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**GYPSUM-KARST COLLAPSE IN THE BLACK HILLS,  
SOUTH DAKOTA-WYOMING, USA**

**KRAŠKI UDORI V SADRI, BLACK HILLS,  
SOUTH DAKOTA-WYOMING, ZDA**

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**Izvleček**

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**Jack B. Epstein: Kraški udori v sadri, Black Hills, South Dakota-Wyoming, ZDA**

Medplastno raztapljanje sadre in anhidrita v štirih stratigrafskih enotah starosti od karbona do jure na področju Black Hills, South Dakota in Wyoming, je povzročilo mnogo udorov, ki so se prvotno razvili v zgornjih netopnih kamninah. Udori so prizadeli več naseljenih območij. Podzemeljsko medplastno raztapljanje anhidrita Minnelusa formacije je povzročilo regionalno podorno brečo, velike prekinitve plastnatosti, mnogo vrtač ter brečaste kope, izmed katerih se nekatere razprostirajo 300 m v zgoraj ležeče plasti. Recentni udori so povzročili strme vrtače globlje od 20 m, udore v vodnjakih in izvirih, ki so posledica prekinitve sedimentov in onesnaženja ter sveže morfološke stopnje, ki obkrožajo plitve depresije. Veliko plasti sadre je deformiranih zaradi ekspanzije, kar je posledica njene hidracije iz anhidrita. Mnogo sadrinih žilic najdemo vzdolž naključnih razpok v matičnih plasteh sadre. Ob izvirih se pojavlja več vrtač. Ker čelno raztapljanje anhidrita v podzemlju Minnelusa formacije napreduje vzdolž vpada in radialno izven centra dviganja področja Black Hills, bodo ti izviri presahnili, pojavili pa se bodo novi skladni z geomorfološkim razvojem področja Black Hills. Stare brečaste kope, ki so ohranjene v prečnih profilih sten soteske, kažejo na nekdanji položaj čelnega raztapljanja. Mirror Lake, ki se razprostira proti SZ vzdolž smeri vpada, je lokalna primerjava napredujočega čela raztapljanja.

**Ključne besede:** kras, anhidrit, sadra, raztapljanje, vrtače, Black Hills, Wyoming, South Dakota.

**Abstract**

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**Jack B. Epstein: Gypsum-karst collapse in the Black Hills, South Dakota-Wyoming, USA**

Intrastratal dissolution of gypsum and anhydrite in four stratigraphic units of Pennsylvanian to Jurassic age in the Black Hills of South Dakota and Wyoming has resulted in many collapse features that have developed primarily in the non-soluble overlying rocks. Subsidence has affected several areas that are undergoing urban development. Subsurface intrastratal dissolution of anhydrite in the Minnelusa Formation has produced a regional collapse breccia, extensive disruption of bedding, many dolines, and breccia pipes and pinnacles, some of which extend upwards more than 300 m into overlying strata. Recent collapse is evidenced by steep-walled dolines more than 20 m deep, collapse in water wells and natural springs resulting in sediment disruption and contamination, and fresh circular scarps surrounding shallow depressions. Many beds of gypsum are contorted because of expansion due to its hydration from anhydrite, and many gypsum veinlets extend downward along random fractures from parent gypsum beds. Several dolines are sites of resurgent springs. As the anhydrite dissolution front in the subsurface Minnelusa moves downdip 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. Old dolines and breccia pipes, preserved in cross section on canyon walls, attest to the former position of the dissolution front. Mirror Lake, which is expanding northwestward in a downdip direction, is a local analog of a migrating dissolution front.

**Key words:** karst, anhydrite, gypsum, dissolution, dolines, Black Hills, Wyoming, South Dakota.

## INTRODUCTION

The occurrence of limestone karst in the United States is well known as shown by the distribution of caverns in limestone and dolomite (Fig. 1). The distribution of karst in gypsum and anhydrite, which underlies more than one-third of the country (Fig. 2), is less well known. In the eastern United States, collapse features due to dissolution of these evaporites are not common because of the rapid dissolution and removal of the calcium sulphate near the surface. In the more arid western United States, surface karstic collapse is common (Johnson, 1996) such as in the Black Hills of South Dakota and Wyoming.

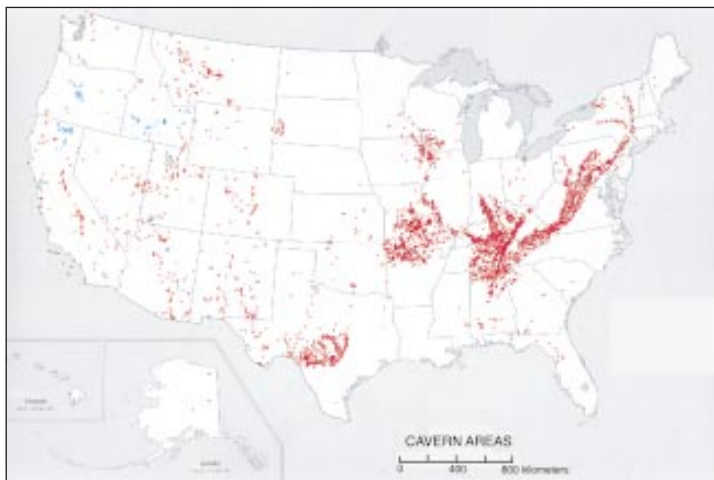


Fig. 1: Carbonate karst in the United States as shown by the distribution of cavern areas (from Davies, 1970).

