Plenary Lecture:

Mysteries of the Black Hills Caves, USA

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Introduction: Many caves in dry karst regions form by deep processes or by the enlargement of ancient openings (paleokarst) from older time periods. Unlike stream caves in humid regions, their potential cannot be estimated from the size of their drainage basins. This presentation focuses on caves of the Black Hills in South Dakota. They follow a paleokarst zone, but their origin involves a great many complex processes. They include two of the world's longest caves, and the potential cavernous zone extends hundreds of kilometers around the perimeter of the hills. I hope that this presentation encourages the investigation of similar unusual caves in other countries.

Einleitung: Viele Höhlen in den trockenen Karstregionen bilden sich durch Prozesse in der Tiefe oder durch die Vergrösserung von Öffnungen aus älteren Zeitperioden (Paläokarst). Im Gegensatz zu den Wasserhöhlen in den feuchten Regionen kann ihr Potential nicht aus der Grösse ihres Einzugsgebiets abgeschätzt werden. Diese Arbeit konzentriert sich auf die Höhlen der Black Hills in South Dakota, die zwar einer Paläokarstzone folgen, aber deren Genese auf vielen komplizierten Prozessen beruht. Es handelt sich um zwei der längsten Höhlen der Welt und ihre möglichen Fortsetzungen erstrecken sich über Hunderte von Kilometer im Umkreis der Hügel. Ich hoffe, dass diese Präsentation die Untersuchung von ähnlich ungewöhnlichen Höhlen in anderen Ländern anregt.

The Black Hills

The Black Hills consist of a dome-shaped uplift about 150 x 90 km in extent, which formed about 70 - 40 million years ago. Erosion has exposed ancient metamorphic and igneous rocks in the center, surrounded by the eroded edges of younger sedimentary rocks. The highest mountains extend 2200 m above sea level, about 1200 m above the surrounding plains. The sedimentary rocks dip away from the center at an average of about 5 degrees. They include a major limestone, the Madison Formation, which is 360 - 330 million years old (Carboniferous) and is 100 - 150 m thick. The limestone was deeply eroded soon after it was deposited, producing an ancient karst surface and shallow caves. The limestone and karst were later buried by sedimentary rocks up to 2 - 3 km thick, dating from late Paleozoic to late Mesozoic age.

During the Black Hills uplift the limestone was again exposed at the surface. Increased groundwater flow enlarged the paleokarst openings to produce the caves we see today. The largest and best known are Jewel Cave and Wind Cave, which are open to the public.

Cave Discovery and Exploration

The only natural entrance to **Wind Cave** is a round hole about 40 cm in diameter. Wind roars in and out at great velocity whenever the atmospheric pressure changes. The first record of its discovery was in 1881 when a cowboy heard the sound of wind blowing out of the ground. He bent over the hole and the wind blew his hat off. Under private ownership a walk-in entrance was excavated nearby to allow tourists to visit, and later an elevator was installed when the cave was acquired by the National Park Service. Exploration was rapid at first, as the owners and tour operators explored on their own throughout many kilometers of passage. After the cave became part of a national park, exploration slowed considerably, but increased again in the 1960s thanks to volunteer cavers. The cave now contains 223 km of mapped passages (world's fifth longest).

Jewel Cave was first entered in 1900. It had no accessible entrance, but wind blowing out of a narrow slot led some local landowners to blast into the cave. It soon became a National Monument. The known extent of the cave remained small for decades, but from the late 1950s through 1980 a team led by local cavers Herb and Jan Conn pushed the limits to about 90 km. Since then, exploration and mapping have been conducted by a small group of Park Service employees and local cavers. The cave now contains 262 km of mapped passages and is second longest known in the world. Its passage size and area are about twice that of Wind Cave. Remote areas in both caves are difficult to reach because of many very tight places and irregular profiles.

Underground Wind

The cave entrances, and narrow passages inside, contain tremendous barometric winds that respond to weather patterns. All openings to the caves inhale and exhale in unison. In the 1990s, during a sudden rise in atmospheric pressure, a Wind Cave ranger held an anemometer to the large walk-in entrance, and the meter immediately shot up to its greatest capacity of 110 km/hr. That rate continued for hours.

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In 1966, explorer Herb Conn used home-made equipment to make the first study of the winds. He estimated that only a tiny percentage of the caves had been explored. In recent years, with the known size of the caves much larger, Andreas Pflitsch (University of Bochum, Germany) has made more extensive and accurate measurements to show that the known caves are still only a tiny percentage of their true size. How far do these caves extend?

