

PALEOHYDROLOGY AND THE ORIGIN OF JEWEL CAVE

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Abstract

With more than 270 km (168 miles) of mapped cave passages, Jewel Cave is the third longest cave in the world. The passages are beneath an area of 775 ha (3 mi²), located almost entirely within the Hell Canyon drainage basin. The canyon itself is situated in the bottom of a south-plunging syncline and most of the cave passages are located within the east limb. A down-dip cross section shows the cave passages assuming the shape of an elongate lens, located just below the Pahasapa/Minnelusa contact. The lower boundary is a maximum of 75 m (250 feet) below the contact, but thins at each end, where the permeable, basal Minnelusa sandstone is exposed.

Based on these observations, a conceptual model has been created to portray cave development as the result of local groundwater movement in geologically recent time. The apparent recharge was in the Pass Creek and Lithograph Canyon areas, and the discharge was in Hell Canyon. Groundwater initially moved through a shallow confined aquifer comprised of the basal Minnelusa sandstone, which was initially confined by the underlying Pahasapa Limestone and an overlying Minnelusa limestone. Although Laramide fractures provided secondary porosity, there is no evidence of sufficient connectivity to provide landscape-scale permeability. As water from the sandstone circulated into the discontinuous fractures of the Pahasapa, dissolutional enlargement integrated them to form the system of interconnected cave passages known today. The model precludes the need for direct recharge from rainfall, hydrothermal waters rising from below, or prior development of a Mississippian karst.

Introduction

In 1908 Jewel Cave became the first National Monument established for protection of a cave. It became part of the National Park Service (NPS) in 1933.

The first comprehensive geological study of Jewel Cave was conducted by Dwight Deal (Deal, 1962). In

personal communication (c. 1980) he suggested that the Minnelusa sandstone might have something to do with the origin of the cave. The author has subsequently confirmed Deal's speculation and discovered new relationships – some of which are quite unexpected and don't fit what is commonly reported in geological literature. The relationships are compelling, and must be adequately addressed by any theory proposing an explanation of the origin of Jewel Cave. This paper presents the new concepts and attempts to integrate them into a broad framework to encourage and facilitate future research.

The ultimate goal is to develop a clear understanding of the nature of Jewel Cave. This will ensure a better interpretive story for the visiting public and provide a compelling justification for decisions that address external land issues. It improves the knowledge base necessary for better cave management.

Stratigraphy

Over the last 15 years, Jewel Cave National Monument has supported several projects to produce detailed geological maps of the Jewel Cave quadrangle and surrounding areas. These efforts have documented six distinct subunits within the Minnelusa Formation (Table 1), with a variety of lithologies, including limestone (LS), dolomite (DS), and sandstone (SS).

Table 1. Subunits I through VI, within the Minnelusa Formation. Top of subunit VI is not present within the Jewel Cave quadrangle. Adapted from Davis (2003).

Minnelusa Formation		Thickness
VI	brecciated SS, anhydrite	?
V	varicolored sandstones	37 m (120 feet)
IV	interbedded DS and SS	37 m (120 feet)
III	SS with LS cap	37 m (120 feet)
II	thin bedded cherty LS	15 m (50 feet)
I	cross-bedded SS	12 m (40 feet)

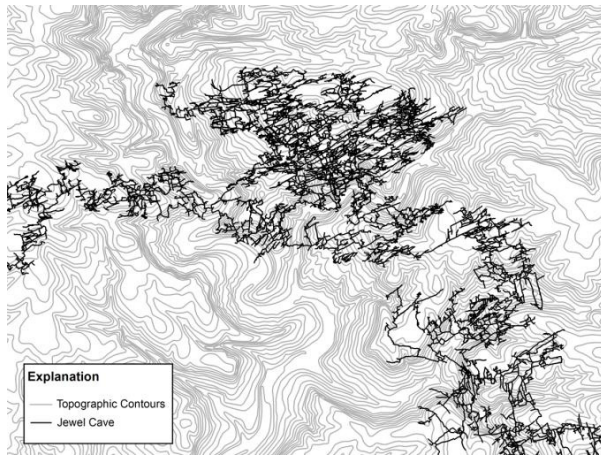


Figure 1. Relationship between Jewel Cave and the surface topography.

