Hydrology, Hazards, and Geomorphic Development of Gypsum Karst in the Northern Black Hills, South Dakota and Wyoming

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Abstract

Dissolution of gypsum and anhydrite in four stratigraphic units in the Black Hills, South Dakota and Wyoming, has resulted in development of sinkholes and has affected formational hydrologic characteristics. Subsidence has caused damage to houses and water and sewage retention sites. Substratal anhydrite dissolution in the Minnelusa Formation (Pennsylvanian and Permian) has produced breccia pipes and pinnacles, a regional collapse breccia, sinkholes, and extensive disruption of bedding. Anhydrite removal in the Minnelusa probably dates back to the early Tertiary when the Black Hills was uplifted and continues today. Evidence of recent collapse includes fresh scarps surrounding shallow depressions, sinkholes more than 60 feet deep, and sediment disruption and contamination in water wells and springs. Proof of sinkhole development to 26,000 years ago includes the Vore Buffalo Jump, near Sundance, WY, and the Mammoth Site in Hot Springs, SD. Several sinkholes in the Spearfish Formation west of Spearfish, SD, which support fish hatcheries and are used for local agricultural water supply, probably originated 500 feet below in the Minnelusa Formation. As the anhydrite dissolution front in the subsurface Minnelusa moves down dip and radially away from the center of the Black Hills uplift, these resurgent springs will dry up and new ones will form as the geomorphology of the Black Hills evolves. Abandoned sinkholes and breccia pipes, preserved in cross section on canyon walls, attest to the former position of the dissolution front. The Spearfish Formation, mostly comprising red shale and siltstone, is generally considered to be a confining layer. However, secondary fracture porosity has developed in the lower Spearfish due to considerable expansion during the hydration of anhydrite to gypsum. Thus, the lower Spearfish yields water to wells and springs making it a respectable aquifer. Processes involved in the formation of gypsum karst should be considered in land use planning in this increasingly developed part of the northern Black Hills.

INTRODUCTION

The Black Hills of western South Dakota (fig. 1) is experiencing increased urban development requiring an assessment of ground-water contamination potential. Detailed bedrock and surficial geologic mapping, in cooperation with the Lawrence County Planning Commission and the City of Spearfish, SD, will be useful for assessing aquifer-contamination potential by describing major lithologic characteristics, delineating surface recharge areas, and characterizing subsurface structural configuration. The maps will also be useful for depicting areas of potential landsliding, soil erodability, and subsidence due to solution of underground gypsum and anhydrite.

The Black Hills comprise an asymmetric uplift, about 130 miles long and 60 miles wide. Erosion has exposed a core of Precambrian metamorphic rocks which are rimmed by shallow marine to nearshore-terrestrial sediments of Paleozoic and Mesozoic age which dip away from the center of the domal uplift (fig. 1). The homoclinal dips are locally interrupted by monoclines, structural terraces, low-amplitude folds, faults, and Tertiary igneous intrusions. One fold, the LaFlamme anticline, is a prominent structure west of Spearfish (see fig. 9). It plunges to the northwest, it is at least 10 miles long, about 8 miles wide, has a structural relief in places of more than 600 ft (260 m), and the dips on its flanks are as much as 20^{o}.

More than 300 ft (91 m) of gypsum and anhydrite were deposited at various times in evaporite basins. Rocks of the Madison Limestone (Pahasapa of other reports), Minnelusa Formation and older sediments form the “limestone plateau” that rims the central Precambrian metamorphic core. Erosion of weak red siltstones and shales of the Spearfish Formation has formed the "Red Valley" (fig. 1), the main area of present and proposed future development. Resistant sandstone forms the hogback that encircles the Black Hills and defines its outer physiographic perimeter.

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STRATIGRAPHY OF CALCIUM SULPHATE-BEARING ROCKS

Whereas karstic features in limestone and dolomite, such as caves, sinkholes, and underground drainage, are abundant in the Black Hills, similar solution features are also abundant in gypsum ($CaSO_4 \cdot 2H_2O$) and its anhydrous counterpart anhydrite ($CaSO_4$). Calcium sulphate rocks are much more soluble than carbonate rocks, especially where they are associated with dolomite undergoing dedolomitization, a process which results in groundwater that is continuously undersaturated with respect to gypsum (Raines and Dewers, 1997).

