National Evaporite Karst--Some Western Examples

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ABSTRACT

Evaporite deposits, such as gypsum, anhydrite, and rock salt, underlie about one-third of the United States, but are not necessarily exposed at the surface. In the humid eastern United States, evaporites exposed at the surface are rapidly removed by solution. However, in the semi-arid and arid western part of the United States, karstic features, including sinkholes, springs, joint enlargement, intrastratal collapse breccia, breccia pipes, and caves, locally are abundant in evaporites. Gypsum and anhydrite 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. Dissolution of the host evaporites cause collapse in overlying non-soluble rocks, including intrastratal collapse breccia, breccia pipes, and sinkholes. The differences between karst in carbonate and evaporite rocks in the humid eastern United States and the semi-arid to arid western United States are delimited approximately by a zone of mean annual precipitation of 32 inches. Each of these two rock groups behaves differently in the humid eastern United States and the semi-arid to arid west. Low ground-water tables and decreased ground water circulation in the west retards carbonate dissolution and development of karst. In contrast, dissolution of sulphate rocks is more active under semi-arid to arid conditions. The generally thicker soils in humid climates provide the carbonic acid necessary for carbonate dissolution. Gypsum and anhydrite, in contrast, are soluble in pure water lacking organic acids. Examples of western karst include the Black Hills of South Dakota and the Holbrook Basin in Arizona. A draft national map of evaporite karst is presented here.

INTRODUCTION

The present, the map indicating engineering aspects of karst (Davies and others, 1984, scale 1:7,500,000) adequately shows the distribution of carbonate karst in the United States, but the widespread distribution of evaporite karst is inadequately portrayed. The map depicts areas of karstic rocks (limestone, dolomite, and evaporites), and pseudokarst, classified as to their engineering and geologic characteristics (size and depth of voids, depth of overburden, rock/soil interface conditions, and geologic structure).

In the eastern United States, where average annual precipitation commonly is greater than 30 inches, gypsum deposits generally are eroded or dissolved to depths of at least several meters or tens of meters below the land surface. So, although gypsum in the east may locally be karstic, the lack of exposures makes it difficult to prove this without subsurface study of the gypsum and its dissolution features. In the semi-arid western part of the United States, however, in areas where the average annual precipitation commonly is less than about 32 inches, gypsum tends to resist erosion and typically caps ridges, mesas, and buttes. In spite of its resistance to erosion in the west, gypsum commonly contains visible karst features, such as cavities, caves, and sinkholes, attesting to the importance of ground-water movement, even in low-rainfall areas. Salt karst is less common at the earth's surface than gypsum karst because it is so soluble that it survives at the surface only in very arid areas.

While the distribution of carbonate karst on the Davies' map is generally adequate, the map only depicts gypsum karst in a few areas (fig. 1). In an extensive text on the back of the map, caves and fissures in gypsum in western Oklahoma and the eastern part of the Texas Panhandle is mentioned. The

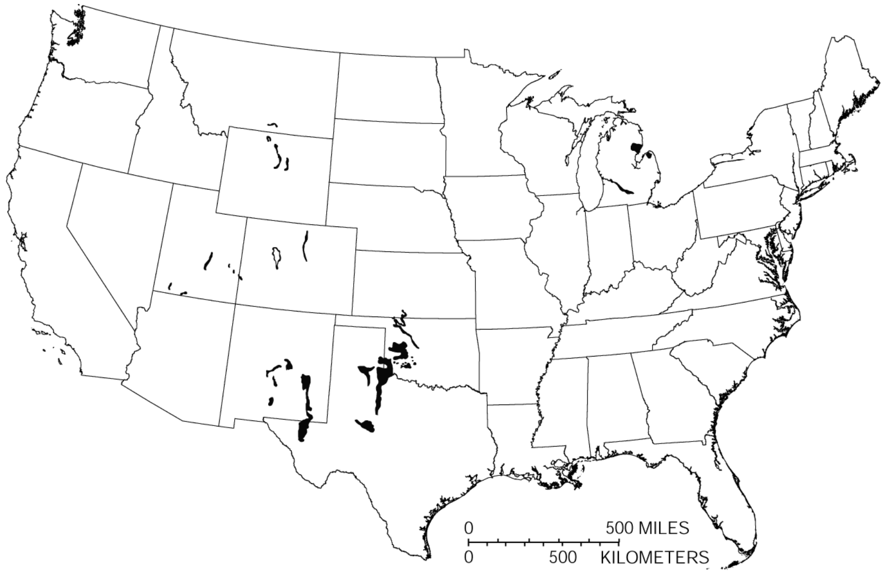

Figure 1. Map showing areas of evaporite karst in the United States, as depicted by Davies and others (1984).

map does not show the distribution of salt or salt karst even though the text mentions natural subsidence and man-induced subsidence due to solution mining in salt beds in south-central and southwestern Kansas.