Sl. 1: Karbonatni kras v ZDA, kot ga kaže razširjenost kraških jam (Davies, 1970).

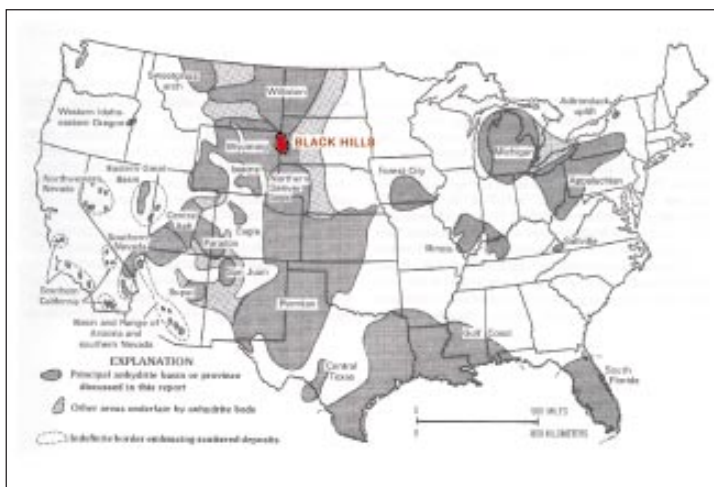


Fig. 2: Areas in the conterminous United States where thick beds of anhydrite are present at moderate depths (from Smith et al. 1973).

Sl. 2: Področja v ZDA, kjer so plasti anhidrita prisotne v zmernih globinah (Smith et al., 1973).

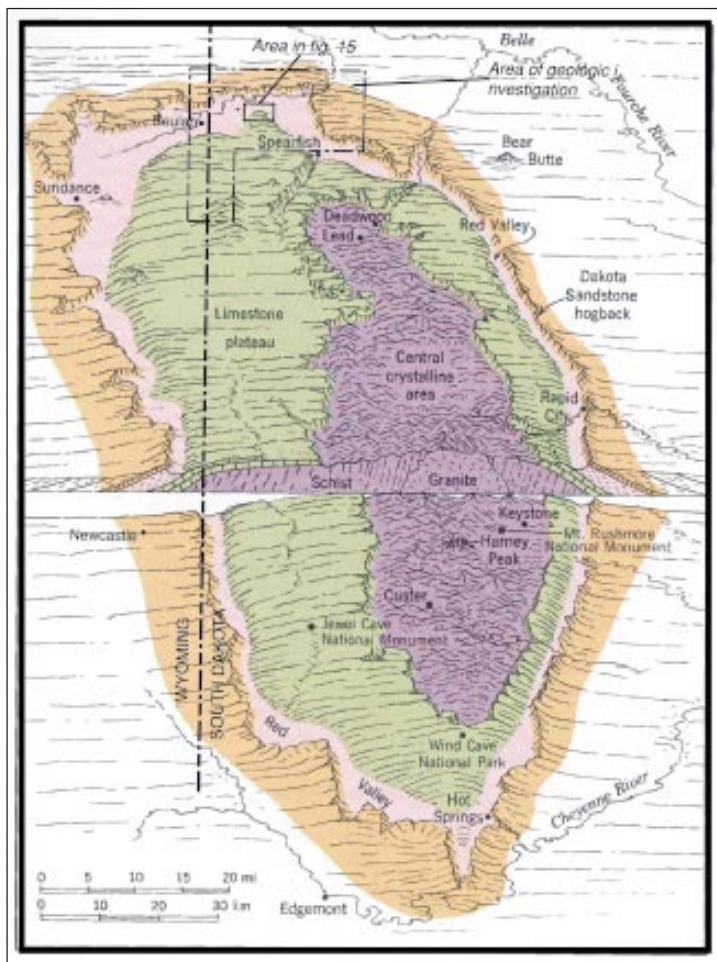


Fig. 3: Generalized diagram showing the geology and geomorphology of the Black Hills. Most of the urban development and karst features are in the Red Valley, underlain by Triassic red beds (where gypsum karst is becoming a growing concern), and in the limestone plateau, underlain by a variety of Pennsylvanian and Permian rocks. Modified from Strahler and Strahler 1987, with permission.

Sl. 3: Diagram, ki kaže geologijo in geomorfologijo področja Black Hills. Večina naseljenih območij in kraških značilnosti je v Red Valley, ki je zgrajena iz triasnih rdečih plasti (kjer kras v sadri postaja velik problem) in na apnenčasti planoti, ki jo gradijo različne karbonske in permijske kamnine. Prirejeno z dovoljenjem po Strahler & Strahler 1987.

The US Geological Survey is preparing detailed 1:24,000-scale bedrock and surficial geologic maps in the northern Black Hills (Fig. 3). This is an area of increasing urban development, and these maps will be useful for assessing the vulnerability of ground-water aquifers to contamination by describing major lithologic characteristics, delineating surface recharge areas, and characterizing sub-surface aquifer 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 irregularly shaped uplift, about 210 km long and 100 km wide and elongated in a north-northwest direction. A core of Precambrian metamorphic rocks is rimmed by a series of sediments of

Paleozoic and Mesozoic age that generally dip away from the center of the uplift. These rocks are overlapped by Tertiary and Quaternary sediments and have been intruded by scattered Tertiary igneous rocks. The Paleozoic and Mesozoic sedimentary rocks were deposited under shallow marine to near shore-terrestrial conditions and include sub-tidal, carbonate-platform, tidal-flat, sand-dune, and fluvial environments. More than 90 m of gypsum and anhydrite were deposited at various times in evaporite basins.