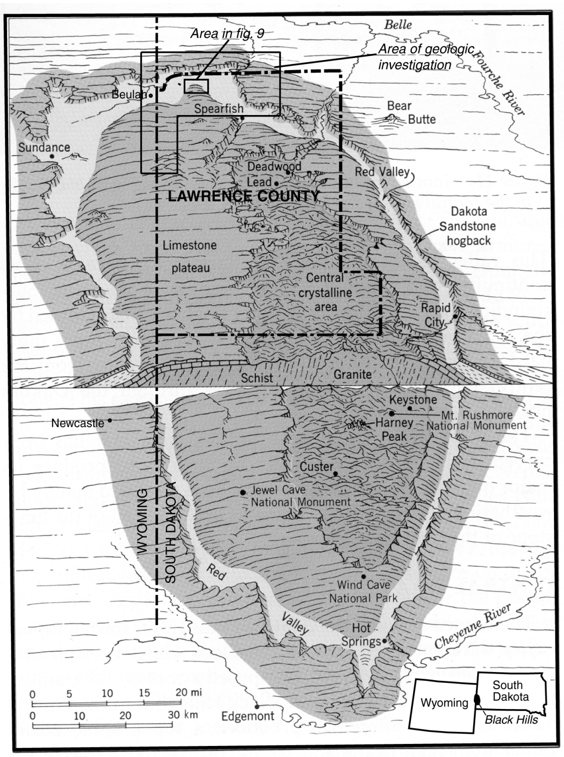

Fig. 1. Generalized diagram showing the geology and geomorphology of the Black Hills. Most of the urban development and karst features in Lawrence County are in the Red Valley, underlain by Triassic red beds (where gypsum karst is becoming a growing concern) and in the limestone plateau, underlain by a variety of Pennsylvanian and Permian rocks. Modified from Strahler and Strahler, 1987, with permission.

Gypsum and anhydrite are conspicuous evaporite deposits in four sedimentary rock units in the Black Hills (fig 2). They comprise about 30 percent of the Minnelusa Formation (generally present only in the subsurface), less than 5 percent of the Opeche and Spearfish Formations, and about half of the Gypsum Spring Formation.

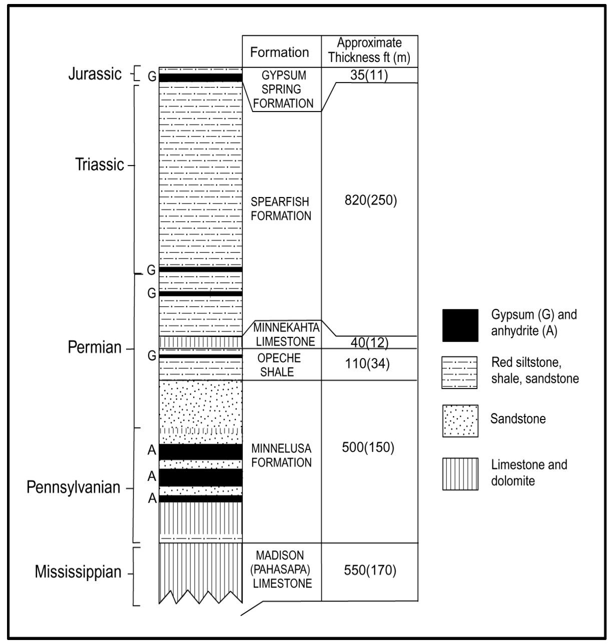

Fig. 2: Stratigraphic column showing distribution of gypsum and anhydrite in the northern Black Hills.

The Minnelusa Formation in the northern Black Hills consists of approximately 500 feet (150 m) of dolomite, sandstone, and shale with anhydrite prevalent in the middle. The anhydrite is mostly absent in surface outcrops, having been removed by solution in the subsurface. The solution of anhydrite and consequent formation of voids in the Minnelusa at depth resulted in foundering and fragmentation of overlying rocks, producing extensive disruption of bedding, a regional collapse breccia, many sinkholes, and breccia pipes and pinnacles (e.g., Epstein, 1958a,b; Brobst and Epstein, 1963; Bowles and Braddock, 1963)(Figs. 3,4,5). Some sinkholes and resistant calcite-cemented pinnacles extend upward more than 1,000 ft (300 m) into overlying strata (Bowles and Braddock, 1963). The collapse breccia consists of angular clasts of limestone, dolomite, and sandstone in a sandy matrix that is generally cemented with calcium carbonate. It has a vuggy secondary porosity, which, along with the porous sandstone, makes the upper half of the Minnelusa an important aquifer in the Black Hills.