Several national maps of evaporite deposits were summarized by Epstein and Johnson (2003) who prepared a map showing the present perception of evaporite distribution and evaporite karst in the United States (fig. 2). The map includes gypsum/anhydrite and halite basins, and incorporates the limited areas of evaporite karst depicted by Davies and others (1984) compared to the larger areas of the same shown by Johnson (1997). Collapse due to human activities, such as solution mining, are also shown, as well as a line of mean annual precipitation (32.5 in.) that approximates the boundary between distinctively different karst characteristics, between the humid eastern United States and the semi-arid west. Also shown are the Holbrook Basin in Arizona and the Black Hills of South Dakota and Wyoming, whose variety of surface and subsurface evaporite-karst features are described here.

HOLBROOK BASIN, ARIZONA

Many workers have reported a variety of evaporite- and carbonate-karst features in Arizona (fig. 3A) that are not found on Davies (1984) map (fig. 3B). Subsurface halite deposits were mapped by Eaton and others (1972), Johnson and Gonzales (1978), Ege (1985), and Neal and others (1998); more detailed mapping of salt deposits in the Holbrook Basin was done by Peirce and Gerrard (1966) and Rauzi (2000). An area of breccia pipes was delimited in northwest Arizona by Harris (2002); they were probably the result of collapse over carbonate rocks, but evaporite collapse could not be ruled out. Scattered gypsum and anhydrite localities were shown by Withington (1962). Comparing this composite map with the Davies map (fig. 3*B*) shows that many types of karstic features could be shown in both evaporite and carbonate rocks in Arizona.