*Fig. 4: Typical exposure of gypsum interbedded with red shale and siltstone in the Spearfish Formation of Permian and Triassic age in the Black Hills. Sl. 4: Značilen izdanek sadre, ki se izmenjuje z rdečimi skrilavci in meljevci, Spearfish formacija permijske in triasne starosti na področju Black Hills.*

Uplift at the end of the Cretaceous and beginning of the Tertiary created an asymmetric dome. Homoclinal dips are locally interrupted by monoclines, structural terraces, and low-amplitude folds and faults. The LaFlamme anticline is a prominent structure west of Spearfish (see Fig. 14). It plunges to the northwest, has a structural relief of more than 260 m, and the dips on its flanks are as much as 20°.

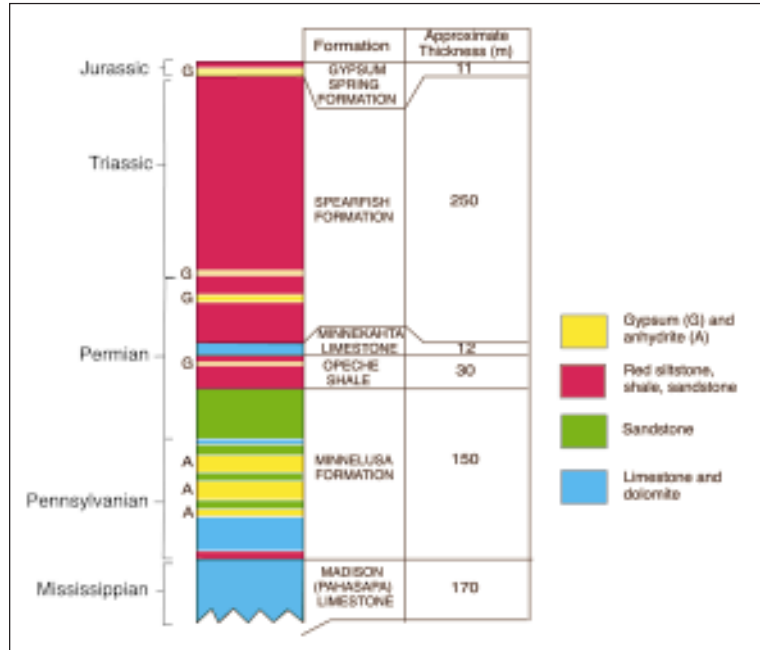
Erosion of these uplifted rocks produced the present landscape. Rocks of the Madison Limestone, Minnelusa Formation and older sediments form the limestone plateau that rims the central Precambrian core. Erosion of red siltstone and shale of the Spearfish Formation has formed the Red Valley, the main area of present and future urban development. White gypsum caps many of the hills in the Spearfish (Fig. 4) and also is a conspicuous landform in the overlying Gypsum Spring Formation. Resistant sandstones that are interbedded with other rocks lie outboard from the Red Valley and form the hogback that encircles the Black Hills and defines its outer physiographic perimeter (Fig. 3).

## STRATIGRAPHY OF CALCIUM SULPHATE-BEARING ROCKS

Karstic features in limestone and dolomite, such as caves, dolines, and underground drainage, are abundant worldwide, including in the Black Hills. Similar solution features are also abundant in gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and its anhydrous counterpart anhydrite ( $\text{CaSO}_4$ ) throughout the United

Fig. 5:  
Stratigraphic column showing formations containing gypsum and anhydrite in the northern Black Hills.

Sl. 5: Stratigrafski stolpec, ki prikazuje formacije, ki vsebujejo srebro in anhidrit na severnem področju Black Hills.



States (Fig. 2) and the world (e.g., Clifton 1967; Cooper 1996; Friedman 1997). Calcium sulphate rocks are much more soluble than carbonate rocks, especially where they are associated with dolomite undergoing dedolomitization, a process which results in ground water that is continuously undersaturated with respect to gypsum (Raines and Dewers, 1997).

Gypsum and anhydrite are conspicuous evaporite deposits in four sedimentary rock units in the Black Hills (Fig. 5). They comprise as much as 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.

### MINNELUSA FORMATION

The Minnelusa Formation, about 150 m thick in the northern Black Hills, comprises a mixture of sandstone, dolomite, limestone and shale with abundant anhydrite in the middle portion. Anhydrite generally is not present in surface exposures, having been removed by solution at depth and the exact thickness at depth is not known in the area of this research. However, more than 60 m of anhydrite is known at depth in the southern Black Hills. The solution of anhydrite and consequent formation of voids in the Minnelusa resulted in foundering and fragmentation of overlying rocks, producing extensive disruption of bedding, a regional collapse breccia, dolines, and breccia pipes (Epstein 1958a,b; Brobst & Epstein 1963; Bowles & Braddock 1963; Figs. 6, 7, 8). Some resistant calcite-cemented pipes extend upward more than 300 m into overlying strata (Bowles and Braddock 1963). Many of the breccia pipes erode into isolated pinnacles after having been separated from canyon walls (Fig. 9). 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



Fig. 6: Doline (outlined) in the Minnelusa Formation in 120-m-high cliff in Redbird Canyon, about 15 km east of Newcastle, Wyoming. The collapse resulted from removal of anhydrite prior to fluvial erosion which exposed the doline on the canyon wall. These cliffs are adjacent to large stream meanders, but only small creeks occupy the valleys at present, suggesting climatic changes in the recent geologic past.



