# EVOLVING INTERPRETATIONS OF HYPOGENE SPELEOGENESIS IN THE BLACK HILLS, SOUTH DAKOTA

*Arthur N. Palmer[1] and Margaret V. Palmer[1]*

The origin of caves in the Black Hills has long been debated. Their history is long and complex, involving early diagenesis, meteoric karst (now paleokarst), deep burial, tectonic uplift, and, finally, enlargement of previous voids to the caves of today. The final stage is usually the only one recognized and is the topic of this paper. Genetic hypotheses include artesian flow, rising flow (preferably thermal), diffuse infiltration, and mixing of various water sources. The last process best fits the regional setting and water chemistry.

## INTRODUCTION

The Black Hills were formed by Laramide uplift between 65 and 30 Ma. The central peaks consist of Precambrian igneous and metamorphic rock, and the truncated edges of overlying sedimentary strata dip off to the sides, forming concentric ridges and valleys around the central mountains. Caves are located in the Madison Formation (limestone and dolomite) of early Carboniferous age (Mississippian in North America). The largest caves (Wind and Jewel) are dense fissure networks with several levels concordant to the strata, which locally dip about 5 degrees away from the central uplift.

Their main (final) phase of cave origin has long been debated. Most of the accepted hypotheses involve hypogene processes. They have been attributed by various researchers to (a) artesian flow, (b) rising water, probably thermal, (c) enlargement of relict paleokarst, (d) diffuse recharge through the basal sandstone of the overlying Minnelusa Formation, and (e) mixing of two or more water sources. Each model is examined below vs. local cave morphology, geology, hydrology, and geochemistry. There is evidence for each, some of it spotty, but only the last process (e) survives the scrutiny. Our own interpretations have evolved considerably over the past 35 years.

## CAVE MORPHOLOGY

The caves occupy only the upper 100-150 m of the limestone. They are located only beneath the thin up-dip edge of the Minnelusa Formation, which consists mainly of quartz sandstone (Palmer and Palmer, 1989; Wiles, 2005). Updip from the edge of the Minnelusa the caves become very sparse and disappear a short distance away. They are also very sparse beneath incised valleys that have cut through the Minnelusa into the limestone. Passages beneath the limestone do not terminate in breakdown, but instead simply stop or become very narrow. The caves contain no significant vadose passages. Instead they give the impression of being entirely phreatic, with many domed ceilings and cupolas. Most of these, however, appear to have formed by condensation corrosion via convection cells, a process that continues today.

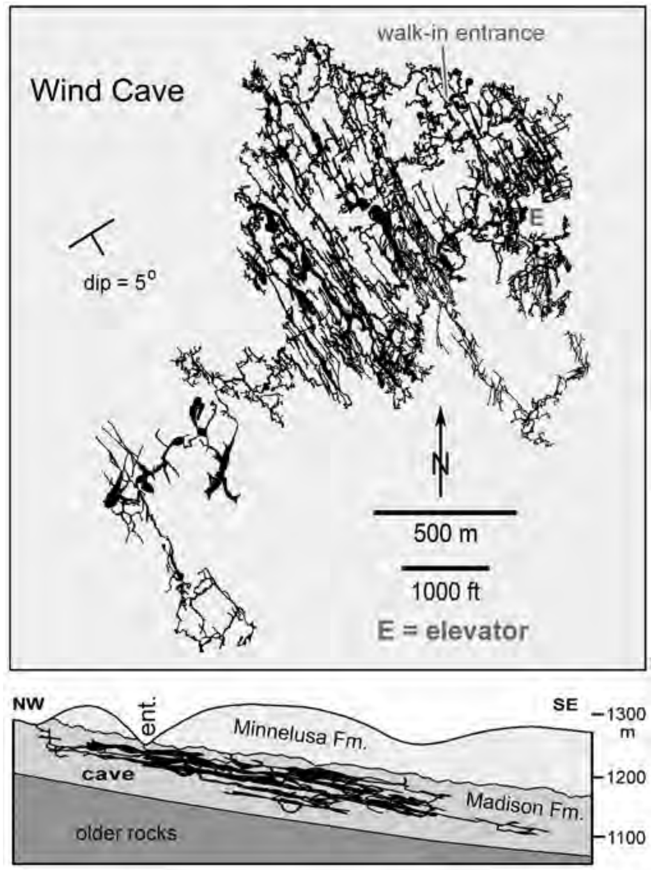


Figure 1. Plan view and simplified geologic profile of Wind Cave, Wind Cave National Park, in the southeastern Black Hills.