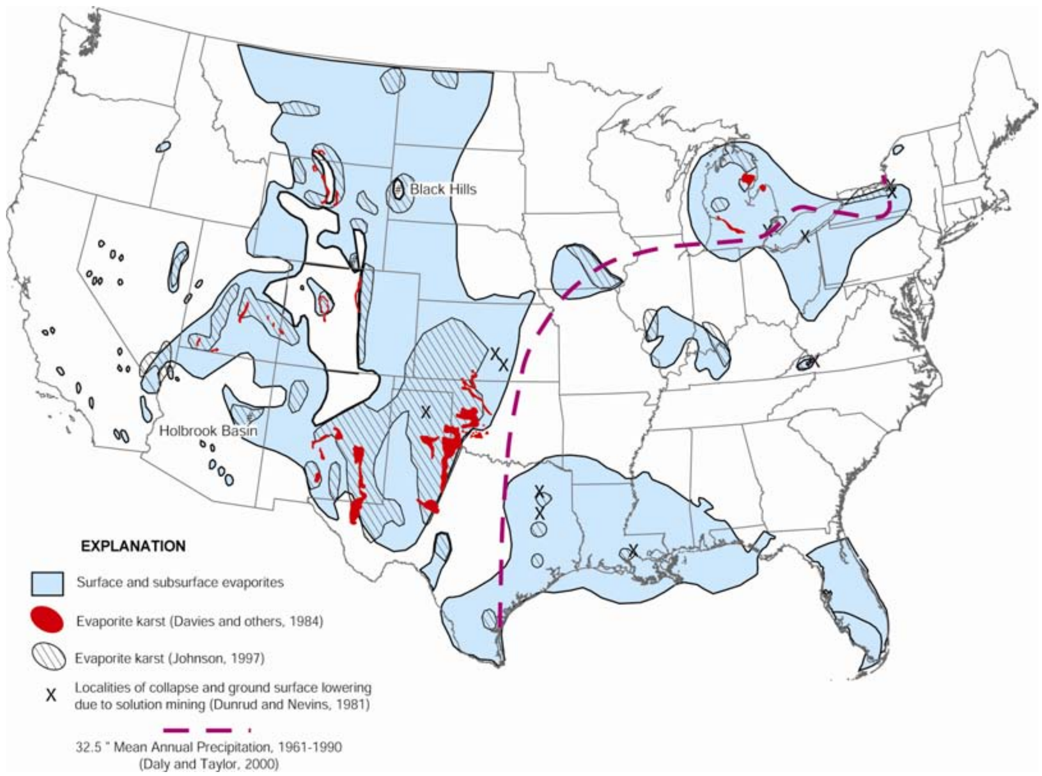

Figure 2. Distribution of outcropping and subsurface evaporite rocks in the United States and areas of reported evaporite karst (from Epstein and Johnson, 2003). The 32.5" mean-annual-precipitation line approximates a diffuse boundary between eastern and western karst.

The Holbrook Basin in east-central Arizona demonstrates that dissolution of deeply buried evaporites can cause subsidence of overlying non-soluble rocks. The basin is more than 100 miles wide and contains an aggregate of about 1,000 feet of salt, anhydrite, and sylvite interbedded with clastic red beds in the Permian Sedona Group (formerly the Supai Group) (Peirce and Gerrard, 1966; Neal and others, 1998; Rauzi, 2000). The top of the salt is between 600 and 2,500 ft below the surface (Mytton, 1973). These workers describe the removal of evaporites at depth along a northwest-migrating dissolution front, causing the development of presently active collapse structures in the overlying Coconino Sandstone and Moenkopi Formation.

For example, in the area about 10 mi northwest of Snowflake, AZ, the Coconino and other rocks dip monoclinally southward along the Holbrook anticline towards a large depression enclosing a dry lake. The depression is the result of subsidence due to evaporite removal. Collapse extends upwards from the salt, forming a network of spectacular sinkholes in the overlying Coconino Sandstone (fig. 4, 5*A*) (Neal and others, 1998; Harris, 2002). Draping of the Coconino has caused opening of extensive tension fissures, some of which are many tens of feet deep (Neal and others, 1998; Harris, 2002) (Fig. 5*B*). If the definition of “karst” is allowed to include subsidence structures due to the dissolution and removal of soluble rocks below and extending upwards into non-soluble rocks, then a separate map category may be needed to delineate these rocks. Thus, any karst map must show non-soluble rocks whose collapse structures are the result of dissolution of evaporite rocks below. A somewhat similar situation prevails in the Black Hills of South Dakota and Wyoming and was alluded to at Stops 3 and 4 of the Southern Field Trip (Epstein, Agenbroad, and others, this volume, 2005).