Sl. 6: Vrtača (poudarjeno) v Minnelusa formaciji v 120 m visoki steni soteske Redbird, okrog 15 km V od Newcastle-a Wyoming. Udor je nastal zaradi odstranitve anhidrita pred aktivnostjo rečne erozije, ki je odprla vrtačo na steni soteske. Te stene mejijo na velike rečne okljuje, znotraj sedanjih dolin pa najdemo le majhne potoke, kar dokazuje na klimatske spremembe v bližnji geološki preteklosti.

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Fig. 7: Disrupted bedding and breccia pipe (arrow) in the Minnelusa Formation. Cliff in Cold Brook Canyon, just north of Hot Springs, SD.



Sl. 7: Prekinjena plastnatost in brečasta kopa (puščica) v Minnelusa formaciji. Stena v Cold Brook soteski, S od Hot Springs, South Dakota.

Fig. 8: Erosion of resistant breccia pipe cemented by calcium carbonate forms a pinnacle. These are common within the brecciated upper part of the Minnelusa Formation. Red Bird Canyon, about 15 km east of Newcastle, WY.



Sl. 8: Erozijska odporne brečaste cevi cementirane s  $\text{CaCO}_3$  ustvarja brečasto kopo. Te so pogoste znotraj brečaste-ga zgornjega dela Minnelusa formacije. Soteska Red Bird, okrog 15 km V od Newcastle-a, Wyoming.



Fig. 9: Breccia pipe still connected to canyon wall. Progressive erosion will isolate it forming a pinnacle similar to the one in figure 8.

Sl. 9: Brečasta kopa, ki je še vedno povezana s steno soteske. Progressivna erozija jo bo osamila, tako da bo nastala kopa podobna tisti na sliki 8.



Fig. 10: Brecciated rocks above covered slope overlying non-brecciated unit in the Minnelusa Formation in Cold Brook Canyon, near Hot Springs, SD. Many tens of meters of anhydrite have been removed in a zone above the non-brecciated beds.



Sl. 10: Breča nad pokritim pobočjem pokriva ne-brečaste kamnine Minnelusa

formacije v Cold Brook soteski, blizu Hot Springs, South Dakota. Več 10 m anhidrita je bilo odstranjenega v coni nad ne-brečastimi plastmi.

secondary porosity, which, along with the porous sandstone, makes the upper half of the Minnelusa an important aquifer in the Black Hills.

The brecciation is present in the upper part of the Minnelusa, whereas the beds below are generally not brecciated (Fig. 10). This relationship locates the original anhydrite within the rocks above the non-brecciated beds.

Fig. 11: Contorted gypsum in the Spearfish Formation in the Red Valley of the southwestern Black Hills, south-east of Newcastle, Wyoming.



Sl. 11: Deformirana sadra v Spearfish formaciji v Red Valley na JZ Black Hills, JV od Newcastle-a, Wyoming.

*Fig. 12: Thin gypsum veinlets, averaging less than 1 cm thick, extending down from parent gypsum bed and filling a multitude of fractures in the lower part of the Spearfish Formation in the southern Black Hills.*

*Sl. 12: Tanke žilice sadre, ki so v povprečju debele manj kot 1 cm, lahko najdemo navzdol od matičnih plasti sadre,*

*kjer zapolnjujejo razpoke v sp. delu Spearfish formacije v J delu Black Hills.*



### **OPECHE FORMATION**

The Opeche Formation, consisting of approximately 30 m of poorly exposed red shale, siltstone, and fine-grained sandstone, is a confining unit between the aquifers in the Minnelusa Formation and Minnekahta Limestone. Gypsum is not abundant.

### **SPEARFISH FORMATION**

The Spearfish Formation consists of about 250 m of red shale, siltstone, and fine-grained sandstone with several beds of gypsum in the lower 60 m, aggregating less than 30 meters thick. Anhydrite, which probably was the original form of calcium sulphate to be deposited, underwent about a 40 percent expansion when it was hydrated to form gypsum. As a result, beds of gypsum in the Spearfish Formation are commonly highly folded (Fig. 11). Some gypsum became mobile during dissolution and was injected into many thin variably oriented fractures in the underlying red beds (Fig. 12). These veinlets are generally less than 1 cm wide and they contain gypsum fibers lying perpendicular to the fracture walls. Thus, the lower 60 m or so of the Spearfish has developed secondary fracture porosity. This part of the formation supplies water to wells, has many dolines developed in it, and resurgent springs are numerous. Ground water flows through the fractures and solution cavities in the gypsum. Although the entire Spearfish is generally considered to be a hydrologic confining unit because of the presence of shale, the lower 60 m of the formation is an aquifer because of the enhanced permeability. 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 180 m thick, lacks gypsum. 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 unit.

## **GYPSUM SPRING FORMATION**

The Gypsum Spring Formation consists of about 11 meters of rock equally distributed between ledge-forming white gypsum at the bottom and shaley siltstone with thin gypsum at the top. Many dolines have developed in the Gypsum Spring causing subsidence to many man-made structures.