The remarkably consistent thicknesses enabled the mapping of subtle geologic structures that were previously unknown. Wiles (1992) identified the high permeability of the subunit I sandstone.

Spatial Relationships

In previous work, Wiles, Ohms, and Pflitsch (2009) demonstrated a close relationship between Jewel Cave

and many modern day features, including topography, geologic structure, and stratigraphic contacts.

1. Topography

Most of Jewel Cave's passages are found beneath the hillsides. Extensive mazes of larger passages bottle down to just a few crawlways where the cave approaches Hell Canyon and Lithograph Canyon. Only a few passages actually cross beneath the surface canyons. The lack of surface fill material clearly shows that the cave has not been dissected by the canyons, after the fact. Thus, it appears that the cave formed concurrently with the canyons, and that its development was controlled by their hydrology.

2. Structure

Jewel Cave's passages correlate with Laramide structures, particularly in their relationship with faults and folds (Figure 2). Individual joint-controlled cave passages tend to terminate (or originate) at normal faults, with up to 12 m (40 feet) of vertical displacement. In some cases, small passages with atypical patterns cross a fault zone and connect with joint-controlled passages on

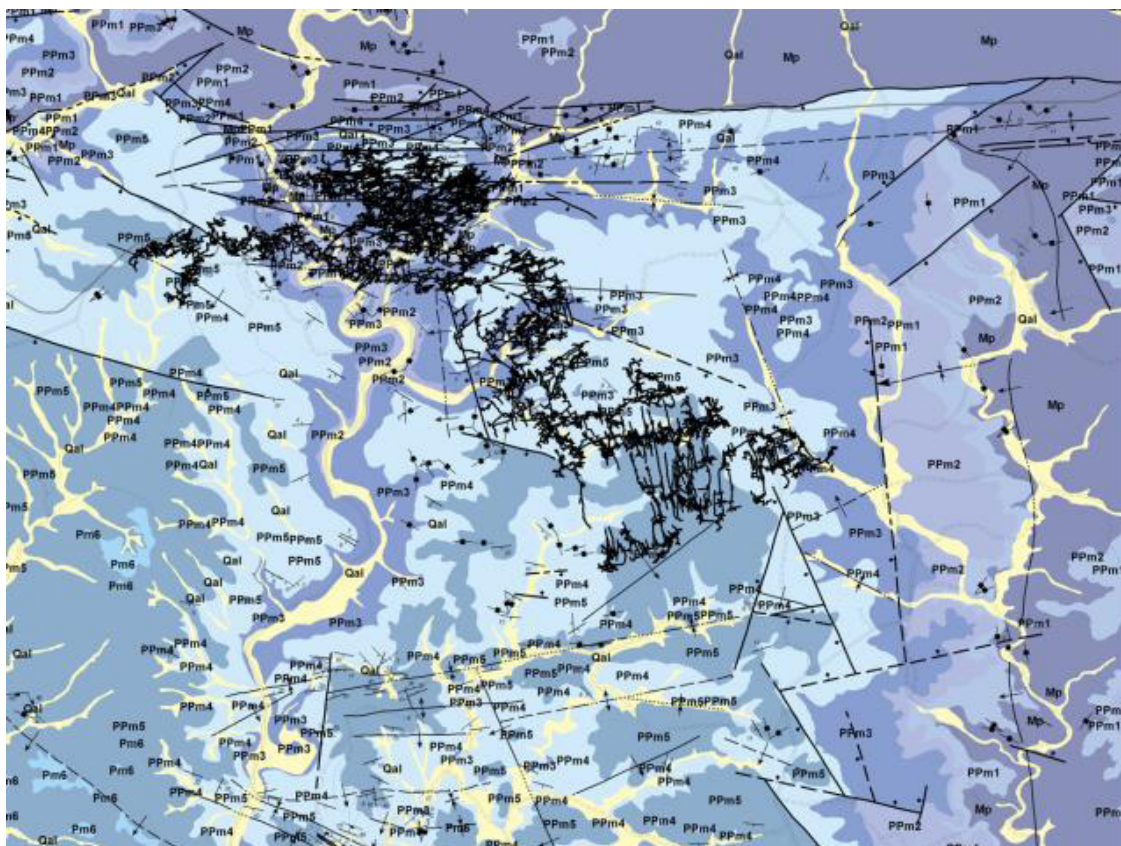


Figure 2. Relationship between cave and geology. Adapted from Fagnan (2009).

the far side, but there is no evidence of fault displacement cross-cutting pre-existing passages. All faults appear to pre-date the cave, and may even have played a role in directing phreatic groundwater flow and influencing the final distribution and character of cave passages.

Furthermore, Hell Canyon formed in the bottom of a broad, south-plunging syncline. The cave itself is congruent with this structural feature (Figure 3). It follows a curved geologic strike, and – with one exception, at the far southeastern extent of the known cave – dips toward the synclinal trough.

3. Geologic Contacts

All the large caves in the southern Black Hills exist beneath the Minnelusa cap, as it is configured today (Figure 4). Cave entrances are located at the contact, and the bulk of the passages are beneath the cap.

Currently, Jewel Cave has 270 km (168 miles) and Wind Cave has 227 km (141 miles) – over 500 km

(300 miles) total. In sharp contrast, no cave over 150 m (500 feet) long is known to exist within the uncapped limestone.

This spatial relationship is compelling evidence that the Minnelusa was in some way responsible for the development of large cave systems. But, if this statement is true, two important questions naturally arise: Why didn't large caves form throughout the history of its erosional regression? Why are they only found where the cap remains today?

Considering the aforementioned relationships of the cave with modern topography and post-Laramide structure, a logical answer is that extensive cave development did not occur until around the time the Minnelusa had eroded to its present configuration. If this is correct, an additional question immediately presents itself: Could the present geomorphology have supported a cave-forming hydrologic system in the geologically recent past?