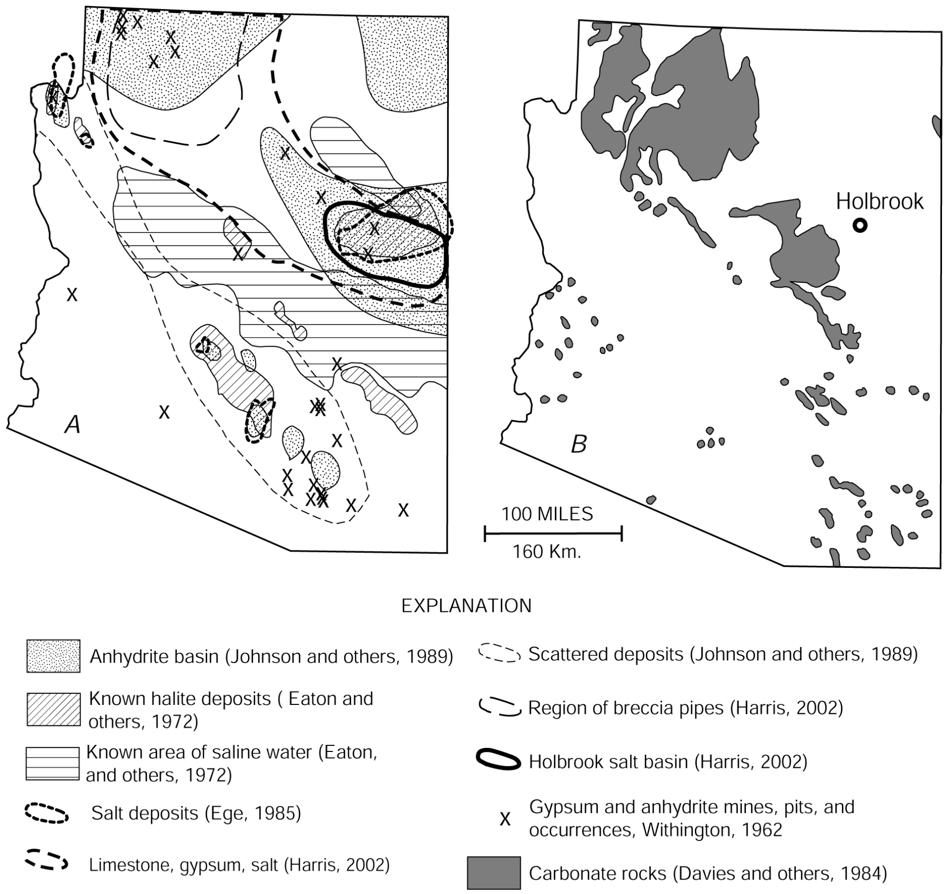

Figure 3. Maps comparing types and distribution of karst features in Arizona: A) distribution of evaporite and carbonate karst as presented by various authors; B) distribution of carbonate karst (no evaporite karst was shown) as presented by Davies and others (1984).

BLACK HILLS, WYOMING AND SOUTH DAKOTA

In the semi-arid Black Hills of Wyoming and South Dakota, significant deposits of gypsum and lesser anhydrite are exposed at the surface in several stratigraphic units (Table 1, Epstein and Putnam, *this volume*), including the Minnelusa, Spearfish, and Gypsum Spring Formations. The field guides that accompany this volume document many of the karst features found in these rocks. The outcrop pattern of sedimentary units in the Black Hills is controlled by erosion on an irregular domal uplift about 130 mi long and 60 mi wide. The central core of Precambrian rock is surrounded by four zones of sedimentary rock with contrasting lithologies and differing karst features. These are, from the center (oldest) outwards: (1) The limestone plateau, made up of Cambrian to Pennsylvanian limestone, dolomite, and silici-clastic rocks, and containing world-class caves such as Wind and Jewel Caves in the Pahasapa Limestone. Overlying these limestones is the Minnelusa Formation, which contains as much as 235 ft of anhydrite in its upper half in the subsurface. This anhydrite has been dissolved at depth, producing a variety of dissolution structures (Stop 1, Epstein, Agenbroad, and others, *this volume;* and Stop 4, Epstein, *this volume*). (2) The Red Valley, predominantly underlain by red beds of the Spearfish Formation of Triassic and Permian age and containing several gypsum beds totaling more than 75 ft thick in places. Dissolution of these evaporites, and those in underlying rocks, has produced shallow depressions and sinkholes, some of which are more than 50 ft deep (Stops 8 and 9, of Epstein, Davis, and others, 2005, this volume). The Gypsum Spring Formation, which overlies the Spearfish, contains a gypsum unit, as much as

15 feet thick, that has developed abundant sinkholes in places. (3) The "Dakota" hogback, held up by resistant Sandstone of the Inyan Kara Group of Cretaceous age, and underlain by shales and sandstones of the Sundance and Morrison Formations. Collapse structures, such as breccia pipes and sinkholes, extend up through some of these rocks from underlying soluble rocks, probably in the Minnelusa Formation. (4) Impure limestone and shale extending outward beyond the hogback, some of which are shown as karstic units on the map of Davies and others (1984), but such features are unknown in those rocks.

Figure 6 compares the map of limestone outcrops shown by Davies and others (1984) for the Black Hills of South Dakota with the more detailed categories that are proposed here, including carbonate and evaporite karst, intrastratal karst, and nonsoluble rocks with collapse features due to dissolution of other rock units at depth. This characterization may also be suitable for other areas of the western United States.

Anhydrite in the Minnelusa is generally not seen in surface outcrops. It has been, and continues to be, dissolved at depth, forming collapse breccias, breccia pipes, and sinkholes that extend upwards more than 1,000 ft into overlying units. Mapping this intrastratal karst is fairly easy, because the outcrop distribution of the Minnelusa is well known. At depth, brecciation of the upper part of the Minnelusa has developed significant porosity, resulting in an important aquifer. Ground water migrates along breccia pipes that extend upwards through overlying formations. A migrating dissolution front (Epstein, 2001; 2003) similar to the situation reported for the Holbrook Basin in Arizona, is summarized below.