Gypsum is not abundant in the 110 ft (34 m) of poorly exposed red shale, siltstone, and fine-grained

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sandstone of the Opeche Formation, a confining unit between the Minnelusa Formation and Minnekahta Limestone.

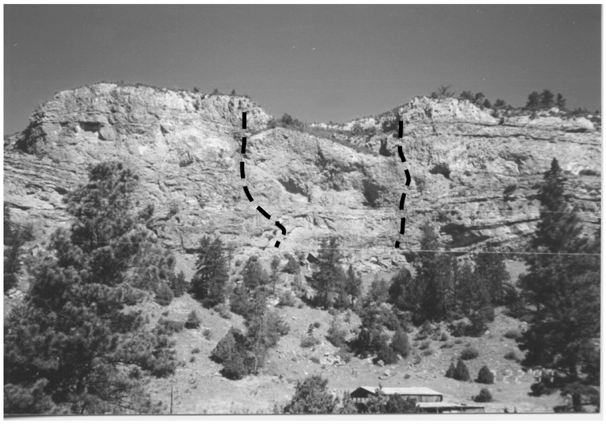

Figure 3. Sinkhole (outlined) in the Minnelusa Formation exposed on 400-foot-high cliff face in Redbird Canyon, about 10 miles east of Newcastle, WY, in Custer County, SD. The collapse resulted from removal of anhydrite by ground water prior to fluvial erosion, which exposed the sinkhole on the canyon wall.

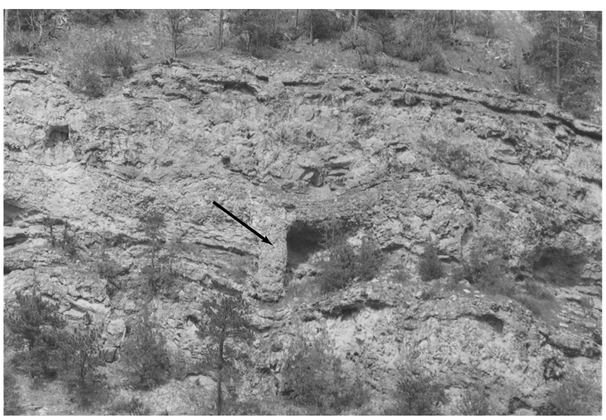

Figure. 4. Disrupted bedding and breccia pipe (arrow) in the Minnelusa Formation. Collapse and disruption were due to dissolution of anhydrite at depth. Cliff in Cold Brook Canyon, just north of Hot Springs, SD.

The Spearfish Formation consists of about 820 ft (250 m) of fine red beds with several layers of gypsum in the lower 200 ft (60 m). Anhydrite, which probably was the original form of calcium sulphate to be deposited in the Spearfish, undergoes about a 40 percent expansion when hydrated to form gypsum.

Figure 5. Erosion of resistant breccia pipe that is cemented by calcium carbonate forms a pinnacle that is common within the brecciated upper part of the Minnelusa Formation. Red Bird Canyon, about 10 miles east of Newcastle, WY.

As a result, beds of gypsum in the Spearfish Formation are commonly highly folded. When gypsum dissolves, it becomes mobile and is injected downward as thin veinlets into fractures in the confining red beds (fig. 6). These veinlets are generally less than ½ inch (1 cm) wide, they occur along a multitude of variably oriented fractures beneath the parent gypsum bed, and they contain gypsum fibers lying perpendicular to the fracture walls. Thus, the lower 200 ft (60 m) or so of the Spearfish has developed a secondary fracture porosity. This part of the formation has supplied water to wells, many sinkholes have developed in it, and resurgent springs are numerous. Ground water flows