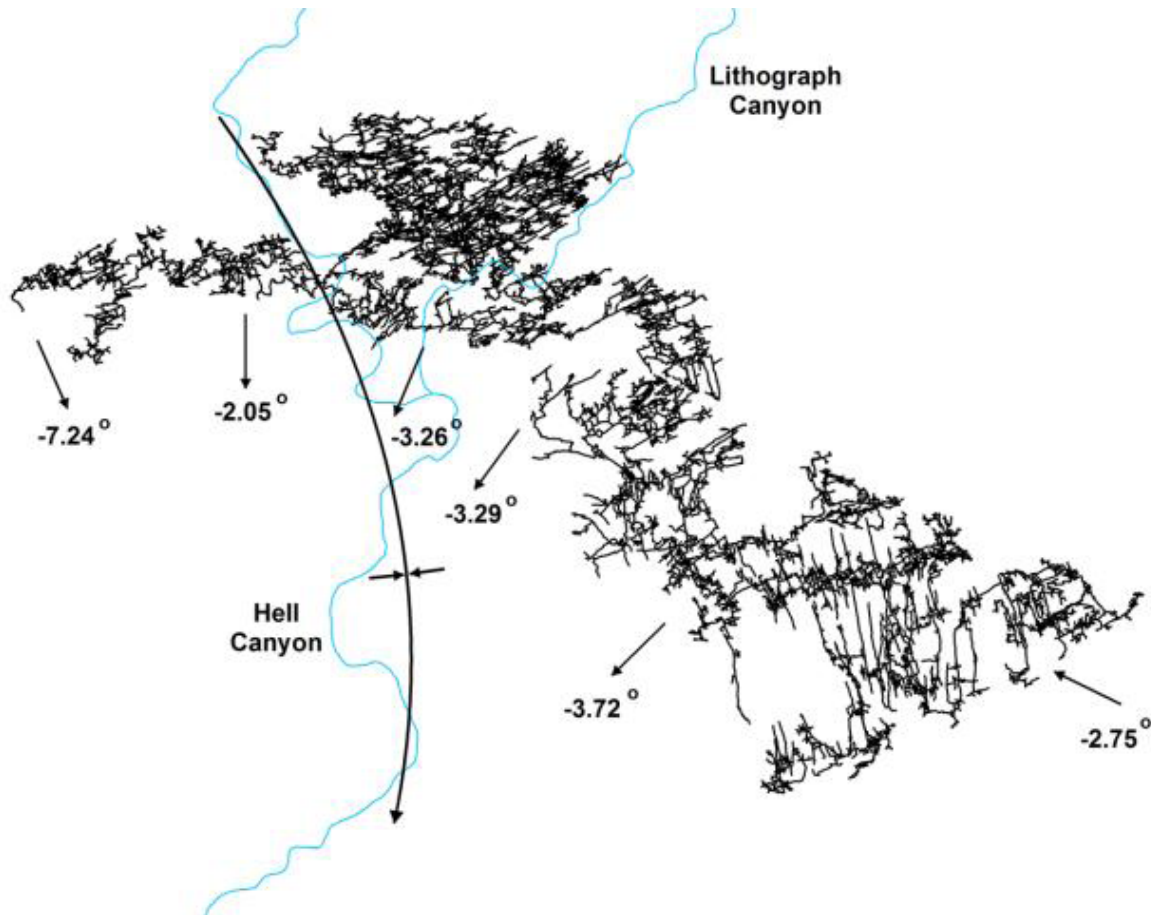


Figure 3. Relationship between the variable dip of the cave and Hell Canyon.