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 (Braddock, 1963; Brobst and Epstein, 1963). Where anhydrite is present in the Minnelusa, its rocks are not brecciated or only slightly so. 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, Mud Lake, Mirror Lake, and McNenny Springs (Stop 8, Epstein, Davis, and others, *this volume*), are near the position of the dissolution front. 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 (see figure 8, Epstein, Davis, and others, *this volume*) attest to the former position 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 up-dip 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.

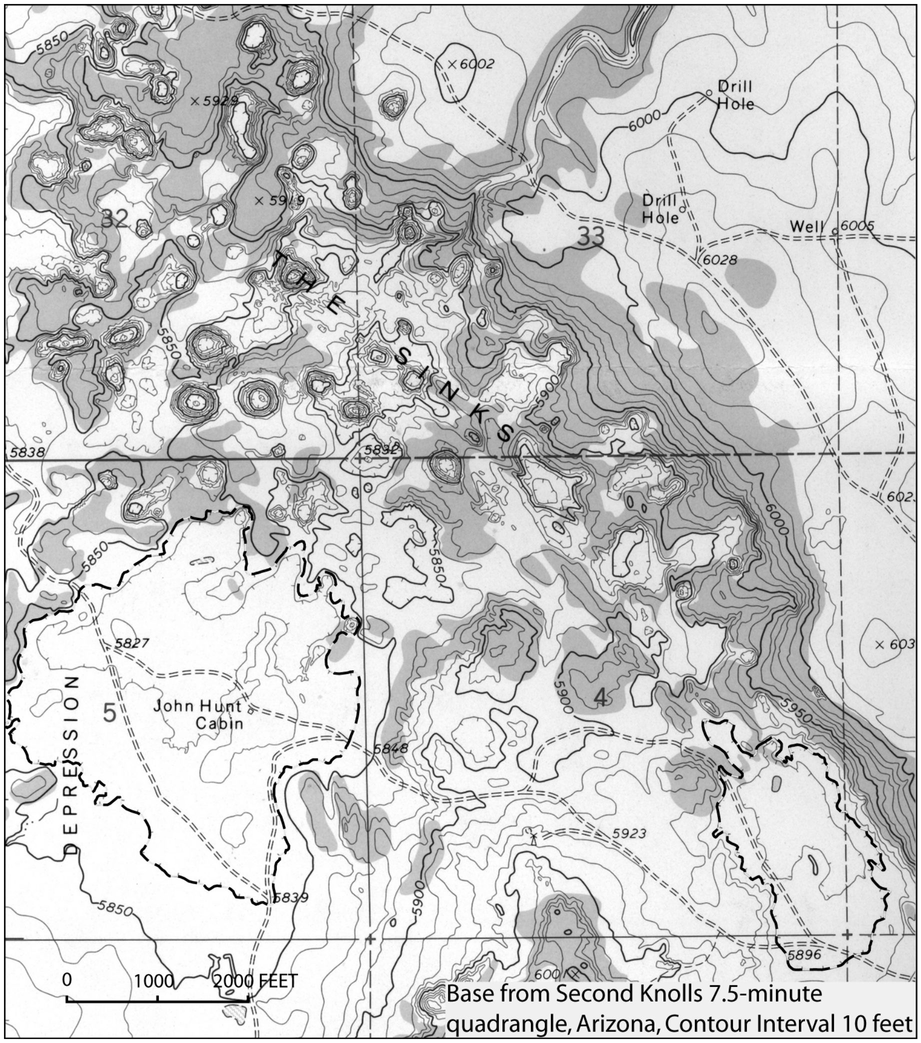

Figure 4. Topographic map of "The Sinks", a series of depressions in the Coconino Sandstone, about 10 miles northwest of Snowflake, Arizona, in the Holbrook Basin. Wide depressions are highlighted with a dashed line; the one in the southwest corner of the map is about one mile long. Other depressions are as much as 100 feet deep.