Geological Puzzles

The caves are insanely complex. In places there are up to 8 different levels that cross each other. Some parts of Wind Cave have a passage density so great that it is almost impossible to show them on a map. The passages cover more area than the spaces between.

The cave patterns are also unusual. These are not simple network mazes of straight intersecting fissures. The passages are extremely irregular, both horizontally and vertically. Narrow passages alternate with large rooms. In many places, this author (who is no giant) must remove most of his clothing to pass through the tight parts of even the main routes. In general, the passages slope along the limestone beds and do not form clear levels, such as those that correspond to former positions of the water table.

In Jewel Cave, most passages are coated with layers of large calcite crystals that average 15 cm thick. In contrast, most of Wind Cave is lined with boxwork – a network of protruding sheets of calcite in a box-like arrangement. Both caves contain ancient sediment where they intersect the paleokarst. Exploring these caves requires great care to avoid damaging delicate features.

The caves are concentrated in parts of the limestone that are capped by a thin layer of overlying Minnelusa sandstone. They very rarely extend up-dip into the area where the limestone is exposed directly at the surface. Where they do, those passages are small, few, and short. The passages also do not extend down the dip very far. Only a few passages in Wind Cave reach the water table, and Jewel Cave does not intersect the water table at all. The caves do not reach the top of the limestone, except in a few places along paleokarst zones. Nor do they reach the bottom of the limestone. In a sense, the caves are “floating” within the limestone and have no significant contact with the outside world.

It is only along the strike of the beds – perpendicular to the dip of the limestone, and parallel to the perimeter of the Black Hills – that the caves extend with no apparent limits. This seems reasonable, because it is in that direction that the speleogenetic conditions remain most uniform. But this means that caves might extend all around the Black Hills with almost no interference.

Arguments about Cave Origin

How did these caves form? Over the past century, diverse arguments have included (1) rising thermal water; (2) confined groundwater moving down-dip to springs; (3) infiltration through the porous sandstone; and (4) relics of the 300-million-year-old paleokarst. All are supported by certain clues, and so the debate continues today.

Evidence for rising thermal water includes the lack of stream passages, maze pattern, ceiling cupolas, and thick crystal coating on many walls. The model is elegant: as groundwater rises, it cools and is able to dissolve more limestone. But as the water table drops below the cave ceiling, loss of CO_2 causes deposition of calcite crystals. This origin is thought to explain the thermal caves of Budapest; but it does not seem to fit the Black Hills, because the caves do not extend to the top or bottom of the limestone. The best support for cave origin by confined flow within the Madison Limestone is the agreement with the present-day groundwater pattern. Today, water drains through the limestone toward the outer edges of the Black Hills and rises to springs around the outer edges of the hills. The maze pattern is also widely considered to be typical of confined flow. But why do the known caves not extend up-dip or down-dip beyond the areas covered by the Minnelusa sandstone?

Infiltration through the overlying Minnelusa sandstone is rarely considered, but this idea is supported by the distribution of caves beneath the thinnest parts of the sandstone. Maze caves are also typical of diffuse infiltration through sandstone, but for that idea to be valid, the caves should cluster at the top of the limestone, directly below the contact with the sandstone. Finally, if the caves are simply remnants of the Carboniferous paleokarst, why do they cluster only beneath the thin cover of sandstone?

Alone, none of these hypotheses is correct. Together, perhaps all of them are. This requires some explanation, which follows:

Reconstructing the past

Interpretation of these caves requires some laboratory work, but it starts by simple underground observations. Evidence for all of the following can be easily seen in the caves:

The Earliest Caves

The cave walls contain many pockets that seem much older than the caves themselves. This is not surprising in paleokarst zones, but many of these pockets are clearly older than the paleokarst. They appear to have formed soon after the limestone was deposited (~330 million years ago). The surrounding rock has been shattered into angular fragments cemented together by brown calcite. Most of the holes are lined by sharp calcite crystals with that same color.