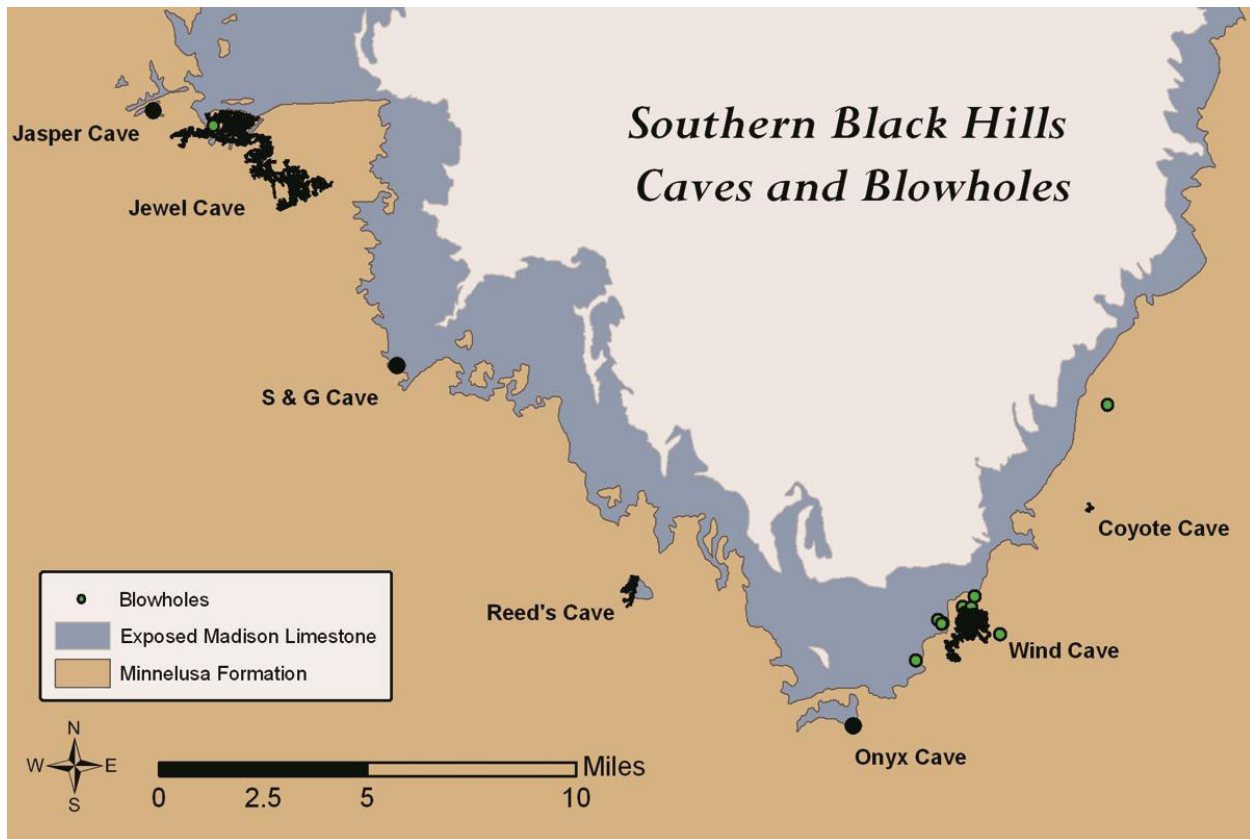


Figure 4. Relationship between large caves and the Minnelusa cap.

Hydrologic Setting

In simplest terms, dissolutional cave development is a mass transfer process, whereby water (the solvent) removes soluble rock (the solute). For this to happen, there must be 1) a recharge area, 2) a discharge area, 3) a gradient between recharge and discharge areas, and 4) initial connectivity between recharge and discharge areas.

At Jewel Cave, the recharge could not have been meteoric water entering directly from above, because of intervening impermeable layers – particularly a 10-foot layer of silica-cemented sandstone, located near the base of subunit III. Even today, direct infiltration occurs in less than 1% of the known passages, where erosion has breached the impermeable layers. In the remaining 99%, there is no evidence of dripping (such as the presence of dripstone), even in the distant past.

It is unlikely that recharge could have come from below, because the Pahasapa Limestone is underlain by the Englewood Limestone which, despite its name, contains enough basal shale to confine the underlying Deadwood aquifer with an average hydraulic head of 30

m (100 feet), based on reports by Dyer (1962) and Davis, Valder, and Sarratt (2006). It functions as an aquiclude, preventing the flow of water from below.

If the recharge didn't come from above or below, then it must have been introduced laterally from a more distant location. For purposes of this discussion, the subunit I sandstone is considered to have provided the primary initial connectivity between recharge and discharge areas.