## **ORIGIN OF BRECCIA IN THE MINNELUSA FORMATION**

The physiography and geologic structure of the Black Hills has favored the development of artesian ground-water conditions. Ground water is recharged by the relatively abundant rainfall in the higher portions of the central part of the range. It flows radially outward and down the regional stratigraphic dip. Aquifers, including the rocks of the Minnelusa Formation, alternate with confining layers. The anhydrite in the Minnelusa is dissolved at depth under these confining conditions producing intrastratal karst. The creation of the intrastratal voids causes gravitational collapse extending upwards into the overlying non-soluble rocks. Concentration of collapse causes the development of breccia pipes and dolines projecting into overlying rocks, as much as 300 meters above the Minnelusa. The dolines range between a few meters to more than 300 meters in diameter, may be more than 25 meters deep, and are bowl-shaped with gently sloping sides. Steep-sided dolines occur, especially where collapse has been fairly recent. Blind valleys are present, but not common. Broad-scale regional collapse in the Minnelusa has also produced undulating bedding in overlying formations. This is a very conspicuous feature in the Minnekahta Limestone, a resistant, thin (12 m), evenly bedded unit lying about 30 meters above the top of the Minnelusa and situated between two soft red bed sequences (Fig. 5).

The breccia pipes result from dissolution of anhydrite at depth, upward stoping and elutriation. They are probably aligned along zones of localized intense fracturing or along intersections of vertical fractures, but this relationship has not yet been fully investigated in the field. Klimchouk & Vjacheslav (1996) discussed the origin of breccia pipes and similar features resulting from dissolution of deep-seated soluble rocks and foundering of overlying strata. They termed these structures "vertical through structures" that formed by gravitational collapse into voids that were sequentially created by active ground-water solution and successively filled in with clasts. In the Black Hills this process is accompanied by piping and upward flushing and removal of finer clastic silt and clay (for example, Hayes 1996). The height of breccia pipes in contrast to their much smaller diameter is evidence for their deep-seated origin, confinement along fracture zones, and dissolution by ground water under artesian head. Elutriation may be manifested in present-day springs, such as Cox and Mirror Lakes, discussed below. Eventually, when these resurgent springs are abandoned, their locations are marked by breccia pipes.

## **DISSOLUTION FRONT IN THE MINNELUSA FORMATION**

The middle part 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 the southwestern Black Hills (Braddock 1963), no anhydrite or gypsum crops out. An exploratory well in the upper part of the Minnelusa from Hell Canyon contains 72 m of anhydrite and gypsum (Brobst

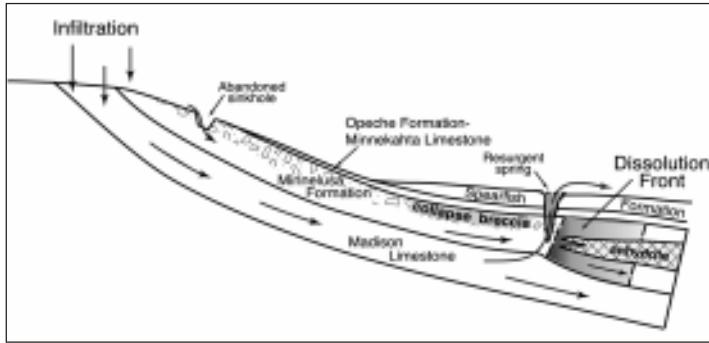


Fig. 13: Dissolution of anhydrite in the Minnelusa Formation and down-dip migration of the dissolution front.

Sl. 13: Raztapljanje anhidrita v Minnelusa formaciji in migracija čela raztapljanja v smeri vpada.

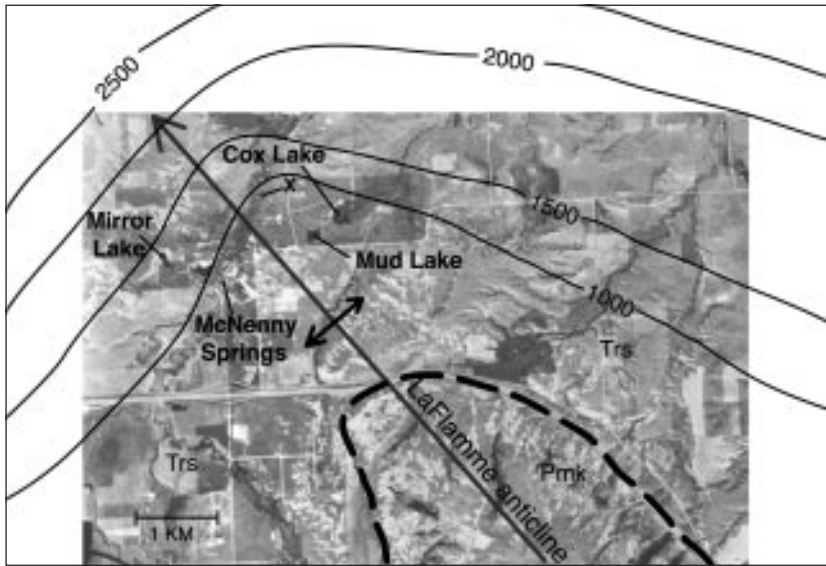


Fig. 14: Air photograph showing location of resurgent springs in the Spearfish Formation adjacent to the LaFlamme anticline. Pmk, Minnekahta Limestone; Trs, Spearfish Formation. The specific conductance in the Minnelusa aquifer (contours in microseimens per second; from Klemp 1995) increases rapidly in this area, marking the dissolution front zone. 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.