The caves do not extend beneath the areas of thick overlying Minnelusa or indefinitely below the water table. The water table is reached in only a few places in Wind Cave, with no hint that the caves continue to depth. Jewel Cave does not reach the water table at all. The caves reach the top of the limestone in only a few places where irregularities in a paleokarst surface extends downward. (See Sando, 1988, for a regional description of this paleokarst.) The only direction in which they seem unlimited is along the strike of the beds. The caves are essentially "floating" in the Madison, with almost no contact with boundaries.

[1]619 Winney Hill Road, Oneonta, NY 13820, USA

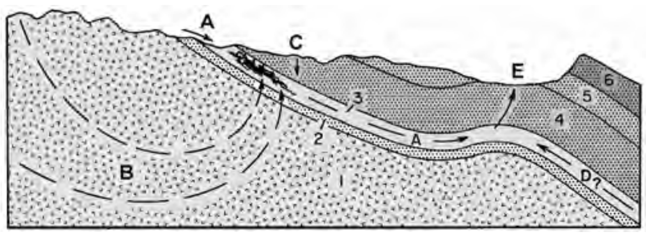


Figure 2. Profile of a typical cave in the Black Hills, showing potential paths for the water flow that formed it. 1 = Precambrian metamorphic and igneous rocks. 2 = Deadwood Sandstone and other strata (mainly Cambrian). 3 = Madison Limestone (Mississippian, lower Carboniferous). 4 = Minnelusa Formation (upper Carboniferous, Pennsylvanian – lower Permian). 5, 6 = overlying strata, mainly shales and sandstones (Triassic–Cretaceous). A = water entering the outcrop area of the limestone (autogenic seepage, allogenic streams). B = rising water, possibly thermal, recharged from the higher hills. C = diffuse recharge through the lower beds of the Minnelusa Formation (mainly sandstone, but with carbonate and sulfate interbeds). D = up-dip flow from surrounding lowlands (unlikely, because it would appear to be against the hydraulic gradient). E = major springs around the perimeter of the Black Hills, where confined water in the Madison passes upward along faults and breccia in the upper Minnelusa and overlying strata (see Rahn and Gries, 1973).

## HYPOTHESES OF CAVE ORIGIN

### Artesian Flow

An artesian origin was favored by many early studies, because the Madison is a well-known semi-confined aquifer overlain by low-permeability rocks (Tullis and Gries, 1938; Deal, 1962; Howard, 1964). Water rises in the valleys around the Black Hills by rising upward along faults and breccia zones. Up-dip from the major caves are broad valleys, drained today only by small under-fit streams, which indicate significant sources of recharge in the past (Palmer and Palmer, 2008). Such recharge points could have provided the flow necessary to form the caves. However, an artesian origin would produce caves that extend indefinitely down the dip, with their maximum size in the recharge area and diminishing size in the direction of flow. Network patterns have long been associated with artesian flow, but when examined in detail this relationship has little hydrochemical merit (Palmer, 1991). The caves do not extend far in the up-dip or down-dip directions. They cease where the overlying Minnelusa is thick or absent.

### Thermal Hypogene Hypotheses

An origin by rising thermal water has gained great favor by the discovery of thermal minerals (quartz crystals, crystalline hematite) and calcite with highly negative oxygen isotopes ($\delta^{18}O$) down to -21‰ (White and Deike, 1962; Bakalowicz et al., 1987). Cupolas and other features resemble those of known thermal caves, as in Budapest, and boxwork veins resemble those of mining areas (Bakalowicz et al., 1987; Ford, 1989). Thick calcite crusts (up to 15 cm) suggest deposition during the last phases of thermal speleogenesis, when rising water approached the water table, degassed, and became supersaturated with calcite. These are strong arguments. However, the thermal minerals, and those with lowest $\delta^{18}O$, formed in palokarst voids during 200 My of deep burial prior to mountain uplift and were intersected by the main cave enlargement. The thick calcite crusts overlie bedrock with deep subaerial weathering, and also cover many older vadose speleothems. They do not relate to the cave origin per se. The lightest oxygen isotopes are those of a 1-cm-thick crust of white scalenohedral calcite, which lines only the remnants of paleokarst voids and was clearly formed during deep burial prior to mountain uplift (Palmer and Palmer, 2008). No dates are available for them because their U content is too low – typical of deep-seated deposits remote from redox boundaries. However, the thickest calcite crusts show U/Pb dates of 25-14.7 Ma (Victor Polyak, in Palmer et al., 2009). These coincide with the peak thickness of the Oligocene White River sediments, which covered springs in the outskirts of the Black Hills and were removed by well-documented mid-Miocene erosional entrenchment (Harksen and Macdonald, 1969; Gries, 1996). So the main cave origin pre-dates the late Oligocene and has been inactive since, except for minor vadose corrosion and deposits. Younger calcite crust has U/Th dates of <300 ka (Ford et al., 1993; Paces et al., 2013). Its fluctuations correlate with late Pleistocene climate variations, and with aggradation and entrenchment of nearby surface rivers.

