement along which stresses change and facilitate failures. These faults and fractures probably date back to the movements of the Snake Range Décollement and Basin and Range uplift.
2. Movement along faults both in the cave and nearby during the Basin and Range tectonism resulted in earthquakes and those events shook the entire area. Breakdown in the cave likely accompanied earthquakes at that time. The area now holds low risk of damaging earthquakes occurring (Fig. 6). As the area has been mostly earthquake-free for the last 8 million years and the cave is more than 2.2 million years old, the cave ceiling and walls have likely reached a condition of metastability and present no more danger to visitors of spontaneous ceiling and wall collapse than the average cave visit or walk in the mountains anywhere.

Figure 6. Map showing the predicted frequency of damaging earthquake shaking (USGS, undated).



3. The ceilings, no longer experiencing the partial buoyance of water, and walls, no longer under pressure from the water-filled passage, probably experienced the most active period of collapse as they moved towards stability right after the cave de-watered (millions of years ago).
4. As the area was uplifted and erosion removed most of the overburden, the release of lithostatic pressure (weight of rocks above) would have resulted in expansion of joints and other fractures in the bedrock, probably facilitating ceiling and wall collapses.

5. Several varieties of gypsum are abundant in the cave and crystal wedging undoubtedly contributed to the accumulation of breakdown on the cave floor. The conversion of limestone (CaCO_3) to the much larger gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) molecule is accompanied by significant expansion within the rock. If the process takes place along joints or other cracks in the bedrock, the forces generated by the conversion pry the bedrock apart and commonly results in breakdown on the floor and forms blocky domes in the ceiling. This is a common process in Mammoth Cave, for example.

In conclusion, there is no reason to believe the cave is now particularly prone to ceiling or wall collapses and plenty of evidence from over 120 years of safe tours that it is as stable as most mountainous recreational sites. Most of the previous collapse occurred millions of years ago.

STAGE 3 – SECONDARY DEPOSITS – CALCITE SPELEOTHEMS AND THE PLEISTOCENE

The most notable features in the cave to the average visitor are the abundant calcite speleothems, which appear to have formed almost entirely in the Pleistocene between 2.2 million and 7700 years ago. A couple dozen stalagmites have been dated and the majority grew between 125,000 and 250,000 years ago. The oldest date, however, is 2.2 million years old.

STAGE 4 – CONDENSATION-CORROSION SPELEOGENESIS

Following the Pleistocene, the surface conditions dried and, probably after the natural entrance connected the cave to the surface allowing greater exchange of surface air with the cave air, condensation corrosion due to carbonic acid became the dominant cave process.



It is likely still actively and slowly altering the cave's appearance. Water vapor in the cave has picked up CO_2 from the air then condensed on the walls, ceilings, and calcite speleothems as a film of carbonic acid. This moisture etches the marble bedrock or calcite speleothems (Fig. 7). Condensation corrosion can preferentially etch some portions of a speleothem and reveal the internal crystal structure (Fig. 8).

Figure 7. Eagle's Wing in the Lodge Room provides a good example of a calcite speleothem corroded by acidic condensation.

Dissolution along individual grain boundary in the marble bedrock produces disintegrated sandy or fluffy residue of mostly calcite on the walls and ceilings of the cave. This "punk" rock is soft, flaky, typically beige/tan or gray, and lines much of the walls and ceiling along the Lehman trails where dripstone and flowstone does not cover the bedrock. Some early explorers recognized the soft nature of the rock and left inscriptions scratched into it, forsaking the need for carving tools or soot. The powdery material also sloughs off the walls and ceilings

and accumulates onto the cave floor, similar to the process of the gypsum paste falling onto the floor when the cave first formed.

Figure 8. Internal layers exposed in a Lehman stalactite by condensation corrosion.



Condensate water also enters pores and fractures in the bedrock and speleothems or forms thin films of water and carries its dissolved content along the surface. As this water evaporates or temperatures change slightly, various speleothems may form.

Much or most of the popcorn and aragonite frostwork in the cave likely formed through mechanisms related to condensation water. This manner of evaporation-and-condensation is most common in caves where circulation of air between entrances is limited and where there is little running water. It is typical of hypogenic caves in dry climates, both active and inactive. Lehman Caves certainly matches these descriptions.

CALCITE SPELEOTHEMS

A comprehensive discussion of the wide variety and abundance of calcite in the cave would require a book-length report and a great deal more observation and research. Good information on the most typical speleothems in the cave, such as stalactites, stalagmites, columns, drapery/curtains, flowstone, and helictites, is available from many sources and their story is told in nearly every commercial cave in the world. For more detailed and a very comprehensive explanation of these and less common speleothems, please check out Hill and Forti's 1997 book, *Cave Minerals of the World* in the park library. Another excellent reference on all things cave is Art Palmer's 2007 book, *Cave Geology*, which is also available in the park library.

So, I will offer some explanations here to some of the oddities in the cave that often raise questions from visitors and guides.