Sl. 14: Letalski posnetek, ki kaže položaj izvirov v Spearfish formaciji, ki meji na LaFlamme antiklinalo. Pmk, Minnekahta apnenec, Trs, Spearfish formacija. Specifična prevodnost v Minnelusa vodonosniku (izolinije v mikrosiemensih na sekundo; Klemp 1995) hitro narašča in označuje cono čelnega raztapljanja. Možno je, da so kamnine vodonosnika bolj močno pretrte na področju antiklinalne LaFlamme, kar dovoljuje večjo sekundarno poroznost in permeabilnost ter pripomore k lokaciji položaja teh izvirov.



and Epstein 1963). Where anhydrite is present in the Minnelusa, its rocks are not brecciated, and where the rocks are brecciated in outcrop, anhydrite is absent. Clearly, the brecciation is the result of collapse following subsurface dissolution of anhydrite.

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 must 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 et al. (1974, p. 45) and is shown here in figure 13. Consequences of this model include (1) the updip part of the Minnelusa is thinner than the downdip part because of removal of significant thicknesses of anhydrite, (2) the upper part of the Minnelusa should be continually collapsing, even today, (3) the chemical properties of the water in this transition zone may be different than elsewhere, (4) the dissolution front moves downdip as the Black Hills is slowly lowered by erosion, and (5) earlier formed dolines will be left high on canyon walls.

Removal of anhydrite in the Minnelusa probably began soon after the Black Hills was uplifted (early Tertiary) and continues today. Recent subsidence is evidenced by newly formed dolines, collapse in water wells and natural springs resulting in sediment disruption and contamination, fresh scarps, and calcium sulphate in many spring waters throughout the Black Hills.

The thickness variations in the Minnelusa to be expected by this model are confirmed in numerous water well logs on file at the USGS Water Resources Office in Rapid City, SD. Recent

*Fig. 15: Cox Lake, a resurgent (artesian) spring with a flow of nearly 0.5 cubic meters per second in the Spearfish Formation in the northern Black Hills. It occupies a doline that is more than 20 m deep (outlined by the darker blue 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). Its position is near the anhydrite dissolution front shown in fig. 14.*

*Sl. 15: Cox Lake, arteški izvir s pretokom skoraj 0,5 m<sup>3</sup>/s v Spearfish formaciji na S Black Hills. Nahaja se v vrtači, ki je globoka več kot 20 m (povdarjena s temno modro vodo preko roba doka). Kemijske lastnosti vode kažejo, da sta Minnelusa formacija in spodaj ležeči Madison apnenici izvorno področje vodonosnika (Klemp 1995). Njegov položaj je blizu anhidritnega čela raztapljanja, kar kaže slika 14.*



removal of calcium sulphate is shown in chemical analyses of water from numerous springs throughout the Black Hills (e.g., Brobst and Epstein 1963; Gott et al. 1974). Present-day collapse in the Minnelusa due to anhydrite removal is evidenced by sediment disruption and elutriation in water wells and springs (Hayes 1996). Klemm (1995) characterized the spring and aquifer geochemistry of five springs in the northern Black Hills and noted a rapid northward downdip increase in specific conductance, indicating the zone of anhydrite dissolution in the Minnelusa aquifer (Fig. 14).

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 (Fig. 13), forming collapse breccia, breccia pipes, and resurgent springs which develop at the sites of dolines in the overlying Spearfish Formation. Cox Lake (Fig. 15), Mud and Mirror Lakes, and McNenny Springs, located within the lower part of the Spearfish Formation, are near the position of the dissolution front which is marked by a rapid increase in the regional specific conductance in the Minnelusa Formation (Fig. 14). 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 the regional hydraulic gradient as the geomorphology of the Black Hills evolves. Dolines remaining high on canyon walls (Fig. 6) attest to the former position of the dissolution front. One example is along Crow Creek where a cloud of sediment from an up-welling spring lies 300 m north of McNenny Springs (Fig. 14). This circular area, about 60 m across, might eventually replace McNenny Springs ("X" on Fig. 15).

## **DOLINES IN THE LOWER PART OF THE SPEARFISH FORMATION**

A series of dry dolines and ones that are occupied by springs in the northern Black Hills are located in the lower half of the Spearfish Formation, generally within 60 m of the base of the formation, and at or near where several beds of gypsum are exposed. A collapse doline formed about 1950 in the Spearfish formation (Fig. 16) and was examined by local ranchers who heard running water beneath. A cavern extended horizontally beyond the limits of their flashlight beam. A similar cavern was reported by Cox (1962, 11) at the bottom of a well 4.5 km ENE of Cox Lake. A working hypothesis is that the lower part of the Spearfish contains abundant, interconnected caves and solution fractures along which water flows rapidly and supplies the wells, Cox Lake, and surrounding resurgent springs. This unit is a fractured rock aquifer in which ground water travels by conduit flow.