Finally, the caves do not extend down-dip, and they do not reach the base of the limestone anywhere. Also, they reach the top of the limestone only in a few scattered areas, which are mainly choked with paleokarst fill. This shows that the caves could not have formed by water rising across the strata. Water rising concordantly up-dip through the Madison is a possibility, but it cannot explain why the caves terminate so abruptly both down-dip and up-dip. Also, this water movement would have been against the regional flow pattern, which appears to have been similar to that of today (see reference to thick calcite crusts above). Finally, the clustering of caves beneath the thin Minnelusa cap cannot be accounted for, when we consider that unimpeded flow through nearby uncapped Madison would have been readily available. However, there will always be some enthusiasm for a thermal hypogenic origin, despite formidable limitations.

### Thermal Alteration

A relation to late Eocene thermal mineralization is possible, and a magnetic anomaly in the Precambrian below Wind Cave may be pertinent (Kleinkopf and Redden, 1975; Hildenbrand and Kucks, 1985). Many aspects of mineralization in the northern Black Hills resemble those of the boxwork zones in the caves. However, there is strong evidence that the boxwork and other suspect features in the caves are of early diagenetic origin and involved Mississippian sulfate-carbonate interactions, because they do not extend into the paleokarst zone and are covered by deep-burial thermal minerals that pre-date tectonic uplift. Even if the main phase of cave origin has no relation to the Eocene mineralization, the influence of mineralizing fluids should be considered. There is evidence that anoxic fluids entered the caves during the Cenozoic, as shown by Fe and Mn oxides along minor faults.

## Enlargement of Paleokarst Voids

Enlargement of paleokarst voids has clearly taken place, because the caves intersect many solution pockets lined by deep-burial minerals, including the white scalenohedral calcite (Palmer and Palmer, 1989). The caves are also concentrated around zones of paleokarst, which includes relics of both early diagenetic features and meteoric karst from dissolution of the Madison prior to deposition of the overlying Minnelusa. Nearby canyons in the Madison encounter a few paleo-pockets, but no major caves – definitely not the great density of passages seen in the caves. The diagenetic features (Mississippian) appear to have formed along zones of former anhydrite, as they include much carbonate breccia, calcite veins, early solution voids, and anhydrite inclusions. The meteoric paleokarst (Mississippian-Pennsylvanian) concentrated around the diagenetic features; and the final cave origin concentrated on enlarging both sets of the earlier voids. But the real question centers on the nature of the water that enlarged these voids to form the present cave.

## Diffuse Infiltration

Diffuse recharge through the basal Minnelusa Formation is mildly attractive because many network mazes in other regions cluster beneath thin sandstone caps. However, the caves reach the sandstone/ limestone contact in only a few places, and the upper levels that do reach the contact are sparse irregular rooms, rather than fissure networks. Still, there is some recent support for this idea: Michael Wiles (Jewel Cave, personal communication, 2013) envisions water passing laterally through the Minnelusa, with local loops down into the Madison and then back up again. It is difficult to envision a distribution of hydraulic head that would achieve this flow pattern.

## Mixing Processes

Mixing of two or more water sources of contrasting chemistry applies to seacoast aquifers, but does it also apply in the Black Hills? The model of Bögli (1964) and other authors is pertinent here, where two waters of contrasting $CO_2$ content mix to produce an undersaturated solution. Consider diffuse recharge through the thin sandstone base of the Minnelusa combined with recharge from the outcrop area. Both are active today, but neither contributes significantly to cave enlargement. Most of this paper deals with this model because it seems valid and yet is so seldom discussed. If these two sources were able to mix before the water table dropped, they could have produced the cave in the following way:

Recharge through the sandstone encounters interbedded carbonate rocks near the Minnelusa/Madison contact, and eventually the Madison itself. In closed conditions, with no access to the cave air or soil air, the water would reach calcite saturation at a very low value (~12-15 mg/L) and with extremely low $PCO_2$ (<0.0001 atm). Meanwhile, the water entering from the outcrop area would also have been close to saturation because of low flow rate and lengthy contact with the Madison carbonates. It would have approached calcite saturation at about 200 mg/L with $PCO_2$ of roughly 0.005 atm. A mixture of both saturated waters would produce an undersaturated solution capable of dissolving limestone. Mixing and dissolution would have focused on the old paleo-voids, because they offered the highest permeability. The result is what we see in the caves today, at least where the younger calcite crusts are absent.