The reason for this assumption is that, even with the secondary porosity afforded by fractured limestone, there is no evidence of landscape-scale *connectivity* within the Pahasapa Limestone. Even today, after the maximum enlargement of limestone fractures has occurred, there is an obvious sense of *discontinuity*, with large cave passages extending hundreds of feet before coming to an abrupt end; at which point there might be a small constriction that veers to a side passage or a different level.

Without initial connectivity, there could be no throughflow, and therefore, no mass transfer. However, throughflow *could* occur within the subunit I sandstone if

it had a sufficiently high initial permeability. Sandwiched between two relatively impermeable limestones (the underlying Pahasapa Limestone and the overlying Minnelusa subunit II limestone), it could function as a confined aquifer.

In the immediate Jewel Cave area, subunit I outcrops only in Teepee Canyon, Hell Canyon, Lithograph Canyon, and upper Pass Creek; all of which coincide with modern drainages. The highest elevations in Teepee Canyon and Pass Creek represent viable recharge areas. The outcrops in Hell Canyon and lower Lithograph Canyon are down-gradient, and represent obvious locations for discharge.

In the Figure 5, the upper contacts of subunit I are extrapolated across Hell Canyon and Lithograph Canyon to approximate the exposures prior to the final incision into the underlying Pahasapa Limestone. In Pass Creek, the lower contact was similarly extended to the east. In each case, the upper contact remains as it is seen today.

The sandstone exposures are shown in red and the blue arrows represent the most direct paths that could be taken by water moving from recharge areas to discharge areas. The fact that Jewel Cave's known passages are directly in line with the proposed flow paths appears to be more than mere coincidence. Although this is a rough estimation of what might have occurred, it is consistent with the other considerations just presented.