Several lines of reasoning suggest that these dolines 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 in the lower part of the Spearfish aggregate no more than about 8 m in thickness, whereas the dolines are more than 15 m deep in places; (2) several of the dolines lie below many of the gypsum beds, and (3) the waters of some of the lakes occupying the dolines are derived from underlying formations (Klemm 1995). The dolines were more likely produced by the removal of much thicker anhydrite in the Minnelusa Formation, approximately 150 m below.

Dolines that have been formed in the Spearfish Formation in the recent geologic past include the Vore Buffalo Jump near Sundance, Wyoming (Fig. 17), into which the Plains Indians stam-peded and slaughtered thousands of North American bison about 300 years ago. Another large

doline was the site of a pond near Hot Springs, SD, that was an active trap for large mammals at least 26,000 years ago (Laury, 1980; Agenbrood and Means, 1994).

Fig. 16: Collapse doline in the red beds of the Spearfish Formation that formed about 1950 near Beulah, WY. It developed in a larger and shallower 300-meter wide depression.

Sl. 16: Udornica v rdečih plasteh Spearfish formacije, ki je nastala okrog leta 1950 pri Beulah-u, Wyoming. Razvila se je v večji in plitvejši 300 m široki depresiji.



Fig. 17: The Vore Buffalo Jump, a fifteen-meter deep doline a few kilometers east of Sundance, Wyoming, in the northern Black Hills. The hole was not readily seen by the stampeded buffalo until they reached the rim. Abundant bones indicate that as many as 20,000 of the beasts were butchered for

food by the native Americans who inhabited the Black Hills about 300 years ago.

Sl. 17: Vore Buffalo Jump - 15 m globoka vrtača, nekaj km V od Sundance, Wyoming na S Black Hills. Bizoni, ki so panično bežali, so vrtačo opazili šele ko so bili na njenem robu. Številne kosti dokazujejo, da so Indijanci, ki so v Black Hills živeli pred okrog 300 leti, zaklali okrog 20.000 živali za hrano.

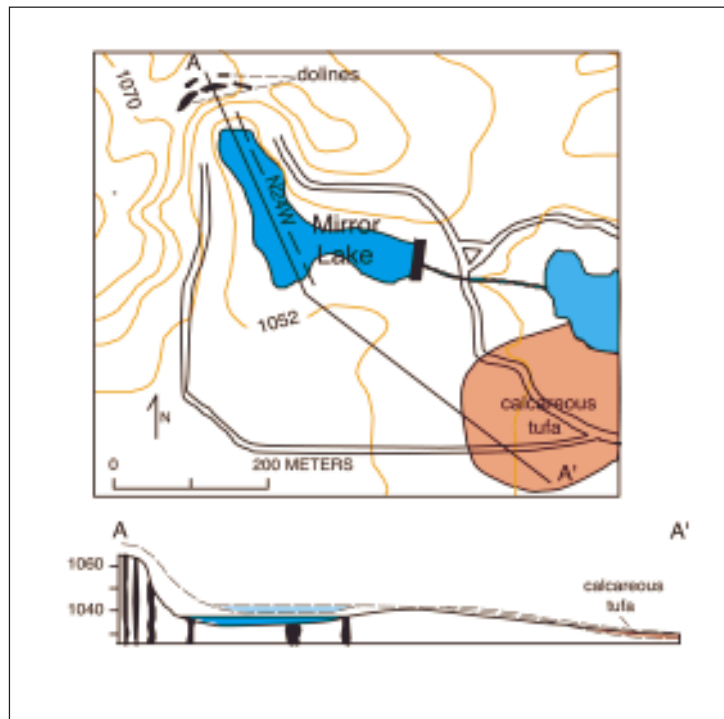


## MIRROR LAKE, AN EXAMPLE OF A MIGRATING DISSOLUTION FRONT BY HEADWARD COLLAPSE

Mirror Lake (Fig. 14) occupies a northwest-trending, 275 meter-long alcove cut into a 15-meter-high ridge of the Spearfish Formation (Fig. 18). It has a dogleg shape; the eastward-trending section is artificial. 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 1.2 m thick, consisting of light-brown, porous limestone with abundant plant impressions is found 200 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 dolines, several meters deep, are found at the north end of the alcove. These are actively forming and indicate that the lake is expanding to the northwest by continued collapse. The lake was probably higher at the time the tufa was deposited (Fig. 18). Continued down cutting 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.

Fig. 18: Map showing dolines at the northwest end of Mirror Lake and the inferred earlier topography on which calcareous tufa was deposited. Contour interval 6 meters.

Sl. 18: Karta z vrtačami na SZ koncu Mirror Lake in domnevna zgodnejša topografija na katero se je odložil lehnjak. Izolinije so na 6 m.



## 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 of many dolines in several areas that are presently undergoing urban development between Rapid City and Spearfish, SD (Rahn & Davis 1996; Davis & Rahn 1997). In 1972, the City of Spearfish constructed a sewage lagoon on the Gypsum Spring Formation. The lagoon leaked into dolines that formed within gypsum in that formation. Subsequently, the lagoon was abandoned in favor of an expensive water treatment plant. The city then planned to convert the lagoon site into a recreation area with construction of buildings and light towers. The USGS prepared a geologic map which showed that at least ten dolines, one of which is about 300 meters long, had developed in the gypsum (Fig. 19). This information was subsequently used by the city planners in their decision to abandon the project.