1. *What have been the biggest growth periods for speleothems?* Dennison (2007) used uranium-series dating techniques to determine the age of dozens of stalagmites within Lehman Caves. His dates ranged from 7740 to 466,600 years old with the majority of dates between about 125 and 250 thousand years ago, associating most calcite speleothem growth with the Pleistocene. One stalagmite date by Lachniet and Crotty (2017) is 2.21 million years old. It appears that very little calcite speleothem growth has occurred since the Pleistocene. An exception is likely to be the abundant cave popcorn that grow in the cave air.
2. *Why are there so many shields in Lehman? How do shields form?* The simplest answer to why shields are so abundant in Lehman is that the bedrock is highly fractured and shields form from water oozing out of cracks. Most shields throughout the world form from deformed, fractured rocks. In addition, Lehman is an old cave (based on the 2.2 million year old date on one stalagmite) and there's been plenty of time for lots of calcite speleothems to grow, including shields. As to how they form, the origin of shields is still something of a puzzle. What we do know is:

- a. Active shields are two, parallel plates of calcite separated by a crack thin enough to only allow capillary seepage.
- b. The two plates grow outward into air-filled passages and develop concentric growth bands, similar to tree rings, around their water sources, which are clearly displayed by many of the half-shields along the tour route of the cave. (Note: There is no evidence that the growth bands in shields represent annual growth as in tree rings.)
- c. Active growth is along the outer edge of the plates, where CO₂ is able to escape into the cave atmosphere and the water becomes supersaturated.
- d. During periods of increased water flow that leads to pressure that overwhelms the capillary seepage, gravitational water deposits stalactites and draperies around the shield edges (e.g., The Parachute).
- e. In many caves, including Lehman, there appears that the internal gap between plates widens toward the shield interior. Thus, undersaturated water seeping out from the original fracture may dissolve calcite from the inside of the already established plates and then re-deposit the calcite when the water reaches the edges of the plates and CO₂ escapes. This eating away from the inside activity may also weaken one plate's attachments to the site and contribute to separation and apparent collapse of the bottom plate of many shields seen within Lehman.

A particularly puzzling feature of several shields in the cave where the lower plate has dropped off is a distinct corrugated pattern on the bottom of the upper plate (Fig. 9). The lines are approximately horizontal and appear to be growths. Speleologists think that the ridges may be strand lines (water lines at the top of standing water...like bathtub lines) formed by chemical precipitation from water pooled inside the crack before the bottom plate fell off.

Figure 9. Corrugated ridges on bottom of an upper shield plate near the entrance.



3. *What caused the offset, tilted, and broken columns in the cave (Fig. 10a and b)?* The most common reason for these features appears to be the removal of debris from under the speleothem. Where observed, the upward growing stalagmite appears to have grown on a bank of clastic deposit (e.g., mud and silt). Later, either the mud compacted or water flowed into the cave and removed some of the clastic material after the stalagmite-stalactite pair began to develop. Shaking from earthquakes may have also caused some of these features.



Figure 10a and b. Two examples of broken and tilted columns in Lehman Caves.

4. *How did all the popcorn form?* Cave popcorn (also called coralloid or coral) is a common speleothem, typically formed of calcite, that usually forms in the air. Although it often appears to have formed as a pool deposit, this is rarely the case. One way popcorn forms is from water seeping out of the cave walls and floor, releasing carbon dioxide or evaporating to the point the water becomes supersaturated, and calcite precipitates. Cave popcorn also grows in splash zones where the shock of impact drives CO₂ out of the water, resulting in a supersaturated solution and precipitation of calcite. Many displays of popcorn are directional (e.g., on one side of a stalagmite or stalactite but not on the other side) and this situation occurs when super-saturated water vapor condenses preferentially on one (upwind) surface over another (downwind) surface.
5. *How did the “bulbous stalactites” form?* First, these features (Fig. 11) probably should NOT be called “bulbous stalactites” as Hill and Forti (1997) reserve that term for stalactites that formed a “bulb” on their end as the result of submergence in a calcite-saturated pool of water. Bulbous stalactites should display a common water line elevation at the top of the bulb. The Lehman ones do not. Instead, the Lehman features appear to be examples of what Hill and Forti (1997) called “turnips.” They note that these speleothems appear to grow in caves with highly fractured

bedrock and are commonly associated with cave shields, as is the case at Lehman. Thus far, however, no fully satisfactory explanation of the Lehman Caves features has been put forth.



Figure 11a. Turnip speleothems in Lehman Caves. Figure 11b. Internal layers exposed in a turnip by condensation corrosion.

6. *What's up with all the scallops on the walls of the cave?* Good question! Scallops are dish-shaped depressions eroded into cave walls, floors, and ceilings by eddies in flowing water. Their presence in Lehman is puzzling and, seemingly, inconsistent with the cave's history previously outlined. Perhaps they represent yet another, fifth era of cave development after the hypogenic phase and before the abundant speleothems formed. Perhaps they are remnants of the earliest, hypogenic phase before the water table started to drop. At this time, there is no good explanation of the scallops and how they fit into the story of Lehman Caves.



Figure 12. Cave scallop example on the wall of another cave.

SUMMARY

Lehman Caves is an extraordinarily cave with a fascinating history. Most visitors will initially view the cave as particularly well decorated and wonder why so many of the stalactites, stalagmites, and shields have been “so badly worn,” likely assuming the corroded surfaces were caused by the cave’s long history of human visitation. But, the corrosion is natural and just the most recent phase in the multi-million year history of the cave. There is so much more to learn, but we already know enough to recognize some of its special history.