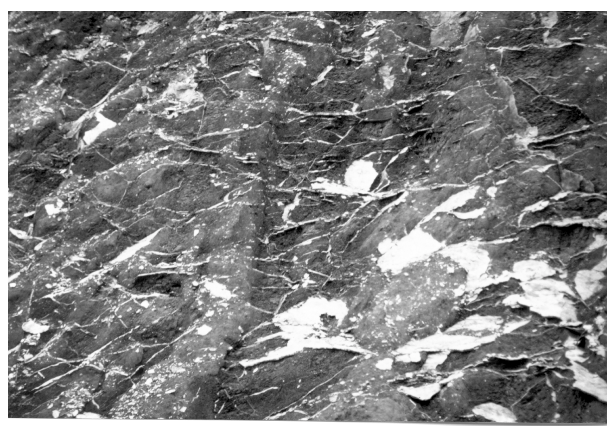

Figure 6. Thin gypsum veinlets extending down from parent gypsum bed (not shown) and filling a multitude of fractures in the lower part of the Spearfish Formation near Cascade Springs, along State Highway 71, 13 miles southwest of Hot Springs, SD.

through the fractures and solution cavities in the gypsum. Although many hydrologists consider the entire Spearfish Formation to be a confining unit, the lower 200 ft (60 m) of the Spearfish is an aquifer, in the northern Black Hills, at least. This is not surprising since high ground-water flow has been reported in gypsum in many areas of the United States (Thordarson, 1989).

The upper part of the Spearfish, about 600 ft (180 m) thick, consists of red siltstone, shale, and very fine-grained sandstone. Gypsum beds are lacking. Bedding is regular and the unit lacks the fractures seen in the lower part of the formation. This part of the Spearfish is a confining layer.

The Gypsum Spring Formation consists of about 35 ft (11 m) equally distributed between ledge-forming white gypsum at the base and shaly siltstone with thin gypsum at the top. Many sinkholes have developed in the Gypsum Spring.

DISSOLUTION FRONT IN THE MINNELUSA FORMATION

The upper half of the Minnelusa Formation contains abundant anhydrite in the subsurface, and except for a few areas near Beulah and Sundance, Wyoming (Brady, 1931), and in Hell Canyon in the southwestern Black Hills (Braddock, 1963), no anhydrite or gypsum crops out. A log of the upper part of the Minnelusa from Hell Canyon contains 235 ft (72 m) of anhydrite and gypsum (Brobst and Epstein, 1963). Where anhydrite is present in the Minnelusa, its rocks are not brecciated. Where the rocks are brecciated in outcrop, anhydrite is absent. Clearly, the brecciation is the result of collapse following subsurface dissolution of anhydrite

The Madison and Minnelusa are the major aquifers in the Black Hills. They are recharged by rainfall on and by streams flowing across their up-dip outcrop area. In the Minnelusa, removal of anhydrite progresses downdip with continued dissolution of the anhydrite (fig. 7), collapse breccia is formed, breccia pipes extend upwards, and resurgent springs develop at the sites of sinkholes. Cox Lake (fig. 8), Mud and Mirror Lakes, and McNenny springs, are near the position of the dissolution front (fig. 9). As the Black Hills is slowly lowered by erosion, the anhydrite dissolution front in the subsurface Minnelusa moves downdip and radially away from the center of the uplift. The resurgent springs will dry up and new ones will form down dip as the geomorphology of the Black Hills evolves. Abandoned sinkholes on canyon walls (fig. 3) attest to the former position of the dissolution front.

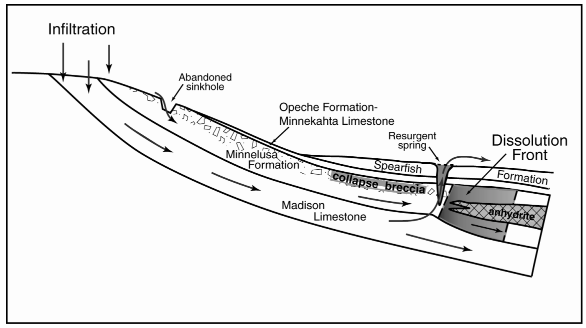

Figure 7. Dissolution of anhydrite in the Minnelusa Formation and down-dip migration of the dissolution front.

Because ground water has dissolved the anhydrite in the Minnelusa in most areas of exposure, and because anhydrite is present in the subsurface, a transition zone should be present where dissolution of anhydrite is currently taking place. A model of this zone has been presented by Brobst and Epstein (1963, p. 335) and Gott and others (1974, p. 45) and is shown here in figure 7. Consequences of this model include (1) the updip part of the Minnelusa is thinner than the downdip part because of removal of significant thickness of anhydrite, (2) the upper part of the Minnelusa should be continually collapsing, even today, and (3) the properties of the water in this transition zone may be different than elsewhere.