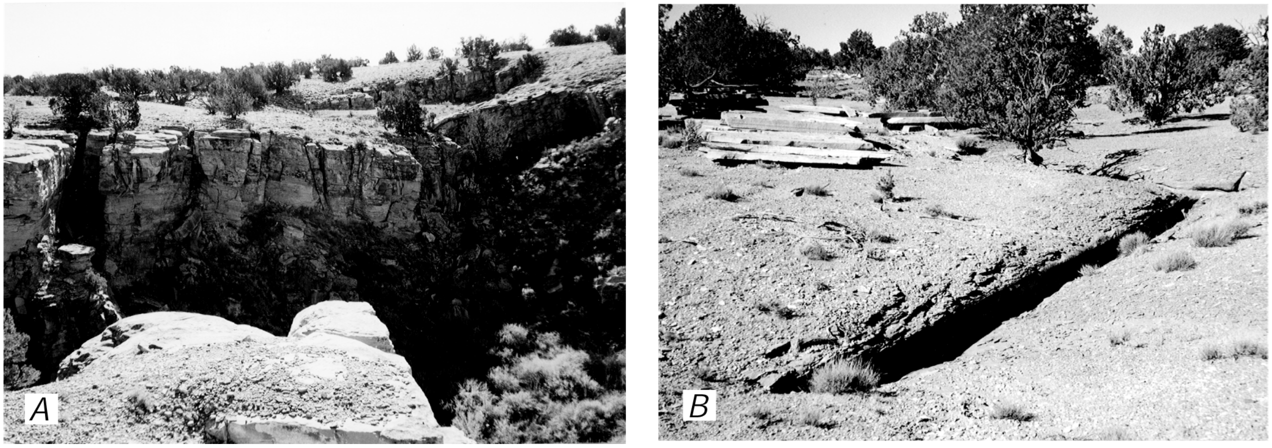

Figure 5. Collapse structures in clastic rocks overlying the salt-bearing Sedona Group in the Holbrook Basin, 8-10 mi northwest of Snowflake, AZ. A) Steep-sided sinkhole in a hole-pocked area called "The Sinks," located in the Coconino Sandstone. Note the variable amount of subsidence along major joints. B) Open tension fractures in the Moekopi Formation caused by flexure of the Holbrook "anticline" (actually a monocline) due to dissolution of salt at depth. Also see figures in Harris (2002).

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 (See figure 15, Stop 8, Northern Field trip Guide). This circular area, about 200 ft across, might eventually replace McNenny Springs.

Age of Brecciation

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 opening up within the last 20 years (See figure 26, Epstein, Davis and others, this volume), collapse in water wells and natural springs resulting in sediment disruption and contamination, fresh circular scarps surrounding shallow depressions, and calcium sulphate and sodium chloride issuing from spring water throughout the Black Hills.

The brecciation of the upper part of the Minnelusa formation occurred after the up-dip portion of the Minnelusa was breached following uplift. Ground water was then able to penetrate the impermeable layers overlying the Minnelusa and the anhydrite was dissolved. Darton and Paige (1925) found "older terrace deposits" with Oligocene fossils on the Minnelusa, indicating that the breaching of the Minnelusa occurred before the Oligocene and after the Late Cretaceous uplift.

An earlier alternative explanation for the cause and timing of brecciation was given by Bates (1955) who believed the brecciation occurred almost concurrently with the deposition of the Minnelusa when ground water converted the anhydrite to gypsum and the resulting expansion heaved and shattered the surrounding strata leaving jumbled blocks that were reworked by the sea. However, field evidence supports the conclusion that brecciation occurred after, not during, the deposition of the Minnelusa. Disruption of bedding in the Minnelusa and in higher stratigraphic units becomes less intense upwards from the zone of anhydrite removal in the Minnelusa (Stop 1, Epstein, Agenbroad, and others, 2005, *this volume*). Subsidence effects in the overlying formations also become less dramatic. The resistant, thin, Minnekahta Limestone, lying between the red beds of the Opeche Shale and Spearfish Formation, contains few collapse features; some sinkholes penetrate the entire thickness of the Minnekahta and are therefore result of collapse from below (Stop 3, Epstein, Davis, and others, *this volume*). The most significant effect on the Minnekahta is the undulations seen in outcrop everywhere in the Black Hills. Breccia pipes and sinkholes are known as high as the Lakota Formation, about 1,000 feet above the Minnelusa.