All things considered, the modern configuration *does* fulfill the requirements for recharge and discharge areas, gradient, and initial connectivity.

Cross-sectional Relationships

Figure 6 is a cross-section A-A' (yellow line in Figure 5) taken along a west-plunging anticlinal axis (superimposed on the broader south-plunging syncline), which coincides with the cave's only known natural entrance – as well as its only known paleontological fill, located just inside the entrance.

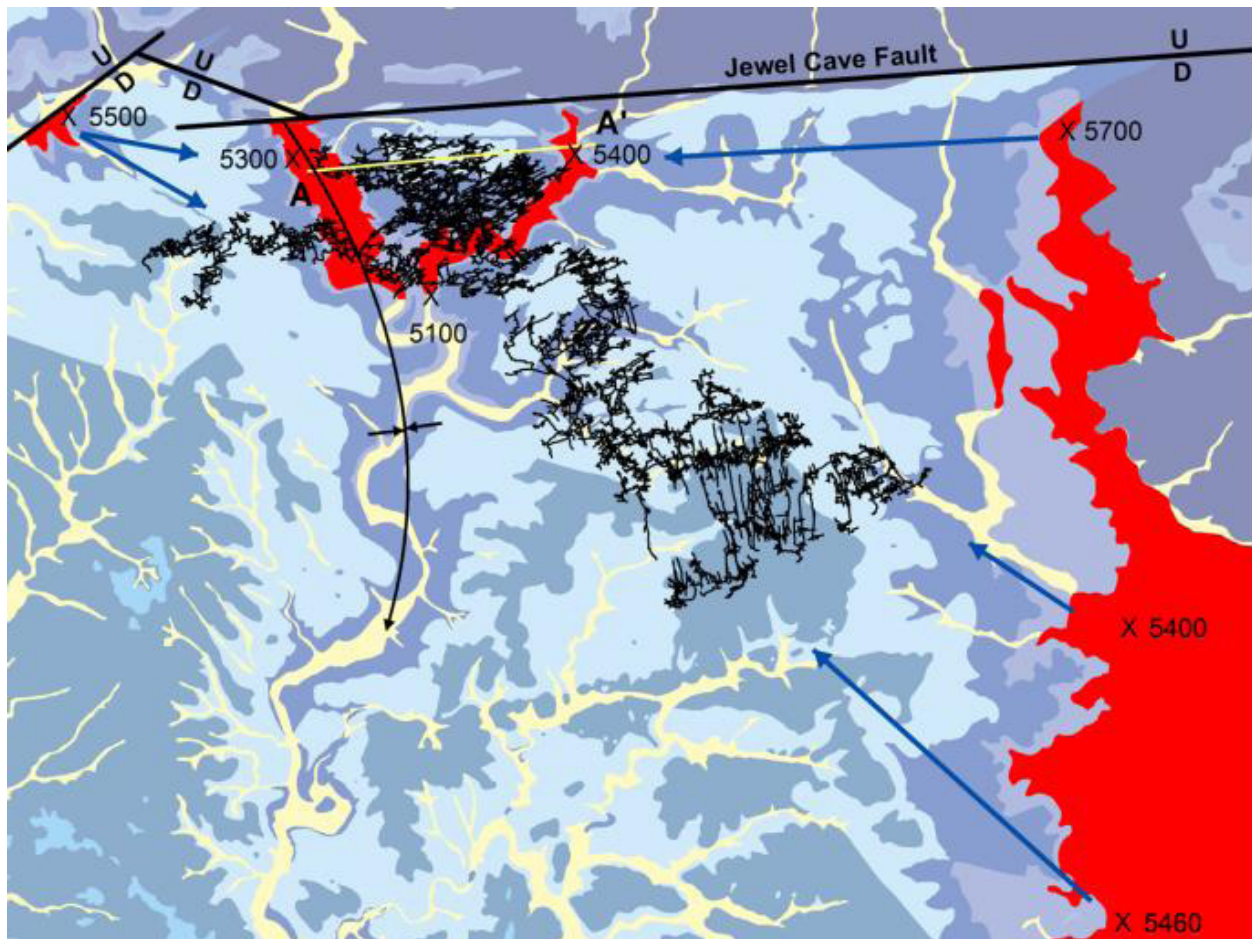


Figure 5. Relationship between cave passages and exposures of basal Minnelusa sandstone.