If this process is correct, then present resurgent springs should be eventually abandoned and new springs should develop down the regional hydraulic gradient of the Black Hills. One example might be along Crow Creek where a cloud of sediment from an upwelling spring lies 1,000 ft (300 m) north of McNenny Springs (fig. 9). This circular area, about 200 ft (60 m) across, might eventually replace McNenny Springs.

Solution of anhydrite in the Minnelusa probably began soon after the Black Hills was uplifted in the early Tertiary and continues today. Recent subsidence is evidenced by sinkholes more than 60 ft (18 m) deep opening up within the last 20 years (fig. 10), collapse in water wells and natural springs resulting in sediment disruption and contamination (Hayes, 1996), and fresh circular scarps surrounding shallow depressions.

Figure 8. Cox Lake, a resurgent (artesian) spring with a flow of nearly 5 cubic feet (0.5 cu m) per second in the Spearfish Formation in the northern Black Hills. It occupies a sinkhole that is more than 60 ft (18 m) deep (outlined by the darker water just beyond the edge of the dock). The chemical signature of the water indicates that the Minnelusa Formation and underlying Madison Limestone are the contributing aquifers (Klemp, 1995). The lake is near the anhydrite dissolution front shown in fig. 7.

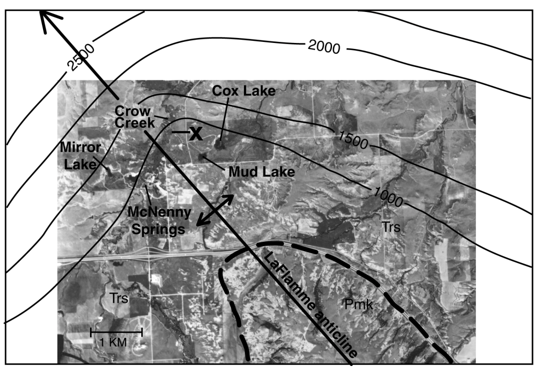

Figure 9. Air photograph showing location of resurgent springs in the Spearfish Formation adjacent to the LaFlamme anticline. X marks site of new resurgent spring along Crow Creek. Pmk, Minnekahta Limestone; Trs, Spearfish Formation. Specific conductance in the Minnelusa aquifer (contours in microseimens per second) from Klemp (1995).

The Plains Indians that inhabited the area 300 years ago trapped and slaughtered thousands of buffalo for their primary food by stampeding the animals over the steep rim of one of the large sinkholes near Beulah, WY (the Vore Buffalo Jump). The site is undergoing archeological excavation by the University of Wyoming. The Hot Springs Mammoth Site in Hot Springs, SD., is another large sinkhole in the Spearfish Formation that was the site of a breccia pipe extending down into the Minnelusa Formation. It was an active trap for large mammals at least 26,000 years ago (Laury, 1980; Agenbroad and Mead, 1994).

Figure 10. Sinkhole in the red beds of the Spearfish Formation that formed about 1950 near Beulah, WY. It developed in a larger and shallower 1000-foot wide depression.

A series of springs that apparently occupy sinkholes, as well as dry sinkholes, occur in the lower half of the Spearfish Formation, generally within 200 ft (60 m) of the base of the formation, and at or near where several beds of gypsum are exposed. Several lines of reasoning suggest that these sinkholes are not the result of solution of gypsum in the Spearfish, even though there is some collapse due to dissolution of gypsum in that formation: (1) The gypsum beds exposed in the lower Spearfish aggregate no more than about 25 ft (8 m) in thickness, whereas the sinkholes are more than 50 ft (15 m) deep in places; (2) Several of the sinkholes lie below many of the gypsum beds, and (3) the waters of some of the lakes occupying the sinkholes are derived from underlying formations (Klemp, 1995).