This hypothesis may seem absurd, but the two waters involved in this process are still present in greatly diminished form, especially in Wind Cave. Trickles of water still enter through the limestone outcrop, and moisture still seeps through the sandstone into the limestone and eventually through the limestone roof. Chemical measurements of these two sources today show a $PCO_2$ of the diffuse infiltration to be unusually low – around 0.0006 atm. Small streams fed by recharge from the limestone

Figure 3. Intense corrosion by seepage of low-$PCO_2$ water into Mammoth Cave, Kentucky, after closed-system dissolution of limestone at the base of a sandstone cap-rock. The $PCO_2$ of the cave air is 0.0008 atm – very low for cave atmosphere. And yet the incoming seepage water readily absorbs $CO_2$ from the cave air and becomes highly aggressive.

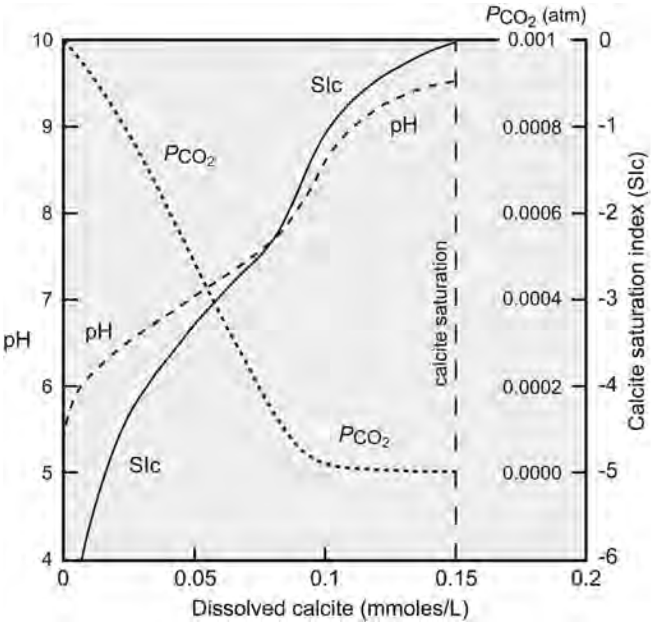


Figure 4. Evolution of water chemistry during closed-system dissolution of limestone. Note the extremely low $PCO_2$ and high pH of the water while it remains within the closed system.

outcrop have a higher $PCO_2$ of ~0.003 atm. $PCO_2$ of the cave atmosphere is ~0.00125 atm, according to analysis of standing pools water. (All analyses calculated from measurements of water chemistry in Back 2011 and Long et al., 2012.) Clearly, before the pH was measured, the diffuse infiltration water had gained $CO_2$ from the cave air, and the water from the outcrop had lost $CO_2$ to the cave air by degassing.

Mixing of these two waters would produce a solution undersaturated with calcite. Undersaturation would have been much greater if these waters had entered a water-filled cave where degassing into the atmosphere could not take place. If it were possible to measure the initial water sources (described above Figures 3 and 4), the amount of undersaturation would be about twice as great. The cave would be concentrated in the mixing zone and could not extend very far down-dip because the solutional aggressiveness would have been largely exhausted – as in mixing-zone caves in seacoast aquifers today.

Most of the present infiltrating water corrodes the cave ceiling, but it has little chance to mix with inflowing water from the limestone outcrop areas, as it did when the caves were presumably filled with water. Also, the water supply appears to be much less today than when the caves were actively enlarging, as shown by the large paleo-valleys up-slope from the caves.