Near *A*, the subunit I sandstone is exposed at Hell Canyon; at *A'*, it is exposed in a tributary of Lithograph Canyon. Surprisingly, the cave has an obvious lens shape, which thins and rises up near Hell Canyon and the natural entrance. This is evidence that the primary dissolution event didn't occur prior to the uplift and erosion of the Hills or before Hell Canyon formed.

Regardless of what might have happened in the late Mississippian, it is clear that any paleocave development would have little bearing on what is seen here. The much-more-recent Hell Canyon clearly controlled the water flow that formed the cave.

It is also noteworthy that cave development consistently remains in the upper 75 m (250 feet) of the limestone, and that this relationship holds true even at Wind Cave, where the limestone is 25 m (80 feet) thinner.

Proposed Sequence of Events

Taking all these observations into account, a simple, straightforward sequence of events is proposed. The following description is based on the area represented by Figure 6, and ignores the possible hydrological influence of the Jewel Cave Fault.

1. Laramide uplift, and subsequent fracturing and erosion, brought the landscape close to its present-day morphology.
2. The Lithograph Canyon tributary (and upper Pass Creek) became losing streams and served as recharge areas. Hell Canyon became a gaining stream in the discharge area.
3. Initially, water flowed primarily through the sandstone (Figure 7), confined by the underlying and overlying limestones. This created a "blanket" of water that could reach all parts of the developing cave in a non-point manner.
4. Water circulated down from the sandstone, through isolated areas of fracture-enhanced permeability, and began to dissolve the cave in isolated "cells." Water in the sandstone would maintain nearly full capacity of CO₂ while the water dissolving the fractures would deplete CO₂, and there would always be active dissolutional mixing where the two waters met.
5. The enlarged cells eventually coalesced, integrating the voids in the limestone and taking on a greater proportion of the flow (Figure 8).

6. The basal Minnelusa sandstone contemporaneously collapsed into the still-forming cave (red spots in Figure 8), creating localized "neo-fill" (Wiles, 2012). The material is Pennsylvanian in age, but it was emplaced approximately 300 million years later.
7. Eventually, Hell Canyon was cut deeper, the climate dried, and the recharge ceased (Figure 9). There was no longer any through-flow, nor a fresh source of acidic water. Lack of flow caused the water to warm and reduced hydrostatic head caused the pressure to drop, resulting in the precipitation of calcite spar. This was followed by precipitation of manganese minerals (not shown).
8. After Hell Canyon had been cut 30 m (100 feet) into the limestone, perennial flow ceased and the cave slowly drained. Without buoyancy from the water, large cave passages collapsed (Figure 10).
9. Evaporative speleothems formed. Limited dripstone formed.