HYDROLOGIC IMPLICATIONS OF SINKHOLES IN THE LOWER PART OF THE SPEARFISH FORMATION;

The Spearfish Formation comprises red shale, siltstone, and fine sandstone with scattered beds of gypsum. In the area of Spearfish, SD, and west to the Wyoming-South Dakota border, the lower part of the formation has different structural and lithologic characteristics that affect its hydrologic behavior. The lower 200 ft (60 m) or so is an aquifer. The overlying rocks are a confining layer. The lower part yields abundant water to wells and springs. It contains gypsum beds, many of which are contorted, and gypsum veinlets that are intruded into fractures at variable angles. Local ranchers examined the sinkhole shown in figure 10 and running water was heard beneath. A cavern extending horizontally beyond the limits of their flashlight beam was seen (Ted Vore, oral commun., 1999). Cox (1962, p. 11) reported a well 2.8 miles (4.5 km) ENE of Cox Lake that bottomed in a cavern in the Spearfish. A working hypothesis is that the lower Spearfish contains abundant, interconnected caves and solution fractures along which water flows rapidly and supplies the wells and Cox Lake and surrounding resurgent springs. This zone is a fractured rock aquifer in which ground water travels by conduit flow. Where the potentiometric surface lies above the ground surface in this zone, the sinkholes are sites of resurgent springs. Where the potentiometric surface lies below the ground surface within this zone, dry sinkholes have developed (fig. 11). It is possible that the aquifer rocks are more intensely fractured in the LaFlamme anticlinal area, allowing for greater secondary porosity and permeability, and accounting for the location of these springs (fig. 8). An analysis of intensity of fracturing is under investigation.

Many of the sinkholes in the Spearfish Formation are too large to be accounted for by solution of the relatively thin gypsum beds within that formation. They were more likely produced by the removal of much thicker gypsum in the Minnelusa Formation, approximately 500 ft (150 m) below. Many sinkholes that extend down through the Spearfish into the Minnelusa are sites of resurgent springs (fig. 7), resulting from fairly recent dissolution of anhydrite in the Minnelusa. These springs are important for recharging to surface streams in the Black Hills. Rainfall recharges aquifers higher up near the core of the Black Hills. The ground water discharges along the flanks of the hills, mainly in or near the upper Spearfish aquiclude, where the potentiometric surface is higher than the ground surface.

ENLARGEMENT OF MIRROR LAKE VIA "HEADWARD COLLAPSE"

Mirror Lake (fig. 12), located in the South Dakota State Wildlife Management Area, has a dogleg shape. The eastward-trending section is artificial. The northwest-trending, 900-foot (275 m)-long alcove is cut into a 50-foot-high ridge of the

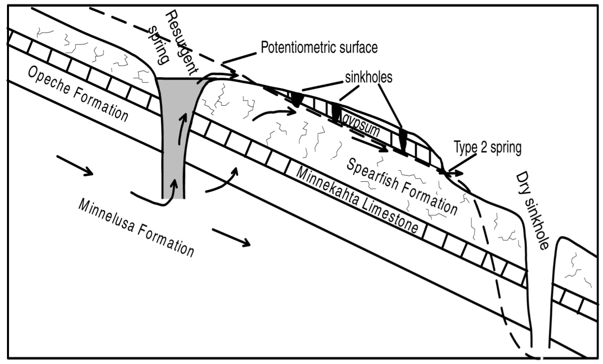

Figure 11. Generalized diagram showing hypothetical flow path of ground water in resurgent spring and in spring emerging from beneath gypsum in Spearfish Formation (type 2 spring of Rahn and Greis, 1973) and sinkholes developed by solution of anhydrite in the Minnelusa Formation. Dry sinkhole lies above potentiometric surface. Gypsum veinlets in fractured rocks of the lower part of the Spearfish shown by jagged lines.

Spearfish Formation (fig. 12). The lake, similar to other lakes in the area, occupies a depression formed by dissolution of calcium sulphate at depth, probably in the Minnelusa, although gypsum underlies the lake as shown by outcrops nearby. A deposit of calcareous tufa, as much as four ft (1.2 m) thick, consisting of light-brown, porous limestone with abundant plant impressions (“moss rock” of local ranchers) is found 1,000 ft (300 m) southeast of the lake. The deposit dips gently to the east, away from Mirror Lake and presumably was deposited earlier by spring water that emerged from the lake. Numerous sinkholes, several feet deep, are found at the north end of the alcove. These presently are active and indicate that the lake is expanding to the northwest by continued collapse due to solution of gypsum at depth. The fine sediment derived from the Spearfish is presumably removed by the emerging spring water. Presumably the lake was once higher at the time the tufa was deposited (fig. 12). Continued downcutting and northwest migration of the headwall has produced the present landform, a pocket valley that has been termed a “steephead” (Jennings, 1971). Dating the sediments in the bottom of the lake may yield the rate of headward erosion of the steephead.