Measurement of infiltration rate through the Minnelusa cap has been measured at both caves by Wiles (1992). They indicate an estimated 12,000 $m^3/yr/km^2$ of infiltration. Again, in today's semi-arid climate the recharge rate appears to be much less than in the past. The landscape has long been rather static, less so than today with its Pleistocene entrenchment. But even using

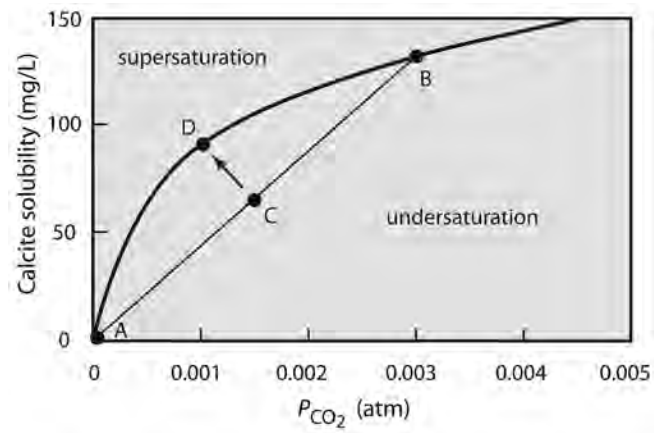


Figure 5. Effect of mixing corrosion between two waters similar to those entering Wind Cave today through the Minnelusa cap-rock (A), and from the Madison outcrop (B). Although both are at or near saturation at their respective $PCO_2$ values, the mixture (C) would be highly undersaturated if mixing took place rapidly. In reality, equilibrium is reached by a continuous migration toward D (following closed-system evolution where $CO_2$ is consumed as calcite dissolves). The overall dissolution rate is governed mainly by the rate of input of the smaller water source, probably the infiltrating water. Note the optimum effect caused by one source having virtually zero $PCO_2$.

Figure 6. Limestone blocks (embedded in paleokarst fill) are being corroded today by seepage water entering Wind Cave today through overlying sandstone and sandy sediment at the base of the Minnelusa Formation (Many similar-looking cupolas and domes are formed instead by condensation corrosion).

the present recharge rates, and water chemistry compromised by $CO_2$ exchange with the cave air, the caves could have been generated within 2 million years. If adjustments are made for the likely water chemistry when the caves were water-filled, the required time would be closer to 1 million years. Was this time span available? Keep in mind that the caves are adjusted to the present landscape and outcrop pattern, and that the thick calcite wall crusts were deposited in the late Oligocene, more than 20 million years ago. The landscape remained nearly static during speleogenesis and has not changed substantially since then.

## CONCLUSIONS

The mixing model, unlikely as it might seem, avoids all of the pitfalls that trouble the other models. It accounts for the cave distribution, fits the geomorphic history, and, most importantly, it relies on geochemistry that is still valid today. There are still some unanswered questions about the nature of meteoric recharge when the caves were enlarging in the mid-Oligocene.

The speleogenetic water was not rising, so by some definitions this process would not be considered hypogenic (e.g., Klimchouk, 2007). Palmer (1991) defines hypogenic cave development as that where aggressiveness is generated by chemical processes below the land surface. By this definition, the mixing process envisioned for the Black Hills caves would qualify as hypogenic, and mixing-zone caves in seacoast aquifers would as well. Many of the features in caves of this origin are similar to those formed by rising water. There is no simple distinction between epigenic and hypogenic cave origin, and therefore any discussion of speleogenesis should include a description of the exact nature of the water source and its chemical aggressiveness.

There is more to the story. The initial sulfate beds within the limestone, together with the diagenetic and meteoric phases of early karst, were essential in preparing the way for Cenozoic enlargement of the caves to their present size. Their genesis also has some open-ended questions, but that topic is beyond the scope of this paper.

## ACKNOWLEDGMENTS

Many thanks to the following: the staff at Wind Cave National Park and Jewel Cave National Monument, both past and present, for their encouragement over the past 35 years; to Victor Polyak of Univ. of New Mexico, Jim Paces of U.S. Geological Survey in Denver, and Derek Ford of McMaster University for dating and isotopic analysis of cave calcite; to Mark Fahrenbach, South Dakota Geological Survey, and John Stamm and Andy Long, U.S. Geological Survey, Rapid City, for information on local geology and water chemistry; to Jeff Hughes and Jennifer Back (NPS, Ft. Collins) for support, and to Dwight Deal (Colorado), Derek Ford, and Mike Wiles (Jewel Cave) for discussions on cave origin.

## REFERENCES

Back J. 2011. Geochemical investigation of the Madison Aquifer, Wind Cave National Park, South Dakota. National Park Service, Natural Resources Program Center, Fort Collins, Co., 50 p.