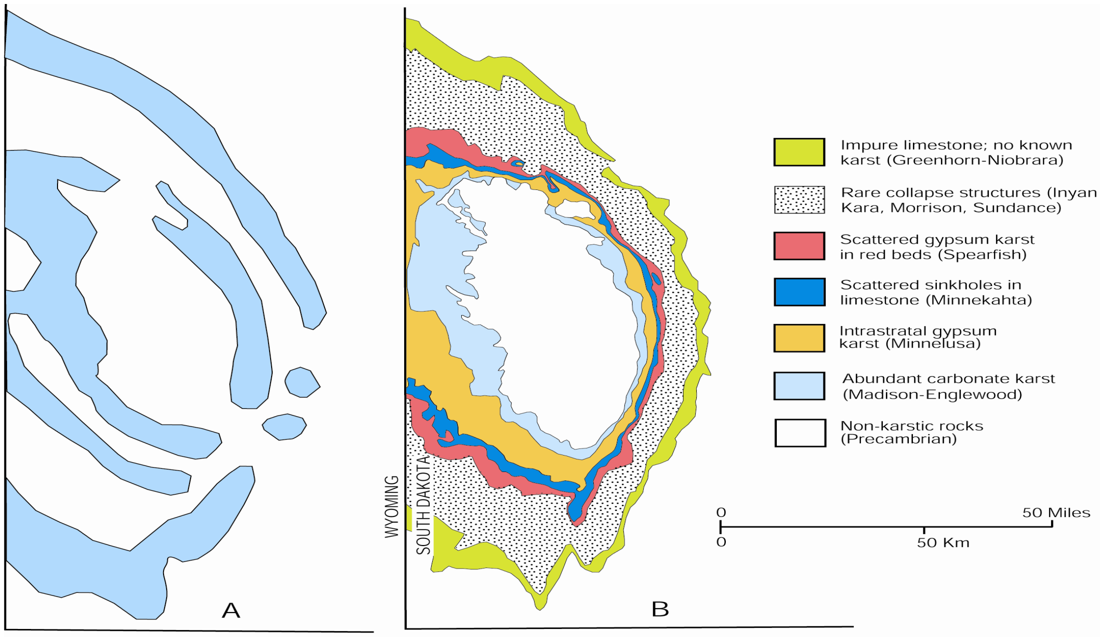

Figure 6. Maps comparing depiction of karst areas in the Black Hills of South Dakota: A) carbonate-karst units, as presented by Davies and others (1984); B) carbonate- and evaporite-karst units, as herein proposed for a new national karst map.

There are several places in the Black hills where bedding in the Minnelusa is moderately or steeply dipping and intruded by breccia pipes. If the pipes formed soon after deposition of Minnelusa sediments, they should be nearly right angles to bedding. Such is not the case, as seen at mileage 59.3 in the Southern Field trip Guide, where the dip of bedding is moderate and shown in figure 8 where the dip is steeper.

HUMID VERSUS SEMI-ARID KARST

Comparing the known locations of surface evaporite karst with a map showing annual average rainfall shows a striking relationship between precipitation and the occurrence of evaporite karst (fig. 2). Most occurrences of surficial karst in gypsum shown in figure 2 lies west of a zone with annual precipitation of about 32 inches (represented by the 32.5-inch isobar). Many of the karst areas shown in figure 2 are due to dissolution at depth. In Michigan, earlier studies suggest that the karstic collapse features there were formed soon after deposition of the Devonian evaporites (Landes, 1945), but Black (1997) showed that sinkhole development occurred after the most recent glaciation.

The degree to which soluble rocks are dissolved depends, in part, on the amount of rainfall and the solubility of the rock. Sulphate-bearing rocks--gypsum and anhydrite--are perhaps 10-30 times more soluble in water than carbonate rocks (Klimchouk, 1996). Both carbonates and sulphates behave differently in the humid eastern United States and the semi-arid to arid west. Low ground-water tables and decreased ground-water circulation in the west does not favor rapid carbonate dissolution and development of karst. In contrast, sulphate rocks are dissolved much more readily and actively than carbonate rocks, even under semi-arid to arid conditions. The presence of extensive karst in carbonates in the west probably dates to a more humid history. Additionally, the generally thicker soils in humid climates provide the carbonic acid that enhances carbonate dissolution. Gypsum and anhydrite, in contrast, are more readily soluble in water that lacks organic acids. This relationship suggests an interesting area for future study.