ENVIRONMENTAL CONCERNS

Karstic collapse due to dissolution of gypsum and anhydrite is an active process in the northern Black Hills. Dissolution of gypsum in the Spearfish and Gypsum Spring has resulted in collapse and formation

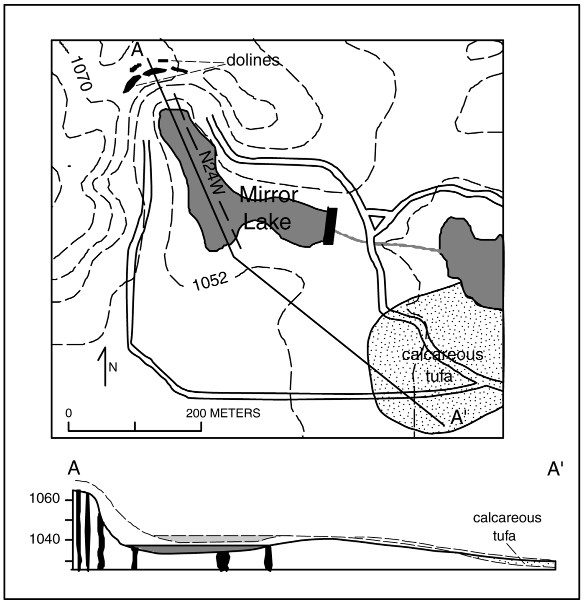

Fig. 12. Map and cross section showing sinkholes at the northwest end of Mirror Lake and the inferred earlier topography on which calcareous tufa was deposited. Contour interval 6 meters.

of many sinkholes in several areas that are presently undergoing development between Rapid City and Spearfish, SD (Rahn and Davis, 1996; Davis and Rahn, 1997). In 1972, the City of Spearfish constructed a sewage lagoon on the Gypsum Spring Formation. The lagoon leaked into sinkholes and the lagoon was abandoned in favor of an expensive water-treatment plant. Recently, the city entertained plans to convert the lagoon site into a recreation area with construction of buildings and light towers. The Public Works Administrator requested the USGS for a judgment on the potential for subsidence at the site. A geologic map was prepared, similar to one prepared by Davis (1979, fig. 3) showing that at least ten sinkholes, one of which is about 1,000 ft (300 m) long, had developed in the gypsum. This information was subsequently used by the city planners in their decision to abandon the project.

The lower part of the Spearfish Formation is also undergoing active collapse and is considered to be an aquifer. This zone is more susceptible to rapid infiltration of contaminants than the upper part of the Spearfish, a fact that should be considered in future land-use planning. Collapse due to dissolution of soluble rocks can be exacerbated by removal of ground water by pumping. If areas in the Red Valley of the northern Black Hills are extensively developed and water supplies derived from pumping, then a possible concern might be the increase in frequency of such collapse in the Spearfish Formation.

The Minnelusa Formation is a heterogeneous unit. The upper part, which is highly brecciated and contains numerous breccia pipes, has a greater fracture porosity than the lower part. Care should be taken in not considering the entire Minnelusa as a unified aquifer, especially within and updip of the dissolution front.

CONCLUSION

Dissolution of gypsum and anhydrite in the Minnelusa and Spearfish Formations in the northern Black Hills has led to subsidence and collapse resulting in the development of disrupted bedding, breccia pipes and pinnacles in the Minnelusa, and sinkholes and breccia pipes extending up into the Spearfish and higher formations. Many of these sinkholes in the Spearfish are sites of resurgent springs where the potentiometric surface is above the land surface. Dry steep-walled sinkholes are located where the potentiometric surface lies below the bottom of the sinkhole. The largest sinkholes are the result of dissolution of the thick anhydrite in the subsurface Minnelusa and consequent stoping to the surface. As the dissolution front of the Minnelusa anhydrite moves radially outward from the center of the Black Hills, and as the potentiometric surface falls to lower stratigraphic levels while the land surface is lowered by erosion, the present springs will dry up and new ones will develop down the regional dip. Abandoned sinkholes attest to the former position of these springs. The down-dip migration of these springs is exemplified by Mirror Lake where headward spring migration resulted from continued sinkhole collapse of the headwall of this steephead valley. The location of many of the sinkholes within the lower part of the Spearfish may be related to the greater fracturing of that part of the Spearfish due to downward intrusion of gypsum veinlets that developed highly fractured bedrock. The springs emerge at or near a prominent gypsum horizon. Above that horizon siltstone and shale are highly impermeable restricting the upward movement of ground water. Appreciation of the processes involved in the formation of gypsum karst should be considered in land use planning in this increasingly developed part of the northern Black Hills.