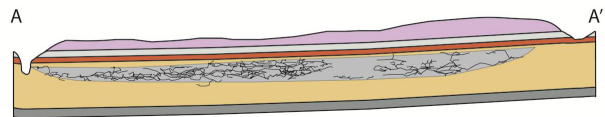


Figure 6. *Lens shape of cave passages.*

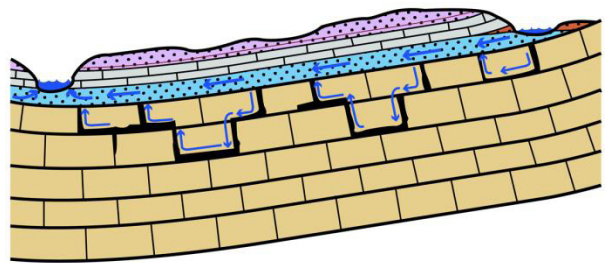


Figure 7. *Initial flow moves primarily through subunit I sandstone.*

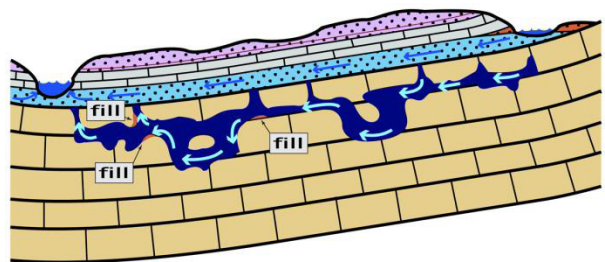


Figure 8. *Dissolution of fractured limestone.*

Conclusions

Several lines of evidence point to a geologically recent origin for Jewel Cave. Although the exact timing has not yet been pursued, it is reasonable to believe that cave development began just prior when the landscape reached its modern configuration. New information has been incorporated into a conceptual model that is simple and straightforward, and geomorphically compatible with the main surface and cave features. It precludes the need for direct recharge from rainfall, hydrothermal waters rising from below, or prior development of a Mississippian karst.

This conceptual model should not be viewed as a final answer, but as a challenge for future researchers to find answers that will adequately incorporate all the observations. It is a good starting point for addressing questions that, until recently, were not even known to exist.

The top two resources management goals identified in Jewel Cave's General Management Plan are: 1) to continue cave exploration and 2) to pursue methods of predicting where undiscovered passages will be found. This is especially important for a cave where nearly 50% of the known passages are located outside the park boundaries, and 97% remain undiscovered (Wiles, Ohms, and Pflitsch, 2009).

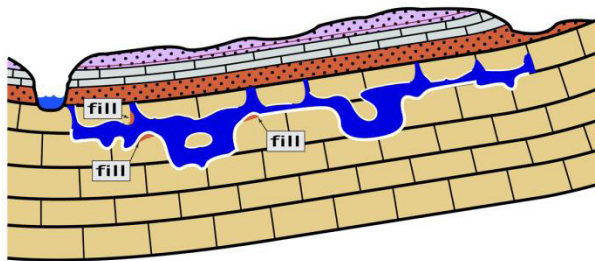


Figure 9. Deposition of calcite spar.

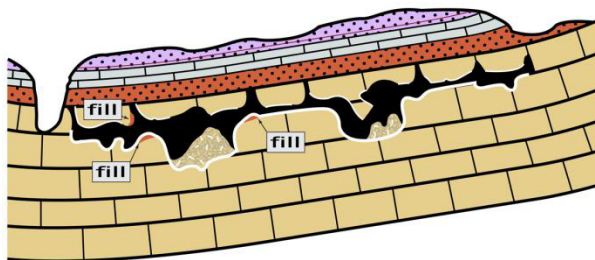


Figure 10. Cave drains and large rooms collapse.

Building on previous work, the model is the next logical step toward predicting the location of undiscovered passages. It bolsters the park's ability to justify external protection actions, such as mineral withdrawals and land exchanges. The early research has already been used to justify mineral withdrawals 1990 and 2008, totaling 2,825 ha (6,983 acres); and a land exchange in 2000, that converted 148 ha (366 acres) from private to Forest Service Land.

The NPS is mandated to make science-based management decisions. The better the science, the more meaningful the decisions will be.

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Biography

Mike Wiles was born in Huron, S.D. He was introduced to caving at the age of 20, by members of the Paha Sapa Grotto, of the National Speleological Society, then a student grotto at South Dakota School of Mines and

Technology. Since then, he has volunteered more than 7,000 hours toward the exploration of Jewel Cave and has helped discover more than 70 miles of passages. Mike has earned a B.S. in Chemical Engineering and an M.S. in Geological Engineering, both from SDSM&T. His 1992 Master's thesis is entitled, "Infiltration [of groundwater] at Wind and Jewel Caves, Black Hills, South Dakota. Mike has worked at Jewel Cave National Monument for over 30 years, first as an Interpretive park ranger, then as a Cave Specialist, and is currently the Chief of Resource Management for the park.