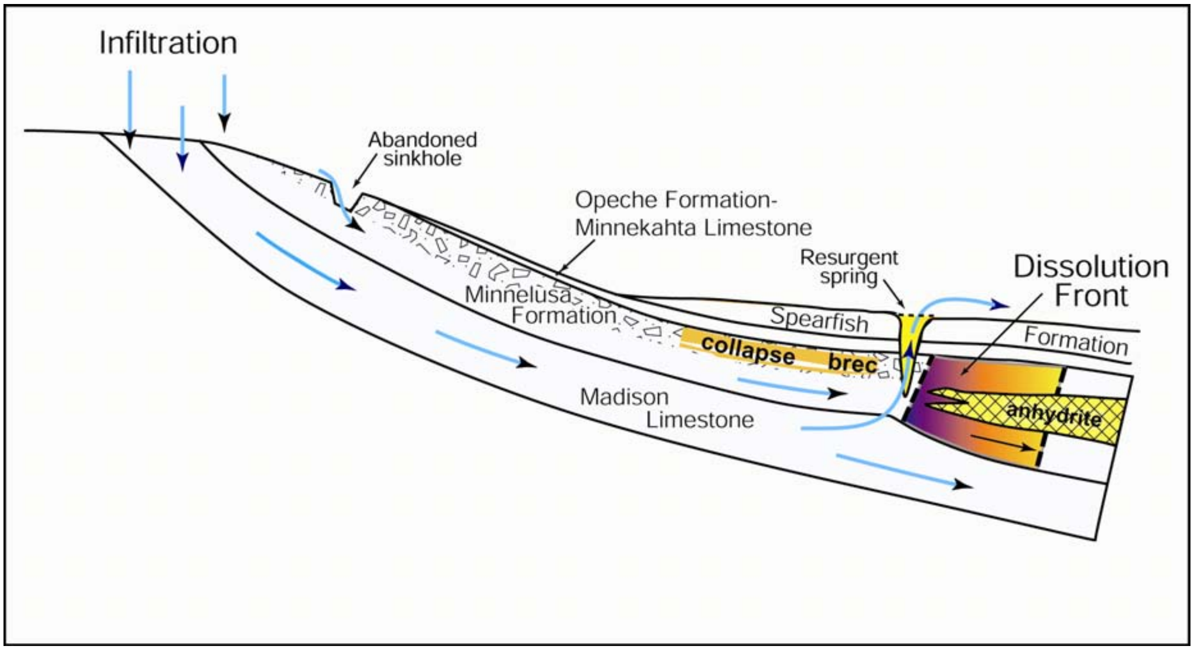

Figure 7. Dissolution of anhydrite in the Minnelusa Formation and down-dip migration of the dissolution front.

In the eastern United States karstification occurs by acid-charged water percolating *downward*, altering soluble rocks below. While this is partly true in the west, much of the karst, such as in the Black Hills, is produced by artesian water migrating *upward*, affecting overlying rocks in a different manner than in the humid east. Thus, as shown above, non-soluble rocks bear the imprint of karst.

HUMAN-INDUCED KARST

It is well known that subsidence in karstic rocks can be exacerbated by human activities. Lowering of the water table by well-pumping or by draining of quarries can reduce support of soils overlying sinkholes, thus causing their collapse. Subsurface mining of salt and other evaporites may eventually cause collapse of overlying rocks, such as at the Retsof mine in Livingston County, NY (Nieto and Young, 1998; Gowan and Trader, 2003). Localities of subsidence due to solution mining were mapped by Dunrud and Nevins (1981) and are shown in figure 2. The bibliographic list of ground subsidence due to evaporite dissolution of Ege (1979) contains many instances where such subsidence was due to human activities. Knowing the location of shallow and deep mines is important to local officials, in order to understand the potential for such subsidence. For example, abandoned gypsum mines in western New York are abundant, and recent settlement of many houses near Buffalo, New York, partly may be the result of subsidence over these mines.

Figure 8. Near-vertical breccia pipe (short dash) in steeply dipping beds (long dash) of the Minnelusa Formation, Frannie Peak Canyon, Fanny Peak 7.5-minute Quadrangle, six miles southeast of Newcastle, Wyoming, NW1/4 SE1/4, T. 44 N., R. 60 W.

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