REFERENCES CITED

Agenbroad, L.D., and Mead, J.I., eds., 1994, The Hot Springs Mammoth Site: A decade of field and laboratory research in paleontology, geology, and paleoecology: The Mammoth Site of South Dakota, Hot Springs, South Dakota, 457 p.

Braddock, W.A., 1963, Geology of the Jewel Cave SW Quadrangle, Custer County, South Dakota: U.S. Geological Survey Bulletin 1063-G, p. 217-268.

Brady, F. H., 1931, Minnelusa formation of Beulah district, northwestern Black Hills, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 15, p. 183-188

Bowles, C.G., and Braddock, W.A., 1963, Solution breccias of the Minnelusa Formation in the Black Hills, South Dakota and Wyoming, in Short papers in geology and hydrology: U.S. Geological Survey Professional Paper 475-C, p. C91-C95.

Brobst, D.A., and Epstein, J.B., 1963, Geology of the Fanny Peak quadrangle, Wyoming-South Dakota: U.S. Geological Survey Bulletin 1063-I, p. 323-377.

Cox, E.J., 1962, Artesian water, Minnelusa and Pahasapa Formations, Spearfish-Belle Fourche area: South Dakota Geological Survey Special Report 19, 23 p.

Davis, A.D., 1979, Hydrogeology of the Belle Fourche, South Dakota water infiltration gallery area: Proceedings of the South Dakota Academy of Science, v. 58, p. 122-143.

Davis, A.D., and Rahn, P.H., 1997, Karstic gypsum problems at wastewater stabilization sites in the Black Hills of South Dakota: Carbonates and Evaporites, v. 12, p. 73-80.

Epstein, J.B., 1958a, Gravity sliding, brecciation, and structure, Fanny Peak quadrangle, Wyoming-South Dakota [abs.]: Geological Society of America Annual Meeting 1958, St. Louis, Mo. p. 56.

Epstein. J.B., 1958b, Geology of part of the Fanny Peak quadrangle, Wyoming-South Dakota: M.A. thesis, University of Wyoming and U.S. Geological Survey Open-File Report.

Gott, G.B., Wolcott, D.E., and Bowles, C.G., 1974, Stratigraphy of the Inyan Kara Group and localitzation of uranium deposits, southern Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 763, 57 p.

Hayes, T.S., 1996, Suspended-sediment “reddening” in Cascade Springs, southern Black Hills, South Dakota: Geological Society of America, Abstracts with Programs, Rocky Mountain Section, April 18-19, Rapid City, South Dakota, p. 11.

Jennings, J.N., 1971, Karst, The M.I.T Press, Cambridge, Mass, 252 p.

Klemp, J.A., 1995, Source aquifers for large springs in northwestern Lawrence County, South Dakota: Rapid City, South Dakota, South Dakota School of Mines and Technology, unpublished M.S. Thesis, 175 p.

Laury, R.L., 1980, Paleoenvironment of a late Quaternary mammoth-bearing sinkhole deposit, Hot Springs, South Dakota: Geological Society of America Bulletin, v. 91, p. 465-475.

Rahn, P. H., and Davis, A. D., 1996, Gypsum Foundation Problems in the Black Hills Area, South Dakota: Environmental and Engineering Geosceince, v. 2, p. 213-223.

Rahn, P.H., and Gries, J.P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey Report of Investigations 107, 46 p. U.S. Department of Commerce, 1990, Climatological data for South Dakota, annual summary: Asheville, North Carolina (issued annually).

Raines, M.A., and Dewers, T.A., 1997, Dedolomitization as a driving mechanism for karst generation in Permian Blaine Formation, southwestern Oklahoma, USA: Carbonates and Evaporites, v. 12, p. 24-31.

Strahler, A.N., and Strahler, A.H., 1987, Modern Physical Geography: New York, John Wiley & Sons, 544 p.

Thordarson, William, 1989, Hydrogeology of anhydrite, p. 95-105, in Dean, W.E., and Johnson, K.S., eds, 1989, Anhydrite deposits of the United States and characteristics of anhydrite important for storage of radioactive wastes: U.S. Geological Survey Bulletin 1794, 132 p.