Microscopic inspection shows that these features are the result of very early interaction between the limestone and local beds of gypsum. The gypsum was soft enough to flow in response to the weight of the overlying beds. Changes in heat and pressure also caused the gypsum to lose and re-gain some of the water that is part of its composition. Dissolution of gypsum also removed much of the support for overlying limestone beds. Much of the gypsum reacted with organic materials in the sea water to produce hydrogen sulfide (the rotten-egg gas, H_2S). This combined with dissolved iron to produce pyrite (FeS_2). As the region uplifted above sea level, fresh water from the surface began to replace the original seawater that saturated the rocks. Oxidation of pyrite and hydrogen sulfide produced sulfuric acid, which attacked the carbonate bedrock to produce the very first solutional holes. These voids are up to ~2 m in diameter and most are lined by calcite-cemented bedrock fragments, and later coated by yellow-brown calcite crystals. Most have been engulfed by later dissolution. The original holes can still be seen where bedrock collapse has exposed them in the present caves.

As the flow of fresh water increased, the remaining gypsum was replaced by calcite. Both calcite and gypsum contain Ca, but calcite is much less soluble. So when calcite-saturated water dissolves gypsum, the sudden increase in Ca forces calcite to precipitate. Iron oxides and fossil filaments of iron-oxidizing bacteria are abundant in this calcite, producing the distinct yellow-brown color. Uranium/lead (U/Pb) dating of this calcite confirms the Carboniferous age of the calcite. Thus the earliest solution pockets are more than 300 million years old.

The boxwork dates from the same time as the early fracturing. Orientations of the boxwork veins are highly scattered. Their small scale, high density, and diverse fracture patterns suggest a relation to the early stresses produced by the movement, recrystallization, and dissolution of the interbedded gypsum. At first the fractures were filled with gypsum. Although sulfuric acid dissolved the limestone, it had almost no effect on the gypsum veins, which protruded from the limestone as boxwork. Later the gypsum veins were replaced by calcite as the flow of fresh water increased. The boxwork seen today has been strengthened and thickened by later calcite growth. This type is rare in most caves, but it is common in certain mining regions.

The bedrock alteration and boxwork are concentrated only in the caves and disappear a few tens of centimeters into the surrounding bedrock. These features are rare in surface exposures.

Carboniferous Karst and Caves

Already the Black Hills caves had a history more complex than is seen in most karst areas – and long before the Black Hills formed. Time for another phase of cave development! As the land continued to be lifted above sea level, about 330 - 300 million years ago, the limestone was exposed to surface weathering. A karst surface of dolines and fissures was produced, and caves formed in local zones about 20 - 40 m below the karst surface. These represented the main phase of what is now the paleokarst that occurs at the top of Carboniferous limestone throughout most of the western USA. In North America the Carboniferous Period is divided into Mississippian (older) and Pennsylvanian (younger), separated by an erosion surface and usually paleokarst.

Most of the caves and fissures were limited to the upper third of the Madison limestone. Exposures in canyon walls and in the present caves show that the Carboniferous caves were mainly low arched rooms up to roughly 8 m wide and high. They appear to have survived deep burial, and also later uplift of the Black Hills, without much change. Large upper-level rooms in the present caves are apparently enlarged versions of these caves.

The early gypsum-hosted fractures, boxwork veins, etc., surround the remnants of these early caves and are intersected by them, so it appears that the earliest caves and karst features were guided by the even older fracture zones. These paleo-caves resemble present-day caves that form in zones of mixing between fresh water and sea water, as is typical of seacoast caves.

Deep Burial of Early Caves

The continent surface subsided again later in the Carboniferous Period. All of the surface depressions and most of the caves in the future Black Hills area were completely filled with sediment (Minnelusa Formation), which directly overlies the Madison carbonate rocks. Some paleo-caves have only thin fine-grained deposits of this material on their floors, which suggests that the caves were well isolated from the overlying sedimentary deposits. Sediments that filled the dolines and fissures are clearly exposed in the caves today. The earliest sediments were carbonate sand produced by weathering of the local limestone. These are overlain by yellow clay and quartz silt beds, and then by poorly bedded red sand containing bedrock fragments. This clearly defined sequence is important for determining whether the paleo-sediment is in its original position, instead of disturbed or redistributed by later mountain uplift or by gravity.

Sediment continued to be deposited through the Mesozoic Era, burying the paleokarst to depths of 2 - 3 km. During deep burial, a thin coating of pure white calcite was deposited on the walls of all caves and solution pockets that were not completely filled with sediment. It also lined pockets in the paleofill. U/Pb dating of this calcite has so far been unsuccessful because of its low uranium content. But it contains isotopic evidence for high temperature, which agrees with the deep-burial interpretation.