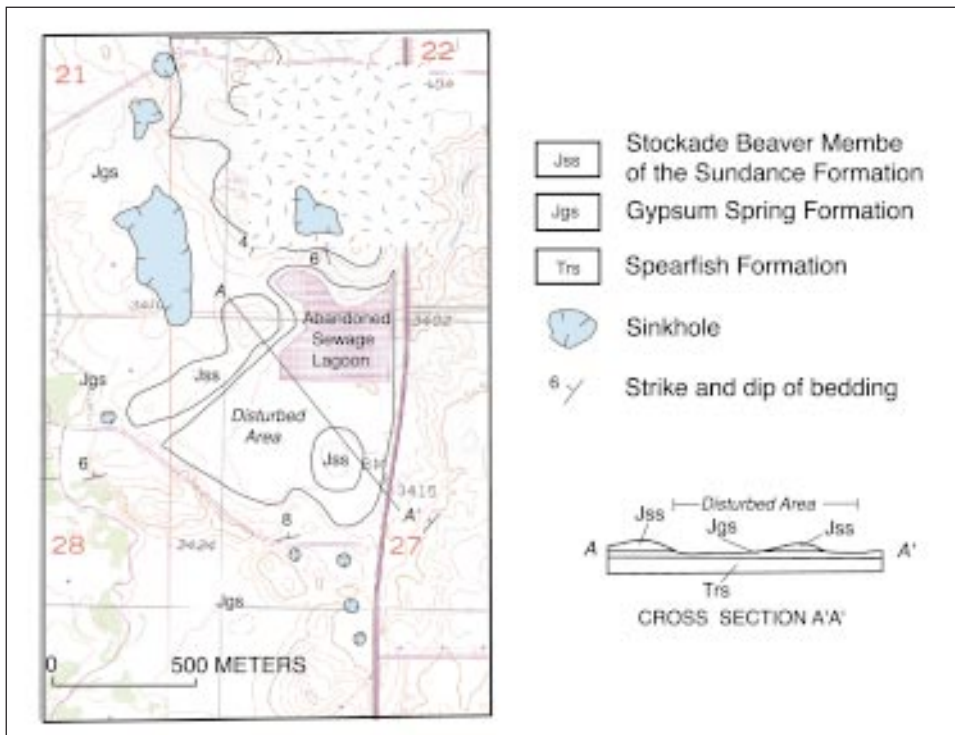


Fig. 19: Geologic map of the abandoned sewage lagoon area west of US 85, 1.5 km north of Spearfish, SD.

Sl. 19: Geološka karta velikega jezera za odplake Z od ceste US 85, to je 1,5 km S od Spearfish, South Dakota.

The lower part of the Spearfish Formation is also undergoing active collapse and is demonstrated to be an aquifer. This zone is more susceptible to rapid infiltration of contaminants than the upper part of the Spearfish, a characteristic which 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 there may be a possible increase in frequency of such collapse in the Spearfish Formation.

## 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 dolines and breccia pipes extending up into the Spearfish and higher formations. Many of these dolines in the Spearfish are sites of resurgent springs where the piezometric surface is above the land surface. Dry steep-walled dolines are located where the piezometric surface lies below the bottom of the doline. The largest dolines 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 piezometric 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. Exposed dolines attest to the former position of the springs. The down-dip migration of these springs is exemplified by Mirror Lake where headward spring migration resulted from continued doline collapse of the headwall of this steephead valley. The location of many of the dolines 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 which 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 the northern Black Hills where urban development is increasing at a rapid rate.

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## **KRAŠKI UDORI V SADRI, BLACK HILLS, SOUTH DAKOTA-WYOMING, ZDA**

### **Povzetek**

Raztapljanje sadre in anhidrita v Minnelusa in Spearfish formacijah na S Black Hills je povzročilo udore, ki so oblikovali deformirano plastnatost, brečaste kope v Minnelusa formaciji ter vrtače in brečaste kope v Spearfish in višje ležečih formacijah. Veliko vrtač v Spearfish formaciji predstavlja mesta z izviri, kjer je gladina talne vode nad površjem. Suhe, strme vrtače se nahajajo tam, kjer je gladina podtalnice pod dnom vrtač. Največje vrtače so rezultat raztapljanja debeloplastnatega anhidrita na površju Minnelusa formacije. S tem ko se čelo raztapljanja Minnelusa anhidrita premika radialno izven centra Black Hills, in ko nivo podzemeljske vode vpade na nižje stratigrafske nivoje, medtem ko se površje zniža z erozijo, sedanji izviri presahnejo, novi pa se razvijajo v smeri regionalnega vpada. Položaj vrtač se sklada z bivšim položajem izvirov. Migracija teh izvirov po vpadu navzdol je ponazorjena z Mirror jezerom, kjer je premik izvira pogojen s postopnim udorom čelne stene te strme doline. Položaj številnih vrtač znotraj spodnjega dela Spearfish formacije se lahko vzporeja z večjo razpokanostjo tega dela Spearfish formacije, zaradi intruzije sadrinih žilic, ki so razvite v močno pretiti matični kamnini. Izviri se nahajajo blizu ali v pomembnejših sadrinih horizontih. Nad tem horizontom ležijo skrilavci in meljevci, ki so neprepustni in preprečujejo dviganje talne vode. Potrebno je upoštevati nastanek kraških procesov v sadri na naseljenih področjih na S Black Hills, kjer naseljenost izredno hitro narašča.