Bakalowicz M., Ford D., Miller T., Palmer A., Palmer M. 1987. Thermal genesis of dissolution caves in the Black Hills, South Dakota. Geological Society of America Bulletin, 99: 729–738.

Bögli, A. 1964. Mischungskorrosion, ein Beitrag zur Verkarstungs-problem [Mixing corrosion, a contribution to the problem of karstification]: Erdkunde, 18:83−92.

Deal D. 1962. Geology of Jewel Cave National Monument, Custer County, South Dakota. M.A. thesis, University of Wyoming, Laramie, Wyo., 183 p. + 3 plates.

Ford D. 1989. Features of the genesis of Jewel Cave and Wind Cave, Black Hills, South Dakota. National Speleological Society Bulletin, 51(2): 100−110.

Ford D., Lundberg J., Palmer A., Palmer M., Schwarcz H., Dreybrodt W. 1993. Uranium-series dating of the draining of an aquifer: The example of Wind Cave, Black Hills, South Dakota. Geological Soc. America Bulletin, 105: 241–250.

Gries, J. 1996. Roadside geology of South Dakota. Mountain Press, Missoula, Montana, 358 p.

Harksen J., Macdonald, J. 1969. Guidebook to the major Cenozoic deposits of southwestern South Dakota. South Dakota Geological Survey, Guidebook 2, 103 p.

Hildenbrand T., Kucks R. 1985. Model of the geothermal system in southwestern South Dakota from gravity and aeromagnetic studies. In W. Hinze (Ed.). The utility of regional gravity and magnetic anomaly maps. Society of Exploration Geophysics, pp. 233–247.

Howard A. 1964. Model for cavern development under artesian ground water flow, with special reference to the Black Hills. National Speleological Society Bulletin, 26(1): 7−16.

Kleinkopf M., Redden J. 1975. Bouguer gravity, aeromagnetic, and generalized geologic maps of part of the Black Hills of South Dakota and Wyoming. US Geological Survey, Geophysical Investigations Map GP-903, 11 p.

Klimchouk A. 2007. Hypogene speleogenesis: hydrogeological and morphogenetic perspective. National Cave and Karst Research Institute, Carlsbad, NM, Special Paper 1, 106 p.

Long A., Ohms M., McKaskey J. 2012. Groundwater flow, quality (2007-10), and mixing in the Wind Cave National Park area, South Dakota. U.S. Geological Survey, Scientific Investigations Report 2011-5235, 50 p.

Paces J., Palmer, A., Palmer, M. 2013. History of late Pleistocene water-table fluctuations in Wind Cave: Progress Report, February 2013. Open-file report, National Park Service, Ft. Collins, Co., 40 p.

Palmer, A. 1991. Origin and morphology of limestone caves. Geological Society of America Bulletin, 103: 1–21.

Palmer A., Palmer M. 1989. Geologic history of the Black Hills caves, South Dakota. National Speleological Society Bulletin, 51(2): 72−99.

Palmer A., Palmer, M. 2008. Field guide to the paleokarst of the Black Hills. In: I. Sasowsky, C. Feazel, J.E. Mylroie, A. Palmer, and M. Palmer (Eds.). Karst from Recent to Reservoirs. Karst Waters Institute, Leesburg, Va., Special Publication 14, pp. 157–162.

Palmer A., Palmer M., Polyak V., Asmerom Y. 2009. Geologic history of the Black Hills caves, South Dakota, USA. International Congress of Speleology, Kerrville, TX, Proceedings 2, pp. 946-951.

Rahn P., Gries J. 1973. Large springs in the Black Hills, South Dakota and Wyoming. South Dakota Geological Survey, Report of Investigations 107, 46 p.

Sando W. 1988. Madison Limestone (Mississippian) paleokarst: A geologic synthesis. In: N.P. James and P.W. Choquette (Eds.) Paleokarst. Springer-Verlag, New York, pp. 256–277.

Tullis E., Gries J. 1938. Black Hills caves. The Black Hills Engineer, 24(4): 233–271.

White W., Deike G. 1962. Secondary mineralization in Wind Cave, South Dakota. National Speleological Society Bulletin, 24: 74–87.

Wiles M. 1992. Infiltration at Wind and Jewel Caves, Black Hills, South Dakota. M.S. thesis, South Dakota School of Mines and Technology, 70 p.

Wiles M. 2005. Mapping surface geology to protect cave and karst resources of the Jewel Cave System [abstract]. Proceedings, 17th National Cave and Karst Management Symposium, Albany, N.Y., p. 165.