Mountain Uplift and Cave Enlargement

Uplift during the late Cretaceous and early Cenozoic allowed the sedimentary rocks to be removed from the central Black Hills, while their eroded edges were exposed around the perimeter. Groundwater flow increased, and by about 30 - 40 million years ago the flow pattern reached the situation we see today, where most of the Madison groundwater rises to surface springs through the overlying Minnelusa Formation along fracture zones, especially along anticlinal crests. The paleokarst was partly uncovered and paleo-caves were enlarged. Some new caves were formed, but they tended to follow the paleokarst zones because those were the most favorable flow paths. When the present caves formed, the topography had reached a stage nearly identical to that of today. Most cave walls show evidence that after their main phase of enlargement they were exposed to lengthy weathering above the water table.

Late Cenozoic Burial and Uncovering

During the Oligocene-Miocene Epochs, about 30 - 15 million years ago, drying of the climate caused thick deposits of sediment (gravel, sand, clay, volcanic ash) to accumulate in the plains around mountain uplifts. The edges of the Black Hills were covered to elevations of more than 1800 m. The caves and surrounding landscapes were buried. Weathered bedrock surfaces in the caves were coated with calcite during the last half of this time, when the springs along the edges of the Black Hills were buried and groundwater stagnated. In Jewel Cave, where these crusts average about 15 cm thick, U/Pb dates give a range of 26 to 14.7 million years. The last date was apparently when enough sediment had been eroded to uncover the springs and allow the cave to drain once more. Wind Cave is still draining, and its lowest wall crusts are of Pleistocene age (less than 250'000 years). The mid-Cenozoic landscape that is contemporary with the caves is still being uncovered and is well preserved in today's semi-arid climate. This late-Cenozoic burial and re-exposure represents yet another phase of paleokarst. All of these events, from early Carboniferous onward, have produced a karst system that may be more complex in history and detail than any other documented in the world.

Speleogenesis: Some Conclusions

Most of the cave enlargement took place in slow phreatic flow, where mixing of several sources could take place along the paleokarst zones, which afforded the greatest permeability. The caves show little or no evidence for rapid groundwater flow except for local boulders carried in from intersecting canyons during floods. Presently accessible caves are highly constrained upward, downward, up-dip, and down-dip. The caves have their greatest extent along the strike of the beds, maintaining a somewhat narrow vertical range. This pattern suggests that dissolution was focused where groundwater converged from many sources – a combination of water sinking along the eroded edge of the limestone, infiltrating from above through the Minnelusa, and probably also rising from below. Each source had a different chemical character (for example, CO_2 content), and the mixture would be more solutionally capable than any individual source.

So what hypothesis of cave origin explains these caves – thermal, confined, diffuse infiltration, paleokarst relics? All of them apply at different times and to different degrees. Often several of them operated at the same time. Also, the character of the caves has been affected by many processes that are not usually considered speleogenetic, such as early chemical changes in the bedrock. The caves have recorded the entire geological history of the area since the limestone was deposited, and each phase can still be clearly recognized by careful observation. This, more size and extent, is what makes these caves so unusual.

Unanswered Questions

Explorers wonder why their discoveries sometimes expand into huge areas, but pinch down to tight passages elsewhere – or simply end with no continuation at all. Despite the dense array of passages seen in the accessible caves, most surface canyons contain very few cave passages in their walls. The caves are not uniformly distributed. Is this related to the pattern of the original distribution of gypsum deposits, which were so important in producing the earliest fractures and solutional openings?

How far do the caves extend along the perimeter of the Black Hills? The air-flow studies show that there is enough cave volume to account for the entire zone of cave-friendly limestone between Jewel Cave and Wind Cave, which are separated by more than 30 km along the limestone outcrop. Will Wind Cave and Jewel Cave ever be connected? The air-flow measurements show a poor correlation between the two, but suggest that they could come very close to each other. Explorers realize that a true connection by humans is essentially impossible because of the many interruptions in the caves caused by faulting and unexplained constrictions. Even if there is a humanly passable connection, no one can imagine the time and effort required for a through-trip from one to the other. Even today, most of the deep exploration involves multi-day trips that include camping. Wells and canyons near Jewel Cave show enormous winds that correlate with those of Jewel Cave. Other entrances will undoubtedly be dug in the future to provide easier access to yet-unexplored regions.

In all respects these caves pose a challenge not only to exploration but also to the interpretation of complex geologic processes.

For references and further information, see www.speleogenesis.info.

Art Palmer

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